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Morejon, Santiago

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COOPERATIVE RESOURCE ALLOCATION IN 6G PROXIMITY NETWORKS FOR ROBOTIC SWARMS

BY
CARLOS SANTIAGO MOREJÓN GARCÍA

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Cooperative Resource Allocation in 6G Proximity Networks for Robotic Swarms

Ph.D. Dissertation

Carlos Santiago Morejón García

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PhD supervisor:	Prof. Preben Mogensen Aalborg University
Assistant PhD supervisor:	Snr. Specialist Ph.D. Nuno Kiilerich Pratas Nokia Standards Aalborg
PhD committee:	Associate Professor Jimmy Jessen Nielsen (chairman) Aalborg University, Denmark Professor Yonghui Li University of Sydney, Australia Senior Mobile RAN architect Henrik Lehrmann Christiansen TDC NET, Denmark
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Curriculum Vitae

Carlos Santiago Morejón García

C. Santiago Morejón García received his B.Sc. degree in telecommunication engineering from Escuela Politécnica Nacional (Ecuador) in 2012 and his M.Sc. degree in mobile communications from EURECOM/Telecom ParisTech (France) in 2017. From 2012 he has worked in different private companies and public institutions including the Ecuadorian telecommunications regulator (ARCOTEL) and the Ecuadorian public national mobile operator (CNT EP). Since 2019, he pursues his PhD degree at the Electronic Systems Department from Aalborg University (Denmark) in collaboration with Nokia Standards Aalborg. His research interests include radio resource management and interference mitigation for decentralized networks using 3GPP 5G NR sidelink.

Abstract

In recent years, applying swarms of robots to industrial production has been gaining traction thanks to the fourth industrial revolution (industry 4.0). It is motivated by the need for different industries to transition from linear and centralized production lines to more flexible arrangements that enable the re-organization of the production lines in a timely manner. It can be accomplished by introducing mobile robotic platforms interacting with each other. This interaction demands stringent communication requirements among robots to achieve the same levels of reliability as in current linear production, where wired connections are used to deliver the required performance. These requirements include high throughput, low latency, and high reliability, such as 99.99% reliability for data transmissions of at least 10 Mbps data rate with a maximum of 10 ms latency. These requirements are similar to those established by the 3rd Generation Partnership Project (3GPP) during its study of new Vehicular to Anything (V2X) services, including the collective perception of the environment as a use case, which is the essential use case for production supported by robotic swarms.

Enabling such an interaction requires wireless communication where resource allocation of time-frequency resources and interference management can be either centralized (i.e., assisted by the network) or decentralized (i.e., done by the devices themselves). By considering a decentralized approach, 3GPP, in its release 14 of the standard, has introduced device-to-device communication as a sidelink mode 4 resource allocation scheme, which evolved to NR sidelink mode 2 (mode 2) in release 16. However, fulfilling the swarm's stringent communication requirements may be challenging as the performance of mode 2 is degraded due to half-duplex problems (e.g., a device selecting to transmit at a time where other device(s) are transmitting to it) and interference (e.g., due to devices selecting the same time-frequency resources). These issues directly affect communication performance and worsen as the swarm size increases. Therefore, the mode 2 resource allocation by itself is not sufficient to achieve the performance requirements associated with swarm production robots' communication requirements.

This research incorporates cooperative capabilities and well-known techniques to efficiently fulfill the swarm production robot's communication requirement. The first part of the thesis addresses the proof of concept of integrating two different cooperative resource allocation schemes into the mode 2 and compares their performance against the mode 2 baseline. In the first scheme, denoted as *"device sequential"*, the resource allocation is achieved by applying a sequential order, while in the second scheme, the resource allocation, denoted as *"group scheduling"*, is performed by the leader of a group of user equipment (UE)s. For this purpose, a sidelink system-level simulator was developed to simulate the resource allocation and the associated communication between a swarm of devices. The two proposed schemes were evaluated in terms of outage capacity and occupancy per NR slot of system-level simulations for different swarm sizes. In the second part of the thesis, the signaling design of each of the proposed schemes was studied in order to evaluate the impact of the signaling exchange on each scheme's performance and compare it with the mode 2 baseline. The study includes a detailed analysis of the causes of data transmission failures by the different forms of half-duplex and interference problems. It is demonstrated that this knowledge allows incorporating specific techniques to mitigate its effect. In addition to the two proposed schemes, a method was proposed to diminish the presence of a half-duplex between data transmissions and signaling. Beyond that, other well-known techniques were added to reduce data half-duplex and different forms of interference. These techniques include re-transmission schemes and link adaptation, selected according to the use case requirements and added to the system-level simulator. The evaluation of the signaling impact shows a reduction in the performance compared to when the explicit modeling of the signaling overhead was considered error-free. Despite this performance reduction, they outperform the mode 2 baseline by order of magnitude, fulfilling the requirements for more than double of the swarm size.

Even thoughthe application of the two schemes (including different enhancements to these schemes, such as re-transmissions and link adaptation) considerably increases the supported swarm size, interference becomes a critical issue when the swarm size grows enough. It motivates the third part of this thesis, which studies the impact of spatial diversity when robots are equipped with directional antennas, producing beams selected for data transmission and/or reception. It consists of studying the effect of transmitter and/or receiver beam selection on the interference in all schemes. It includes an analytical study, supported by system-level simulations, covering the benefits of beam selection for reliability improvement when not all the allocated NR slots suffer from half-duplex. The potential of beam selection is revealed as it increases the swarm's density of all schemes, but it is more noticeable for the cooperative ones. Based on the presented results, recommendations for indoor factory implementation are provided.

Resumé

I de senere år har anvendelsen af robotsværme til industriel produktion vundet indpas takket være den fjerde industrielle revolution (industri 4.0). Industrien har behov for at gå fra lineære og centraliserede produktionslinjer til mere fleksibel produktion, som muliggør en hurtig omstrukturering af produktionslinjen. Dette kan opnås ved brug af mobile robotplatforme, der interagerer med hinanden. Denne interaktion stiller strenge kommunikationskrav til robotterne, der skal opnå samme pålidelighed som tilsvarende komponenter i nuværende lineære produktionslinjer, hvor kablede forbindelser opfylder kommunikationskravene. Kravene er høj hastighed, lav latenstid og høj pålidelighed, såsom 99,99% pålidelighed for datatransmissioner med hastighed på mindst 10 Mbps med maksimalt 10 ms latenstid. Disse krav svarer til krav fastsat af 3rd Generation Partnership Project (3GPP) under deres undersøgelse af nye Vehicular to Anything (V2X) brugsscenarier, herunder kollektiv opfattelse af miljøet, hvilket også er det essentielle aspekt i en produktion understøttet af robotsværme.

Interaktion i robotsværmen kræver trådløs kommunikation, hvor ressourceallokering af tidsfrekvensressourcer og interferensstyring enten kan være centraliseret (dvs. assisteret af netværket) eller decentraliseret (dvs. styret individuelt af enhederne). 3GPP har inkluderet en mekanisme til decentral ressourceallokering i den 14. udgave af standarden under navnet sidelink mode 4, som har udviklet sig til NR sidelink 2 (mode 2) i den 16. udgave. Opfyldelse af de strenge kommunikationskrav er dog besværliggjort af udfordringer med halv-dupleks (fx kan en enhed gå glip af en indkommende transmission, hvis den samtidig er i gang med at transmittere), og interferens, (når flere enheder vælger at anvende den samme ressource til transmission). Disse problemer har direkte påvirkning på kommunikationen og forværres, når antallet af enheder i robotsværmen forøges. Derfor er der behov for forbedringer af mode 2, som kan sikre, at kommunikationskravene for robotsværme i industriel produktion opnås. I denne afhandling inkorporeres kooperative evner og velkendte teknikker til effektivt at opfylde kommunikationskrav for robotsværme i industriel produktion. Den første del af afhandlingen omhandler bevisførelse for integrering af 2 forskellige kooperative ressourceallokeringssystemer i mode 2, og sammenligner deres effektivitet imod mode 2's udgangspunkt. I det første system, betegnet som "enhedssekventiel allokering", opnås ressourceallokeringen ved at benytte en fortløbende rækkefølge, hvorimod ressourceallokeringen i det andet system kaldet "gruppeallokering" udføres af lederen af en gruppe af brugerudstyr (UE). For at muliggøre sammenligning af mekanismerne, er der udviklet en systemniveau simulator, for at kunne simulere ressourceallokeringen og den associerede kommunikation imellem en sværm af enheder. De 2 foreslåede systemer er blevet evalueret på udfaldskapacitet og belægningsgraden per NR slot i systemniveau-simuleringerne ved forskellige sværmstørrelser.

I anden del af afhandlingen undersøges signaleringsdesignet for kooperativ ressourceallokering for at studere påvirkningen af signaludvekslingen på mekanismernes ydeevne, og vurdere om de stadig kan udkonkurrere mode 2. Undersøgelsen omfatter en detaljeret analyse af årsagerne til datatransmissionsfejl på grund af de forskellige former for halv-dupleks og interferensproblemer. Det demonstreres, at denne viden gør det muligt at inkorporere specifikke teknikker, der kan reducere transmissionsfejl. Der foreslås en metode til at mindske halv-dupleks mellem datatransmissioner og signalering. Samtidig giver andre velkendte teknikker en reduktion af de forskellige former for halv-dupleks og interferens. Disse teknikker omfatter retransmissionsteknikker og linktilpasning, specifikt udvalgt i henhold til use case kravene og er tilføjet systemniveau simulatoren. Evalueringen af signaleringsdesignet viser en reduktion i effektiviteten af de kooperative ressourceallokerings-mekanismer sammenlignet med det tidspunkt, hvor den eksplicitte modellering af signaleringsoverhead blev bedømt fejlfri. Til trods for reduktionen i effektiviteten udkonkurreres mode 2 med en størrelsesorden, der opfylder kravene for dobbelt så tæt en sværm.

Selvom brugen af de 2 systemer (inklusiv forskellige forbedringer på disse systemer så som retransmission og link-tilpasning), øger tætheden betydeligt, hvorved kommunikationskravene bliver opfyldt, bliver interferens et kritisk problem, når sværmen bliver tilstrækkeligt stor. Dette motiverer den tredje del af denne afhandling, som analyserer virkningen af rumdiversitet, når robotter er udstyret med retningsbestemte antenner, der producerer retningsbestemte stråler, hvor data transmitteres og/eller modtages. Det indebærer også en undersøgelse af sender og/eller modtager stråleudvælgelse og dets påvirkning på interferens i de forskellige kooperative ressourceallokeringsmekanismer. Derudover afdækker den et analytisk studie, understøttet af systemniveau simuleringer, af hvordan pålideligheden bliver forbedret, når ikke alle de allokerede NR slots lider af halv-dupleks. Stråleudvælgelse har potentiale til at øge tætheden af sværmen, men den største forbedring ses for de kooperative mekanismer. Baseret på de præsenterede resultater gives anbefalinger til implementering af robotsværme i indendørs fabrikker.

Contents

Glossary

1G first generation

2G second generation

3G third generation

3GPP 3^{rd} generation partnership project

4G fourth generation

5G fifth generation

6G sixth generation

ACK acknowledgement

AGV automated guided vehicle

AMRs autonomous mobile robots

AWGN additive white gaussian noise

BLER block error rate

CA carrier aggregation

CAMs cooperative awareness messages

CCDF complementary cumulative distributed function

CDF cumulative distributed function

CSI channel state information

D2D device-to-device

DM discovery message

eMBB enhanced mobile broadband

eNodeB evolved node B

FR1 frequency range 1

gNB next generation node B

GNSS global navigation satellite system

HARQ hybrid automatic repeat request

HPBW half power beam width

HSPA high speed packet access

IUC inter-UE coordination

KPI key performance indicator

LAAG link adaptation by aggregation

LIDAR light detection and ranging

LTE long term evolution

LTE-A LTE-Advanced

MBB mobile broadband

MCS modulation and coding scheme

MIC mean instantaneous capacity

mMTC massive machine type communication

mmW millimeter wave

MRC maximum ratio combining

NACK negative acknowledgment

NLOS non-line-of-sight

NR new radio

OLPC outer loop power control

PIR packet inter-reception

PPPP ProSe per packet priority

ProSe proximity services

PSCCH physical sidelink control channel

PSFCH physical sidelink feedback channel

PSSCH physical sidelink shared channel

PTT push to talk

QAM quadrature amplitude modulation

QoS quality of service

RM resource selection message

RSRP reference signal received power

RSRP reference signal received quality

SCI sidelink control information

SINR signal-to-noise-plus-interference ratio

SISO single input single output

SL sidelink

SPS semi-persitent scheduling

TTI transmission time interval

UAV unmanned aerial vehicle

UE user equipment

UGV unmanned ground vehicle

V2I vehicle to infrastructure

V2X vehicle to anything

Thesis Details

Thesis Title: Cooperative Resource Allocation in 6G Proximity Networks for Robotic Swarms
PhD Student: Carlos Santiago Morejón García
Supervisors: Prof. Preben Mogensen. Aalborg University
Snr. Specialist Ph.D.
Nuno Kiilerich Pratas. Nokia Standards Aalborg

This PhD thesis is the result of three years of research at the Wireless Communication Networks (WCN) section (Department of Electronic Systems, Aalborg University, Denmark) in collaboration with Nokia Standards (Aalborg). The work was carried out in parallel with mandatory courses required to obtain the PhD degree.

The main body of the thesis consists of the following articles:

Paper A: S. Morejon, R. Bruun, T. Sørensen, N. Pratas, T. Madsen, J. Lianghai and P. Mogensen, "Cooperative Resource Allocation for Proximity Communication in Robotic Swarms in an Indoor Factory", *IEEE Wireless Communications and Networking Conference (WCNC)*, March 2021.

Paper B: R. Bruun, S. Morejon, T. Sørensen, N. Pratas, T. Madsen and P. Mogensen, "Signaling Design for Cooperative Resource Allocation and its Impact to Reliability", submitted in *IEEE Access*, 2022.

Paper C: S. Morejon, R. Bruun, T. Sørensen, N. Pratas, T. Madsen, J. Lianghai and P. Mogensen, "Decentralized Cooperative Resource Allocation with Reliability at Four Nines", *IEEE Global Communications Conference (GLOBECOM)*, December 2021.

Paper D: S. Morejon, R. Bruun, F. Fernandes, T. Sørensen, N. Pratas, T. Madsen and P. Mogensen, "New Radio Sidelink with Beam Selection for Reliable Communication in High-Density Robotic Swarms", submitted in *IEEE Latin-American Conference on Communications (LATINCOM)*, December 2022.

Paper E: S. Morejon, R. Bruun, F. Fernandes, T. Sørensen, N. Pratas, T. Madsen and P. Mogensen, "Robust Decentralized Cooperative Resource Allocation for High-Dense Robotic Swarms by Reducing Control Signaling Impact", submitted in *IEEE Access*, 2022.

This thesis has been submitted for assessment in partial fulfilment of the PhD Degree. The thesis is based on the submitted or published papers that are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and also available at the Faculty.

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Carlos Santiago Morejón García
Aalborg University, August 2022

Part I

Introduction

Introduction

The appearance of a new mobile communication generation brings a set of new characteristics and capabilities reflected in new products and services to businesses and users. It started back in the ’80s when the first generation (1G) employed analog-based wireless connectivity to allow users to make phone calls while in the network’s coverage. In the early ’90s, the adoption of digital communications in second generation (2G) allowed the introduction of new services such as SMS and data connectivity. However, the latter became important after the mobile broadband (MBB) revolution appearance in the third generation (3G) and later fourth generation (4G), where the efforts were focused on increasing the average and peak data rates. In 4G, also known as long term evolution (LTE), direct device-to-device (D2D) were introduced as the first standard to provide proximity services (ProSe) using cellular communications [1]. It was introduced by 3^{rd} generation partnership project (3GPP) on its release 12 and has been evolving in subsequent releases, being public safety the major target application, and lately, vehicle to anything (V2X) communication [2]. The ongoing fifth generation (5G), a.k.a. new radio (NR), opens the door to new applications and services [3] by providing higher reliability to high-throughput data transmissions with lower latency for D2D, which includes ProSe and V2X. It is possible thanks to the introduction of coordination to the resource allocation between devices when using the sidelink (SL) autonomous mode (mode 2) in release 17 of the standard [4].

One of the use cases that lately has gathered much interest is the fourth industrial revolution (Industry 4.0), representing a new paradigm on how production will be carried out in an industrial factory. It proposes transforming a linear production into a modular one that provides flexibility and reconfiguration capabilities [5]. Achieving such change is a big challenge since a linear production consists of several elements interacting with cables connected to a centralized controller. Then, it is necessary to replace part of the cables with wireless communication links and set up a manufacturing control center by enabling its operation in remote edge-cloud configuration [5]. Additionally, autonomous mobile robots (AMRs) are in charge of moving items across the sparse modules in the factory [5]. Swarm-based production is an enabler for such a framework since several simple agents can collaborate to perform a task that can only be done by a complex and highly specialized one [6]. The replacement of part of the production line cables, together with the mobility of AMRs across the factory, leads to the use of wireless communication. However, an industrial environment represents a challenge to the propagation of radio signals due to effects such as reflections, multipath, shielding, etc., affecting the performance of communication links directly [7]. Even though the factory facility may count with a private network, it is inevitable the presence of frequent handovers due to the AMRs' movement [7] that affects the reliability of data reception. Therefore, proximity communications result in an option to cope with such problems by employing one-hop D2D communication between AMRs using 3GPP SL mode 2.

This thesis focuses on providing mode 2, in the release 16 of the standard, with cooperative resource allocation capabilities to support proximity communications in swarms of AMRs with a high probability of success (99.99%) for high throughput data transmissions of 10 Mbps with a maximum latency of 10 ms. This dissertation closely analyses the challenges of achieving reliable decentralized cooperative resource allocation over mode 2, investigates the potential of the current state-of-the-art, and designs two cooperative resource allocation schemes to be on top of mode 2 for efficient support of high-dense swarms. The remaining part of the chapter includes the description of D2D, focusing on 3GPP's standard, presentation of the thesis scope, research methodology, and related contributions.

1 3GPP's D2D Communication Overview

The appearance of D2D, referred to as SL, into the 3GPP standard was not until release 12 [2]. It was the first time the concept of D2D for ProSe was introduced to cellular technologies [8], specifically in LTE-Advanced (LTE-A), to become a competitive broadband communications technology for public safety networks [9]. The concept of two or more devices exchanging data through a direct link(s) without the need to go through the network had a lot of potential value for public safety (e.g., natural disasters, malicious attacks) and commercial use cases. The design in release 12 sidelink contemplates the direct exchange of messages between user equipments (UEs) in three scenarios, depicted in Fig. I.1, i) in-coverage (i.e, evolved node B (eNodeB) assisted), ii) partial-coverage, and iii) out-of-coverage (i.e., no eNodeB assisted) for public safety (i.e., push to talk (PTT)), which only relies on broadcasting transmissions [10]. Release 13 incorporates Layer 3 based UE-to-network relay and ProSe per packet priority (PPPP) to support quality of service (QoS) [2]. A considerable jump was done in release 14 by extending sidelink from D2D

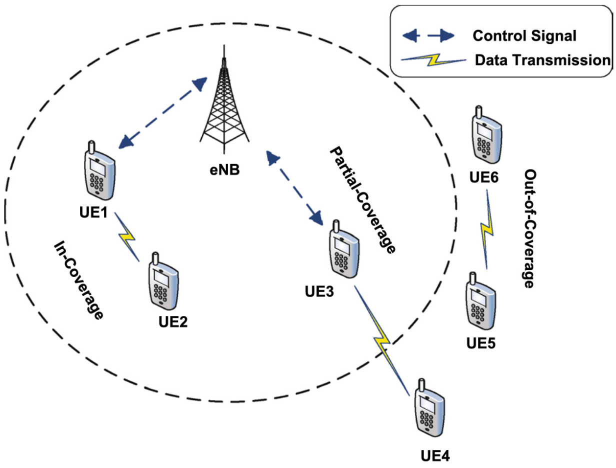

Fig. I.1: Supported scenarios for D2D communications in 3GPP release 12. Source [2]

to V2X by introducing four modes of resource allocation of which two where specifically for V2X (modes 3 and 4) [11]. The LTE-V2X motivation is the support of the demanding reliability, and latency requirements of road safety use cases [11]. In release 15, the efforts were put to enhance throughput and reduce latency by incorporating new capabilities such as carrier aggregation (CA), transmission diversity and quadrature amplitude modulation (QAM) [10]. Release 16 is the first one within 5G NR which is primarily focused on V2X and from four modes available in its predecessor, it provides two, one for in-coverage and other for out-of-coverage, as well as unicast and groupcast support [11, 12]. However, 3GPP has been looking at use cases that demand more stringent communication requirements [3] and mode 2 is not capable of supporting them. Release 17 looks forward to achieving it by incorporating cooperative capabilities (i.e., inter-UE coordination) into the resource allocation. Here, the main goal is to reduce half-duplex problems and interference. The former refers to UEs transmitting in the same time-frequency slot(s), making not possible the reception of each other transmissions. The latter contemplates UEs transmitting in the same time-frequency slot(s) but not intending to exchange information. Both are likely to happen due to mode 2's autonomous resource allocation.

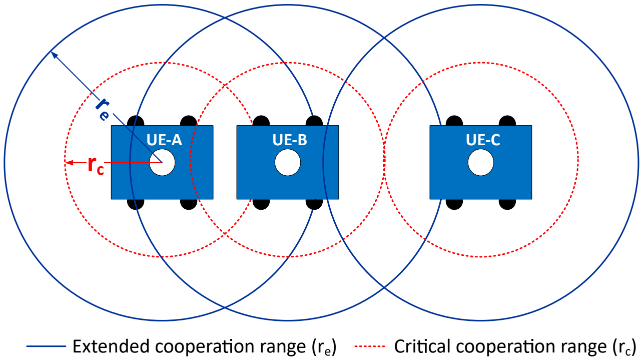

Fig. I.2: Ranges for proximity communication within a swarm of AMRs.

2 Swarm Robotics Decentralized Communication Framework within an Industry Factory

Different kinds of tasks must be completed within an industry factory in the manufacturing process. Production flows, or transport of goods or parts among different workstations, are some examples of processes where manufacturing systems and routing change dynamically, making it an unstructured environment [13]. The replacement of human activities in such an environment by using autonomous mobile robots (AMRs) collaborating among them is an example of an efficient system [14]. Therefore, robotic swarms are expected to be further adopted as production flows, or manufacturing tasks can be performed by AMRs or production robots [14]. The focus of this thesis is on a swarm of AMRs where they communicate with each other without the network's assistance (i.e., decentralized wireless network). Communication is based on proximity; therefore, it is assumed that each AMR incorporates a communication unit (denoted as UE). At the time the Ph.D. was started, release 16 was the latest 3GPP version of the standard; hence, it was considered a baseline scheme. Proximity communication occurs within two device-centric ranges, where UEs exchange different messages. The first one is the *extended cooperation range* (r_e in Fig. I.2) where UEs exchange discovery messages (DM), including their position, speed, and heading direction. This does not differ from cooperative awareness messages (CAMs) requirements, currently supported by 3GPP V2X [15]. UEs use these messages for estimating others AMRs position and channel. The second one is *critical cooperation range* (r_c in Fig. I.2). Within this range, UEs exchange data messages containing video data to enable:

(i) Fast negotiation to avoid collisions between AMRs

3. Challenges to achieve reliable and robust decentralized communication

Table I.1: Data messages requirements referred to [3]

KPI	Min. target value
Reliability of comm. links, (%)	≥ 99.99
Latency, (ms)	≤ 10
Throughput, ($Mbps$)	≥ 10

(ii) Collective perception of the environment to allow better obstacle/object identification (e.g., sharing light detection and ranging (LIDAR) and camera information)

(iii) Collaboration among AMRs for a common task

The requirements for this kind of messages are based on three key performance indicators (KPIs) introduced by 3GPP in [3] for enhancements of 3GPP support for 5G V2X services, as depicted in Table I.1.

The first KPI measures how likely are the communication links among swarm devices to lead to successful communication exchanges. The second reflects the time that a packet takes from the moment generated at the transmitter until it is received successfully at the receiver. The last KPI refers to the channel capacity associated with the link between two or more swarm members.

One important consideration is when a swarms consists of a large amount of AMRs. It would require a high spectral efficiency channel access scheme that enables UEs to transmit at high throughput rates and low latency. The challenges appear since the amount of frequency and time resources are limited, and a large amount of UEs want to access them.

3 Challenges to achieve reliable and robust decentralized communication

Sidelink communication has evolved within the last decade, and currently, mode 2 counts with advanced features such as sensing, re-selection, re-evaluation, and inter-UE coordination [16]. However, the proposed framework is susceptible to two main challenges:

1. **UEs' mobility.-** AMRs (swarm members) move around the factory area. It leads to each UE interacting with different peers within its r_e and r_c as time passes. As a consequence of this dynamic behavior, UEs do not have fixed path loss and shadowing conditions.

2. **Uncoordinated channel access.-** As a UE accesses to the time-frequency resources based on its own decisions (device-centric decision). It might bring into two problems: *half-duplex* and *interference*.

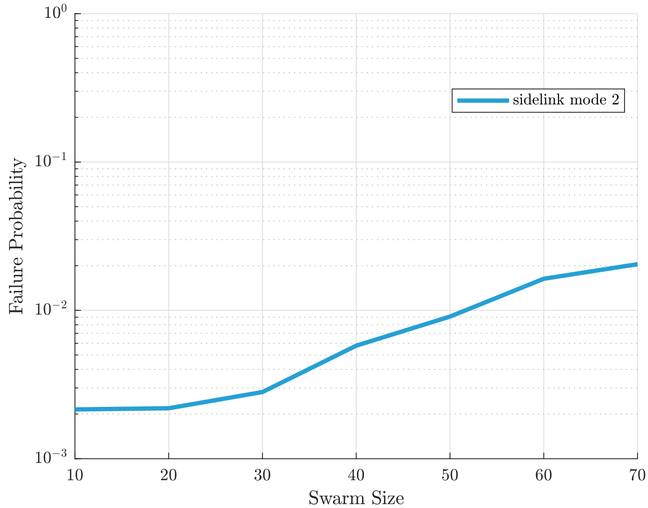

Fig. I.3: Release 16 sidelink mode 2 failure probability for different swarm sizes

(a) *Half-duplex problem.-* UEs needing of data or DMs exchange between them might select the same time-frequency resources as their respective peers located within their r_c or r_e, respectively. It means they transmit and receive data or DMs in the same time and frequency resources. Consequently, these packets will not be successfully transmitted and received, leading to the reliability, latency, and throughput degradation.

(b) *Interference.-* Due to the high density presented in a swarm of AMRs, high channel occupancy leads to considerable interference. Many UEs, with no need to exchange data or DMs between them, select the same time and frequency resources for their transmissions.

Those challenges do not allow the baseline scheme to fulfill the 10 Mbps throughput, 10 ms latency, and 99.99% reliability. Fig. I.3 shows the performance of the baseline scheme for different swarm sizes, assuming that the exchange of DMs have no impact on the performance. The selected KPI is the failure probability directly connected to the reliability. It is defined as the probability of not receiving data with the throughput and latency requirements. A failure probability of 10^{-4} corresponds to 99.99% reliability.

The mode 2 scheme can reach reliability of 99.8% for a swarm of ten robots which degrades as the swarm size increases until it reaches a value of 98% when the swarm size is seventy robots. Its performance is far from the desired one. Therefore, to fulfill the target requirements, it is necessary to address the presented challenges to reduce the failure probability by order of magnitude.

4 Scope and Objectives of the Thesis

The research described in this thesis addresses the problem of insufficient communication reliability to support large swarms of AMRs with 3GPP NR SL mode 2. It is well understood that 3GPP release 16 NR SL mode 2 is very limited since it cannot support high reliability, high throughput and low latency [3, 17]. Therefore it will not be capable of fulfilling the stringent requirements to support large sizes of AMRs swarms. The reliability is compromised as the traffic load increases due to the fundamental trade-off between capacity and reliability. On the basis of these limitations, new solutions that allow for improving reliability and throughput while reducing latency are desired. The objective of the research is to investigate the benefits of current state-of-the-art techniques and incorporate them into the 3GPP NR SL design together with two proposed decentralized cooperative resource allocation schemes. By *"cooperative resource allocation"* we define a process in which all devices share their perspective about the resource's availability. Hence, they will be able to choose resources better and have as many orthogonal resources as possible or, if not possible, in less congested regions of the resource grid. It addresses communication challenges such as half-duplex problems and interference. As a baseline target, this work adopts the minimum requirements of the stringent requirements, including a 99.99% of success probability for proximity D2D links (within r_c) at 10 Mbps throughput with a maximum latency of 10 ms. The proposed solutions are evaluated in a dynamic system-level setting, ensuring a high degree of realism and practical relevance. The scope of the work is illustrated in Fig. I.4 where it is presented the problem, the minimum target requirements, and the proposed solutions studied throughout the thesis. Since the density of the swarm is a key aspect of the system's performance, it is important UEs have as many as possible NR slots for their transmissions or necessary re-transmissions. Since our assumptions contemplate the use of frequency range 1 (FR1) frequencies, the maximum number of available slots, according to the 3GPP specification [18], is *forty* with a numerology (μ) of *two*, being the transmission time interval (TTI) 0.25 ms.

The first stage of the Ph.D. study conducted the understanding of the mode 2 functionality, mainly focusing on its performance limitations. On top of its functionality, we propose two cooperative resource allocation schemes. We assume that the control signaling does not impact their performance (i.e., error-free signaling) and that traffic generation and transmission are semi-persistent to take full advantage of mode 2's sensing mechanism. The two

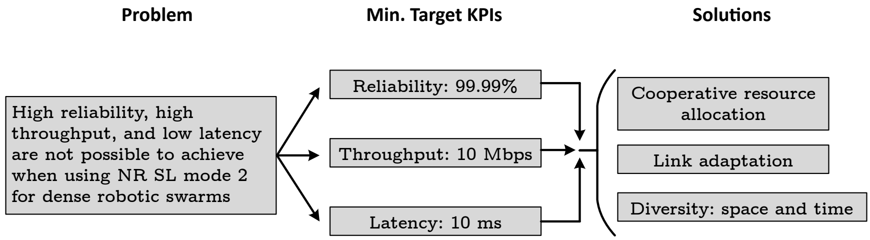

Fig. I.4: Scope of the thesis and evaluation approach

proposed schemes performance is compared against mode 2 within an indoor factory scenario under different swarm sizes. Our focus is to make a proof of concept about the benefits of adding cooperative capabilities to mode 2 to support dense robotic swarms. By two different methods, we evaluate how the two schemes cope with the stringent requirements in comparison to mode 2. The evaluation includes the outage capacity and NR slot occupancy versus the number of swarm members.

The acquired knowledge is then used to design the necessary control signaling flow to achieve cooperative resource allocation. It covers the transmission of relative information in the DMs and the incorporation of resource selection messages (RM) that are used to perform the cooperative resource allocation. The goal is to evaluate the impact of the signaling by comparing it with the error-free evaluation. For this purpose, we introduce a methodology of analysis for separating data communication failures to identify the ones harming the performance and, therefore, propose enhancing techniques to cover them. Evaluations involve failure probability, defined as the probability that within a 10 ms latency constraint, a target receiver does not successfully receive a data message of 100 kb.

Different approaches can be followed to improve reliability. In our case, we have chosen three: *link adaptation, time and spatial diversity*. Link adaptation looks into achieving a relatively low first-transmission block error rate (BLER) target, e.g., $\leq 0.01\%$. In this particular case, it is not possible to exchange of channel state information (CSI) between pairs of UEs since data transmissions are multicast and no unicast. Therefore, it is not supported in NR SL mode 2 [4, 16]. However, we propose an alternative link adaptation to increase the robustness of communication links when a data failure reception occurs.

Time diversity exploits the change of interference and fading conditions while combining the received energy. In our case, we achieve it by adopting hybrid automatic repeat request (HARQ), which is a well-known and utilized technique on a per-transmission basis to increase reliability. Frequency diversity is discarded since, due to the high throughput requirement, we assume that all UEs make use of the whole bandwidth. An important aspect to consider is the fraction of the latency constraint time that UEs must use to perform the first transmission and subsequent re-transmissions, if necessary. Our proposal includes these aspects to evaluate the impact of HARQ alone and with link adaptation to reducing failure probability.

Finally, spatial diversity makes use of directional antennas at the transmitter and receiver, both separately and simultaneously to acquire more energy and to exploit fading differences between the antennas by combining the received signal from each one.

To summarize, this thesis undertakes the problem of achieving high reliability, high throughput, and low latency for data transmissions using NR SL mode 2 as a baseline scheme by incorporating cooperative resource allocation capabilities and enhancing techniques. The main research questions (Q) and their corresponding hypothesis (H) addressed during the Ph.D. study are the following:

A decentralized cooperative resource allocation scheme allows AMRs to allocate time-frequency resources in positions where the grid is not occupied or the interference is as low as possible. To make it achievable, the incorporation of an event trigger is necessary. It will allow moving swarm members (e.g., AMRs) to keep fixed their path-loss and shadowing properties.

H1 A decentralized cooperative resource allocation scheme will be possible with a proper control messaging flow between pairs. The control messaging finishes well before the event trigger period ends.

  Q1 What are the considerations and designing process of a decentralized cooperative resource allocation scheme based on NR Sidelink Mode 2?

Robustness and time and spatial diversity enhancing techniques have shown great potential to combat half-duplex problems and interference.

H2 Properly adapted robustness, time, and spatial diversity techniques will provide high reliability to device-to-device (D2D) links.

  Q2 How can the adoption of enhancing techniques provide 99.99% reliability to 10 Mbps throughput and 10 ms latency for the decentralized cooperative resource allocation schemes?

The incorporation of new control signaling flows, together with the reuse of current signaling information available in 3GPP release 16 NR SL design, will allow the exchange of the required control signaling to enable cooperative resource allocation.

H3 The impact of the new control signaling flows will not affect either mode 2 or cooperative resource allocation schemes' performance significantly.

Q3 How is the incorporation of the decentralized cooperative resource allocation into the 3GPP release 16 NR SL mode 2 design?

5 Research Methodology

The methodology used to pursue the thesis' objectives was a classical approach composed of five steps as follows:

1. **Problem identification and research questions:** The basis of the research process lies in a clear problem description and target definition. Problems identification is based on the requirements of decentralized proximity communication for robotic swarms within an industry factory. For this purpose, a comprehensive survey is conducted to build a solid knowledge about the state-of-the-art, where the established performance baseline is the 3GPP NR SL mode 2. With this approach and interaction with supervisors, academy, and Nokia experts, the limitations to achieving high throughput, low latency, and high reliability are identified. This initial phase also includes the development of the system-level simulator by following the specifications established in the 3GPP's release 16 standard for sidelink.

2. **Formulation of hypotheses along with potential solutions:** Based on the work done in the literature review, it is possible to formulate hypotheses and identify potential solutions. The latter requires a more detailed literature review to find state-of-the-art techniques suitable for solving the formulated hypotheses. Discussions within supervision meetings bring new proposals to cope with problems and behaviors found along with such techniques. Additionally, we design our techniques in cases where no feasible solutions were found. System-level simulations are used to capture the proposed solutions effects since they are intended to be feasible to adapt to the current standard.

3. **Hypotheses validation:** The dynamics in mobility and channel conditions in our study of AMRs within an industry factory make us use heuristic methods to determine sub-optimal solutions to the resource allocation problem (i.e., half-duplex and interference) in a decentralized manner. Since theoretical evaluation results are challenging to follow, a system-level simulator is chosen as the evaluation tool. The simulator is developed by following the 3GPP specifications related to NR SL mode 2 in release 16 of the standard. It is based on mathematical

models covering most of the elements influencing the performance, e.g., mobility, commonly-accepted radio propagation models, etc. The proposed methods are implemented in the simulator, and the Monte Carlo method [19] is used to reproduce results with a high degree of realism.

4. **Results analysis:** The formulated hypotheses are validated or rejected through the system-level simulation results. To obtain statistically relevant results, the number of samples should be high enough for an accurate evaluation of reliability, throughput, and latency. Extensively, the analysis of the results allows for identifying missing behaviors and cases not contemplated in designing potential solutions and/or the hypotheses formulation. In case it happens, potential enhancements will be provided to solve them.

5. **Dissemination of the findings:** The detailed description of the proposed solutions with their performance results is disseminated through scientific publications, presentations in AAU's Wireless Communications Section (WCN) team meetings, and collaboration activities with the partner company Nokia Standards. Additionally, in cases where novel concepts are identified, they are protected and disclosed via patent applications.

6 Contributions

The main findings of the study are summarized below:

1. **Introducing two novel cooperative resource allocation schemes based on NR SL mode 2 functionality.**
   There is a need to considerably reduce half-duplex and interference problems in order to fulfill the reliability, latency, and throughput requirements by using NR SL mode 2. Thus, it is required to adopt mode 2's sensing procedure and replace the resource selection one with two designed resource allocation schemes denoted as device sequential and group scheduling. These schemes differ since the former is based on a device-centric decision for resource allocation. At the same time, the latter contemplates the presence of a group leader, who is in charge of allocating resources for all group members. The introduction analyzes the outage capacity between the proposed schemes' against mode 2 for different swarm sizes. Additionally, the performance of a centralized scheme (i.e., one UE with all knowledge and in charge of allocating resources to all UEs) is included to prove that cooperative schemes are not distanced from such performance, outperforming mode 2.

2. **Analyzing the impact of cooperative resource allocation signaling design in the overall performance.**
The benefits of cooperative resource allocation are not free. The necessary control signal has a direct impact on the overall performance. Therefore, the design aims to incorporate the least number of control signals. The analysis involves the signaling flow for each cooperative scheme and the incorporation of parameters and/or mechanisms to deal with particular behaviors while allocating resources. It also includes an evaluation of the failure probability performance against mode 2.

3. **Introducing a methodology of analysis for separating data communication failures and identifying the most impacting ones of them.**
Data reception failures could happen due to different causalities. Therefore, a methodology that allows the knowledge of the portion each of the possible causes has against the total represents a powerful tool that enables the further adoption or design of techniques to overcome them. It includes an evaluation considering the portions of the causalities that have respected the failure probability.

4. **Proposing techniques to enhance signaling reception reliability**
The methodology proposed allowed the identification of the different types of half-duplex and interference problems UEs experience. This information is the source for the proposal of four techniques to guarantee the reception of RMs. The first aims to avoid the half-duplex problem between DMs and data transmission in the network. The second targets piggybacking RMs to avoid half-duplex or depriving UEs of data transmission when they have not received the RMs from other UEs or group leaders. The last two apply only for group scheduling scheme, including the re-transmission (a.k.a. HARQ) of group leader's RMs or a designed sub-mode where a group member reveals itself as not having received RMs from its leader. An evaluation of the impact these techniques have on the failure probability indicates their benefits.

5. **Studying the potential of link adaptation and diversity to combat data reception failures and, therefore, increase reliability.**
The study includes the incorporation of three well-known techniques into data transmissions. It includes HARQ, directional antennas and beam selection, and a modification of link adaptation to increase the robustness of the link by aggregating slot(s) in following transmissions when a data failure reception takes place. An evaluation of the techniques performance allows the identification of the benefits and disadvantages of each technique. Moreover, an identification of the best combination of the resource allocation scheme and enhancing techniques

is made to establish the maximum number of UEs in the swarm that can fulfill the stringent communication requirements. Additionally, an analysis of the benefits and constraints that device-centric versus group leader decision has on cooperative resource allocation is provided to give an insight into when each approach should be considered.

This thesis is composed of a collection of papers. Formulations, models, ideas, and results from these papers are therefore presented throughout the thesis. The main findings and contributions are included in the following publications:

Paper A: S. Morejon, R. Bruun, T. Sørensen, N. Pratas, T. Madsen, J. Lianghai and P. Mogensen, "Cooperative Resource Allocation for Proximity Communication in Robotic Swarms in an Indoor Factory", *IEEE Wireless Communications and Networking Conference (WCNC)*, March 2021.

Paper B: R. Bruun, S. Morejon, T. Sørensen, N. Pratas, T. Madsen and P. Mogensen, "Signaling Design for Cooperative Resource Allocation and its Impact to Reliability", submitted in *IEEE Access*, 2022.

Paper C: S. Morejon, R. Bruun, T. Sørensen, N. Pratas, T. Madsen, J. Lianghai and P. Mogensen, "Decentralized Cooperative Resource Allocation with Reliability at Four Nines", *IEEE Global Communications Conference (GLOBECOM)*, December 2021.

Paper D: S. Morejon, R. Bruun, F. Fernandes, T. Sørensen, N. Pratas, T. Madsen and P. Mogensen, "New Radio Sidelink with Beam Selection for Reliable Communication in High-Density Robotic Swarms", submitted in *IEEE Latin-American Conference on Communications (LATINCOM)*, December 2022.

Paper E: S. Morejon, R. Bruun, F. Fernandes, T. Sørensen, N. Pratas, T. Madsen and P. Mogensen, "Robust Decentralized Cooperative Resource Allocation for High-Dense Robotic Swarms by Reducing Control Signaling Impact", submitted in *IEEE Access*, 2022.

Papers A-E constitute the main part of the thesis. Additionally, during the study, there were co-authored publications as part of the collaboration with other researchers, but are not included in the thesis. These publications can be accessed through their respective publication channels, which the reader is kindly asked to follow:

(i) J. Romero, R. Adeogun, R. Bruun, S. Morejon, I. de-la-Bandera, R. Barco, "Distributed Deep Reinforcement Learning Resource Allocation Scheme For Industry 4.0 Device-To-Device Scenarios", *IEEE Vehicular Technology Conference (VTC-Fall)*, September 2021.

(ii) R. Bruun, S. Morejon, T. Sørensen, N. Pratas, T. Madsen and P. Mogensen, "The Effects of Multi-path Fading and Diversity Techniques on the Reliability of Decentralized Cooperative Resource Allocation", submitted *IEEE Vehicular Technology Conference (VTC-Spring), June 2023,*.

Furthermore, six patent applications have been filed in collaboration with Nokia Standards in Aalborg:

Patent Application 1: HARQ feedback method for groupcast communications

Patent Application 2: Enhanced single carrier selection for sidelink communications

Patent Application 3: Inter-UE SPS/CG collision detection and resolving

Patent Application 4: Adaptive resource usage based on sidelink condition

Patent Application 5: Bi-directional sidelink configured grant in unlicensed spectrum

Patent Application 6: Enhanced dual carrier selection to support sidelink data duplication

In addition, a considerable part of the Ph.D. study was dedicated to developing a system-level simulator. The simulator includes NR SL mode 2 features in release 16 of the standard since it was the latest available version at that stage of the Ph.D. study. Different modules were incorporated depending on the nature of the addressed problem.

7 Thesis Outline

The thesis is written as a collection of papers, and it is structured in 5 parts where the main contributions and findings are presented. The main articles are presented in Parts II, III, and IV. Each of these parts includes a summary highlighting the motivation and main findings of the papers to help the reader understand the relation between them. The last part presents the conclusions and final remarks of the Ph.D. work. The outline of the thesis is following presented:

- **Part I: Introduction -**This part corresponds to the present chapter, which introduces the Ph.D. topic and motivation of the work, details its objectives, and summarizes the added contributions achieved during the study.

- **Part II: Error-free Signaling Cooperative Resource Allocation Over NR SL Mode 2 -** This part discusses the potential of cooperative resource allocation on top of the baseline scheme NR SL mode 2 to improve the outage capacity and fulfill the stringent requirements. It describes the limitations mode 2 has (i.e., half-duplex and interference) and introduces two cooperative resource allocation schemes that can operate on top of mode 2's functionality. Further, mode 2 against the cooperative schemes is discussed, assuming that signaling exchange has no impact on the performance.
- **Part III: Challenges in supporting Signaling for Cooperative Resource Allocation Over NR SL Mode 2 -**This part covers the signaling design to enable the two proposed cooperative resource allocation schemes on top of mode 2's functionality. It starts with describing the information UEs require to exchange to allocate resources cooperatively. It continues by introducing the signaling flow for each cooperative scheme and its particularities. The system-level simulation results are discussed to present the impact of the error-prone signaling on the failure probability and introduce two mechanisms to mitigate half-duplex problems. The discussion includes the introduction of a methodology to identify the specific causalities of data failures.
- **Part IV: Robustness and Time and Spatial Diversity for Enhancing Reliability of Cooperative Resource Allocation -** This part introduces link adaptation and time and spatial diversity techniques to overcome the presence of half-duplex and interference. It describes the assumptions and approaches followed to incorporate them adequately into the design of both mode 2 and cooperative resource allocation schemes. The discussion of system-level simulation results presents the impact of the mechanisms, individually and simultaneously, to provide a broad perspective of the advantages or disadvantages of using them to support the stringent minimum requirements while increasing the swarm's density.
- **Part V: Conclusions -**This part summarizes the work done. Hypotheses and research questions are recalled together with the main findings. Finally, recommendations concerning further studies that should be addressed are provided.

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Part II

Error-free Signaling Cooperative Resource Allocation Over NR SL Mode 2

Error-free Signaling Cooperative Resource Allocation Over NR SL Mode 2

This part of the thesis covers the issues 3GPP NR SL mode 2 has to achieve high throughput, low latency, and high reliability data transmissions for swarms of AMRs operating within an indoor factory facility. A discussion of the benefits of incorporating cooperative resource allocation capabilities to 3GPP NR SL mode 2 is included to evaluate if they considerably outperform release 16 mode 2. The outage capacity and the NR slot occupancy are the KPIs used to determine if the proposed cooperative schemes provide a significant performance improvement versus mode 2. The study does not contemplate the impact of the required control signaling, which is assumed to be error-free.

1 Problem Description

By the time this Ph.D. project started, release 16 was the latest 3GPP release containing all technical details UEs should follow to perform decentralized D2D communications by using NR SL mode 2 [1, 2]. It contemplates UEs following two established procedures to exchange data, using one or several NR slots. They are denoted as *sensing* and *NR slot selection* [2]. As stated in Part I, traffic generation and transmission are semi-persistent. Thus, *sensing* can detect NR slots where ongoing semi-persitent scheduling (SPS) transmissions are taking place to discard those positions of the resource grid. However, if the resource grid is congested, UEs increase the predefined threshold to tolerate more interference to get at least 20% [2] of candidate slots for their respective transmissions. The set of candidate slots serves as input for the *NR* *slot selection* procedure where UEs randomly select the number of required resources. The selection remains the re-selection counter reaches zero [3]. The counter effect of this approach is that it does not prevent the presence of half-duplex problems of simultaneous resource selections, and the interference allowance when the set of candidate slots is below 20% may cause data transmissions to be unsuccessfully received. Thus, enhancements are required in the *NR slot selection* procedure so that UEs can be aware of others' resource selection while located within r_c. Thus, our hypothesis contemplates that it is achievable if they do it cooperatively. glsues would be able to avoid half-duplex problems and mitigate interference as much as possible depending on the resource pool occupancy as the swarm density increases.

2 Objectives

The objectives targeted in this part of the thesis are the following:

- Understand the limitations mode 2 has to fulfill the stringent requirements demanded by AMRs swarms.
- Investigate the potential of cooperative resource allocation over NR SL mode 2 for AMRs swarms in an industry factory by extensive system-level simulations.
- Evaluate the NR slot occupancy to identify the schemes' behavior while selecting slots to provide insight into the schemes' concurrence to select as many orthogonal slots as possible.
- Evaluate the schemes' performance employing the outage capacity KPI to compare it against mode 2 and a centralized one.

3 Included Articles

The main findings of this part are included in the following article:

Paper A. Cooperative Resource Allocation for Proximity Communication in Robotic Swarms in an Indoor Factory

Proof of concept of cooperative resource allocation. This article studies the impact of two cooperative resource allocation schemes on the swarm communication performance by evaluating the NR slot occupation and outage capacity KPIs. The motivation, assumptions, and design of our two proposed schemes, denoted as device sequential and group scheduling, are presented. The design includes the algorithms describing the process UEs follow to achieve collaboration when allocating resources by following a prioritized sequential order (device sequential) or relying on a local group leader. Additionally, it includes the description of particular situations and the respective solutions (e.g., edge cases in the group scheduling scheme). It presents the assumptions and parameters considered in the system-level simulator development. The evaluation of the KPIs for each scheme was made for different swarm sizes to obtain an insight into the maximum density a swarm can be supported and how the resource selections of each scheme are spread along the resource grid. The study motivates the use of cooperative resource allocation to support high-density swarms of AMRs fulfilling the stringent requirements, which are not feasible with mode 2.

4 Main Findings

Impact of NR slots placement along the resource grid

The random resource selection of NR slots in mode 2 makes them not to be spread along the resource grid. Even though UEs are aware of other SPS transmissions, thanks to the sensing procedure, it does not entirely prevent them from selecting the same slot. The product of this behavior, shown in Fig. II.1, is that a maximum of 70% of the NR slots are occupied by one UE. This value reduces when the swarm size overpasses 60 UEs since the swarm's density increases the grid occupancy. Cooperative schemes support an additional 10% compared to mode 2 but 10% less if we assume a centralized scheme (i.e., one UE has all the necessary information to allocate resources for all swarm members). The trend is inverse at larger swarm sizes (over 90 UEs), and cooperative and centralized schemes deliver a lower value. The absence of orthogonal resources causes it, making them put together UEs that interfere the least possible with each other communication. It is opposite to mode 2, where some slots are occupied by several UEs, with one or might not be occupied.

Another effect of this random selection of resources is the percentage of slots occupied by more than one UE. Contrary to the previous analysis, mode 2 delivers a higher value until a swarm size of 80 UEs, and a lower value beyond it. The cause comes from the random resource selection, making some NR slots be occupied by one UE and others with more than one, regardless they are interfering or causing a half-duplex problem. Cooperative and centralized schemes experience the opposite trend since the primary objective is to allocate orthogonal resources and, when not possible, occupy the ones that do not produce half-duplex or high interference.

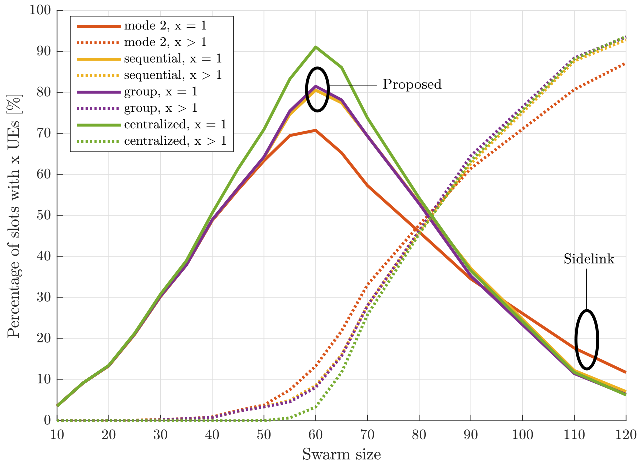

Fig. II.1: Slot occupancy (1 or more than 1 UEs) for different swarm sizes for the three resource allocation schemes: mode 2, device sequential and group scheduling. (Source: Paper A)

Cooperative resource allocation is required to increase outage capacity

Delivering the minimum desired performance for our use case requires that schemes prevent data failure receptions due to half-duplex and interference at the desired reliability percentile (i.e., reliability of 99.99% equals 10^{-4} outage probability level ϵ in Fig. II.2). We selected 50 and 65 UEs in the swarm for this analysis since they represent the point where is present the highest percentage with one UE, meaning its maximum capability to spread resource allocation across the grid to obtain as much as orthogonal transmissions as possible. Mode 2 does not achieve the minimum target value for ϵ and reflects that the amount of slots experiencing half-duplex or interference is high enough to guarantee an ϵ of 10^{-3}. Opposite to mode 2, cooperative schemes quickly fulfill the requirements, and even more, they perform pretty similar to the centralized scheme at the swarm size of 50 UEs. It does not remain when increasing the swarm size by ten UEs since there is a gap between them.

Cooperative resource allocation schemes perform closer to a centralized

Cooperative schemes are the closest to a centralized one because they use all the available information such that UEs make the best possible selection of resources to avoid half-duplex problems and interference with others located within critical cooperation range r_c. The centralized scheme has all the necessary information to allocate resources optimally. On the other hand, it is not the case of device sequential and group scheduling where the op-

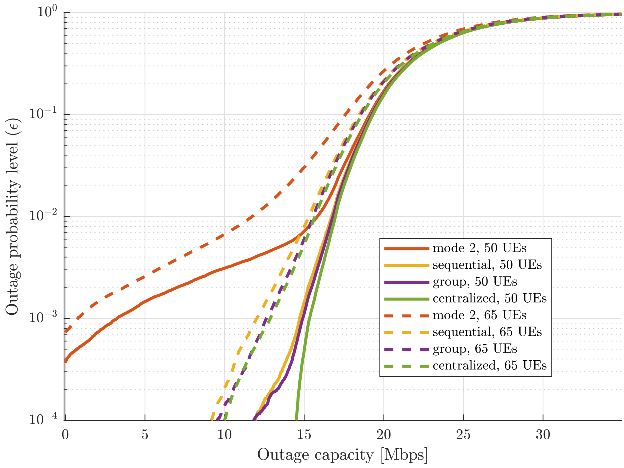

Fig. II.2: Outage capacity at two swarm sizes (50 and 65 UEs) for the three resource allocation schemes: mode 2 (sensing), device sequential and group scheduling. (Source: Paper A)

timal resource allocation is done locally, UE-based or group-based, respectively. When the resource grid gets fully loaded and beyond, a centralized scheme looks for the re-use of the best possible NR slots that do not produce either half-duplex or significant interference to other's transmissions in the whole network. This principle applies to the cooperative schemes with the difference that in device sequential, the re-use of NR slots is made with the available information a UE has from the previous allocations made by higher priority UEs located within its r_e. In the case of group scheduling, the decision is made with the information a group leader has available from its group members located within its r_e. Then the justification for experiencing a gap between cooperative and centralized schemes.

5 Recommendations and follow-up studies

The findings presented in this part of the thesis indicate the benefits cooperative resource allocation brings when added on top of mode 2. They provide similar performance to a centralized scheme until the resource grid is fully occupied; beyond that, there is a small gap between them. Based on these results, the following recommendations are made:

- Even though the benefits of cooperative schemes are clear, the impact of the required control signaling on the performance needs to be studied.
- The identification of the proportion of the causes of the data transmis-

sion failures (e.g., half-duplex and interference) will help identify the schemes' weaknesses and perform the necessary actions to overcome them.

- The gap between the centralized and cooperative schemes requires applying several techniques to increase their robustness.

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Paper A

Cooperative Resource Allocation for Proximity Communication in Robotic Swarms in an Indoor Factory

C. Santiago Morejon, Rasmus Liborius Bruun, Troels B. Sørensen, Nuno K. Pratas, Tatiana K. Madsen, Ji Lianghai and Preben Mogensen

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Abstract

Robotic swarms are becoming relevant across different industries. In an indoor factory, collective perception of the environment can be used for increased factory automatization. It requires reliable, high throughput and low latency communication of broadcasted video data among robots within proximity.

We introduce two new decentralized resource allocation schemes that meet these stringent requirements. The two proposed decentralized schemes are denoted as: (i) device sequential, where robots take turns to allocate resources, and (ii) group scheduling, where robots select local group leaders who perform the resource allocation. A comparative evaluation is performed by simulation against a centralized resource allocation scheme and the current 3GPP release 16 NR sidelink mode 2 scheme.

Our results show that the two proposed decentralized resource allocation schemes outperform sidelink mode 2 due to the mitigation of the half-duplex problem. The proposed schemes reach the throughput target of 10 Mbps with a reliability of 99.99% for a swarm size of 50 robots.

1 Introduction

Nature is a source of inspiration for technological development. Schools of fish, flocks of birds, colonies of ants, and swarms of bees are proof that collaboration between simple agents can achieve complex tasks. Simple agents cooperating in a large swarm result in cheap, parallelizable, energy-efficient, scalable, and stable performance compared to a single highly specialized agent performing the same task [1]. These benefits are the drive behind the development of swarm robotics, with great potential for applications in search and rescue, agriculture, manufacturing, transportation, monitoring, entertainment, military, and many more [2]. In this paper we focus specifically on autonomous robots in industrial settings where collaboration entails collective perception by sharing sensor and video data with other robots in proximity. Collective perception can be used to prevent physical collision between robots and the environment, at the same time increasing their mobility for overall improved factory productivity.

In our work, we are considering a collective perception of the environment based on sharing video streams among robots when they are within *critical cooperation range*, as shown in Figure A.1. In [3], the rate of such video streams are assumed to be up to 10 Mbps, with reliability and latency requirements for cooperative collision avoidance respectively 99.99% and 10 ms.

In the past, applications with high QoS communication requirements were made possible via network aided resource scheduling. However, this might not be the case for swarm communications due to the communication

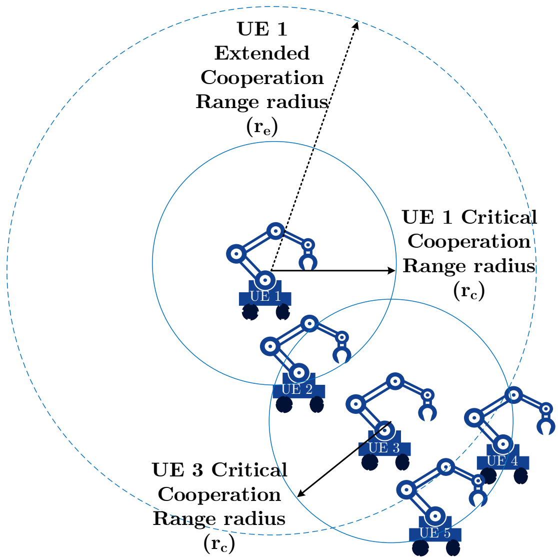

Fig. A.1: Device-centric proximity ranges.

flow between devices, the potential number of devices in the swarm and the possible absence of network infrastructure [2].

The availability of a dedicated communications infrastructure is not always guaranteed. Hence, decentralized and non-network-assisted device-to-device communication becomes a desirable option.

In NR sidelink mode 2, specified in [4], the resource allocation is performed independently at each transmitting device and is composed of three phases, denoted respectively as sensing, selection, and transmission. In the sensing phase the UEs wanting to perform a transmission sense the resource pool for a pre-configured observation/sensing period, with the objective of detecting resources where periodic transmissions are taking place. In the selection phase, the devices remove from the set of available resources, the ones where a periodic transmission with a high reference signal received power (RSRP) from other device(s) is expected; the expectation, or prediction, is based on the current conditions as per the previous sensing. Finally, in the transmission phase, the device randomly selects one (or several) of the resources identified as available.

The resource allocation procedure of NR sidelink mode 2 does not eliminate the risk of selecting interfering communication resources (i.e., nearby transmitting devices selecting the same resource) and specifically, the challenge associated with half-duplex communication (i.e., the device selects a resource where its intended receiver is also transmitting and will therefore be unable to receive the transmission) in dense and dynamic networks which are typical of the considered applications [2].

We hypothesize that meeting such stringent communication requirements in a decentralized swarm communication system requires a coordinated communication scheme that takes into account interference. We note that a 3GPP release 17 study item on sidelink enhancements revolves around exactly inter-UE coordination for resource allocation in what is sometimes referred to as sub-mode 2(d) [5, 6]. To this end, we propose two distributed resource allocation schemes that address node mobility and high node density. Our schemes stand out from the state of the art by enforcing cooperation, among UEs, without performing an extensive optimization procedure. Optimization takes several rounds to converge into an optimal resource allocation, while our schemes find an appropriate resource allocation in a single communication round. In this paper, we focus on interference mitigation through clever resource allocation. We simplify the evaluation to include only the most important system-level effects. Our results show that resource allocation coordination is a promising approach for improving reliability and the evident fact that coordination leads to better performance. Both schemes outperform baseline existing ones and approach a centralized scheduler performance.

The paper organization is the following: Section II explains the system model. Section III presents the prior art of coordinated and uncoordinated decentralized resource allocation schemes, followed by descriptions of the two decentralized coordinated resource allocation schemes. Section IV clarifies simulation assumptions, while simulation results, performance comparison with random and sensing-based NR sidelink mode 2, and discussion hereof are presented in Section V. The paper concludes with final remarks and further work in Section VI.

2 System model

Our scenario includes N_{r} autonomous robots deployed in a rectangular indoor facility (factory/warehouse/hospital). One can imagine these to transport stock, equipment, or materials between physical locations. Robots are uniformly and randomly placed inside the facility and move at a constant speed between random waypoints. As a model simplification, we assume that robots are not affected by the mobility of each other, and allow them to pass “through” each other, as the focus of our evaluations is on communication, not route planning nor collision avoidance.

Robots sense their respective surroundings to trigger the message exchange within two device-centric ranges: *extended* and *critical cooperation ranges*. Within the *extended cooperation range*, swarm members share discovery messages containing their position and mobility information. The receiver can use this information for channel estimation purposes. It is assumed that discovery messages are multicast to all swarm members within the *extended cooperation range* of r_e (see Figure A.1). As 3GPP V2X supports this type of communication, we assume that the exchange of discovery messages is done in a reliable way using sidelink in a different channel or separate resource pool, ensuring that robots are aware of the intended mobility of each other. Discovery messages are not modeled in the remaining part of this work. In other words, any performance degradation due to errors in these discovery messages is not accounted for in the provided results.

Within the *critical cooperation range*, swarm members share video data to allow collective perception within a *critical cooperation range* denoted as r_c. A message with a payload size of 100 kb and 10 ms periodicity is adopted for a throughput of up to 10 Mbps. Messages should be exchanged with reliability of 99.99% within a latency target of 10 ms, as stated for cooperative collision avoidance messages in [3] and [7].

Resource allocation for the data messages is performed in the time domain, by allocating one or more slots of the 5G NR resource grid. The robots transmit messages using the entire 100 MHz channel bandwidth and a single transceiver antenna. We assume the robots to be time-synchronized, e.g., by following the decentralized synchronization procedure from 5G NR as described in [6].

3 Resource Allocation Schemes

We classify the resource allocation schemes relevant to our scenario in Figure A.2. The classification relies on the available information a UE has at its disposal (*none*, *measured*, or *signaled*) to perform the resource allocation. *Measured* info covers the schemes where UEs perform channel measurements (e.g., RSRP, RSSI, etc.) before resource selection (UE-centric). *Signaled* info covers the schemes where UEs exchange information explicitly for resource allocation purposes.

Resource allocation schemes are either *autonomous* or *cooperative*. By *autonomous*, we refer to schemes where the allocating entity takes local (selfish) resource selection decisions which may lead to collisions/interference or half-duplex problems. Conversely, in *cooperative schemes*, the allocating entity coordinates the resource allocation decisions among identified collaborators by exchanging direct messages. For example, in [9] transmitters are autonomously selecting a resource (channel) based on the lowest measured interference level. In contrast, the suggested resource allocation in [15] depends on a cooperative optimization procedure that takes multiple rounds of message exchange between UEs to converge at an optimal allocation.

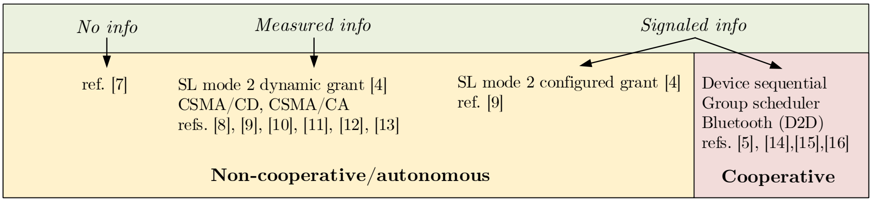

Fig. A.2: Characterization of prior art and proposed resource allocation schemes

3.1 Required resources

Allocation schemes need to know how many NR slots to allocate to whom. Each transmitter individually determines the number of slots required by identifying the receiver within r_c with the lowest expected received power level in dBm ($S_{rx,dB}$),

$$S_{rx,dB} = P_{tx,dB} + H_{g,dB} \tag{A.1}$$

where $P_{tx,dB}$ is the transmitter power and $H_{g,dB}$ the estimated channel gain in dB given by

$$H_{g,dB} = -L_{dB} - X_{dB} \tag{A.2}$$

$H_{g,dB}$ is obtained with the information collected in the discovery phase and modeled here as the sum of path loss (L_{dB}) and correlated shadowing (X_{dB}). The (Shannon) capacity (C_s) achievable in the duration of a slot is calculated as,

$$C_s = B \times \log_2(1+\gamma) \times D_s \tag{A.3}$$

where B is the available bandwidth, γ is the signal-to-interference-plus-noise ratio, and D_s is the time duration of a slot.

The required number of slots (N_s) is the ratio between the throughput requirement (T) times the transmission periodicity (D_p) and the slot capacity (C_s), as depicted in (A.4).

$$N_s = \left\lceil \frac{D_p \times T}{C_s} \right\rceil \tag{A.4}$$

3.2 Resource allocation

The term *resource pool* indicates the time and frequency resources within which the resource allocation procedure assigns resources for data transmission. The same resource pool is available for all UEs. The sidelink mode 2 sensing procedure can determine the resource occupancy based on received

Algorithm RA Resource allocation

Input: $\{(N_\mathrm{s}, R_\mathrm{s})_k\}, k = 1, 2, ..., \mathrm{K}$: set of required slots and sensed resource occupation for all K UEs requesting allocation.
R_e: Resource allocation obtained through message exchange.
Algorithm:
1: **for** each k in descending order of number of devices within *critical cooperation range* **do**
2: Assign $N_{\mathrm{s},k}$ slot(s) to UE k where the channel gain to the closest interferer is the lowest and the half-duplex problem is avoided based on $\bigcup_{n=1}^{K}(R_\mathrm{s})_n \cup R_\mathrm{e}$
3: **end for**
Output: Assigned resource allocation

periodic transmissions (R_s). Resource occupation can also be determined based on the exchange of resource allocation explicitly between UEs (R_e).

Our proposed schemes employ the resource allocation procedure outlined in Algorithm RA. It relies on the resource occupancy (R_s) determined by the sensing and required number of slots (N_s) by each UE. In addition, it utilizes information (R_e) about future resource occupation explicitly obtained from other UEs. The heuristics of the algorithm is the order in which to allocate resources to the requesting UEs. Similar to heuristic graph coloring methods, the order is based on the number of UEs within *critical cooperation range*. We note that Algorithm RA is finite, and its time complexity depends on the number of UEs (k), the size of the resource pool, and the number of interferers identified in each resource. In the following, we introduce our two proposed decentralized coordinated resource allocation schemes: device sequential and group scheduling.

B.1. Device sequential scheme

In this scheme, UEs coordinate their selection of resources based on a sequential messaging procedure. UEs rely on a preconfigured order to advertise their resource selection. The process is sequential within the *extended cooperation range* but could be performed in parallel by nodes further away from each other. Each UE$_i$, $i = 1, 2, ..., N_\mathrm{r}$ collects knowledge (R_e) about resource allocation performed by lower ID UEs within its *extended cooperation range*. When allocation information has been received from all lower ID UEs in *extended cooperation range* it performs Algorithm RA to obtain an allocation of its own. Algorithm A.1 summarizes the device-sequential allocation procedure.

Algorithm A.1 Device sequential resource allocation

Input: N_s, resource pool
Algorithm (run by UE_i):
1: Receive allocation from all UEs in *extended cooperation range* of UE_i with lower IDs
2: Execute Algorithm RA and broadcast the resulting allocation

Output: A_s (slots to use for transmission in upcoming transmission period)

B.2. Group scheduling scheme

Our second proposal, the group scheduling scheme, builds on the idea of having leaders who allocate resources for an entire group of UEs. The group scheduling scheme relies on a leader selection phase before the selected leaders perform resource allocation, indicated in line 1 of Algorithm A.2. The leader selection executes with a periodicity equal to that of discovery messages, and each UE selects a leader among the UEs located within an *extended cooperation range*. The leader is the one with the highest number of UEs in its *critical cooperation range*, and in the case of ties, the UE with the lowest unique ID becomes the leader. Due to the device-centric leader selection procedure, a UE can be a leader, an inferior, or both.

UEs then broadcast a message which contains its leader ID, N_s, R_s, and the edge flag. The edge flag is set in edge cases as depicted in Figure A.3, where UE_B is within *critical cooperation range* of UE_A but outside *extended cooperation range* of L_A (the leader of UE_A). In this case, UE_B forwards the leader selection of UE_A to L_B, thereby making L_B aware of the presence of UE_A. In line 3, if the UE is a leader and has inferiors cooperating with the inferiors of another leader, it must receive the resource allocation (R_e) performed by those leaders with a lower ID. In Figure A.3 L_A has lower ID than L_B, thus its resource allocation is forwarded to L_B. Upon reception, the leader proceeds to allocate resources to its inferiors by following Algorithm RA.

When the UE is inferior as in line 6 of Algorithm A.2, it waits until the reception of resource allocation from its leader. Once received, the inferior forwards the allocation to any leaders inside its *extended cooperation range*. Additionally, those UEs having an active edge flag must relay the resource reservation

between their respective leaders. Algorithm A.2 summarize the described procedure.

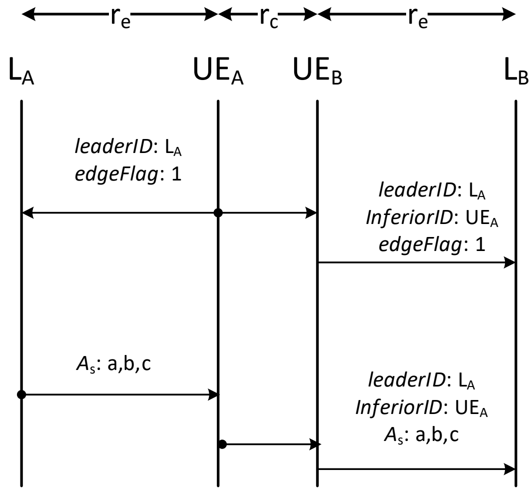

Fig. A.3: Edge flag is set when leaders are out of range.

4 Simulation

We implemented five different resource allocation schemes in our system level simulator: the device **sequential** and **group** scheduling described in Section 3 and the base line schemes of:

- **Random** sidelink mode 2
- **Sensing** based sidelink mode 2
- A **centralized** scheme where resources are allocated by one central entity according to Algorithm RA.

The mobility follows the random waypoint (RWP) model described in Section 2. The channel is modeled as the indoor factory path loss model established by 3GPP [18]. For simplicity, it is assumed that all links are non-line-of-sight (NLOS) and single input single output (SISO). The path loss model, (A.5), consists of the NLOS path loss coefficient (α), reference offset (β), distance between transceivers (d), carrier frequency factor (ψ), and carrier frequency (f_c).

$$L_{\mathrm{dB}} = \beta + \alpha 10 \log_{10}(d) + \psi 10 \log_{10}(f_c) \tag{A.5}$$

Additionally, we consider correlated channels in both space and time. That is, we generate the shadowing component, X_{dB}, from a Gaussian random field with a covariance function defined by the shadowing standard deviation (σ) and an exponentially decaying correlation with a de-correlation

Algorithm A.2 Group scheduling resource allocation

Input: N_s, resource pool
Algorithm (run by UE_i):

Select leader, L_i, and exchange the leader choice and N_s with any UE in r_e. Additionally, relay leader choices of any cooperating UEs outside L_i's *extended cooperation range* to L_i.
if UE_i is a leader **then**
  wait for resource allocation from known leaders with lower ID, then execute Algorithm RA for the group and broadcast the resulting resource allocation.
end if
if UE_i is an inferior **then**
  receive resource allocation (RA)
  if RA is from L_i **then**
    forward RA to leaders in r_e of UE_i and outside r_e of L_i
    forward RA to UEs in r_c of UE_i and outside r_e of L_i
    extract allocated slots, A_s, for UE_i
  else if RA is from a UE in r_c of UE_i and outside r_e of L_i **then**
    forward RA to L_i
  end if
end if

Output: A_s (slots to use for transmission in upcoming transmission period)

distance (δ) [19]. With this approach, we have spatial consistency in the shadowing. Multipath fading has not been accounted for in the simulations.

Table E.2 presents the values of the input parameters for the simulation.

5 Evaluation

In Section II, we defined the reliability of 99.99% for a data message of 100 kb transmitted with a periodicity of 10 ms. It gives us an average target rate of 9.999 Mbps. The chosen key performance indicators (KPIs) for our evaluation are:

Slot occupancy: indicates the average percentage of slots occupied by x UEs (x = 1 or more) at different swarm sizes; it allows us to evaluate how the resource allocation schemes spread resources among swarm members.

Outage capacity: indicates the Shannon capacity C_ϵ at the ϵ outage probability level for which $P[R < C_\epsilon] < \epsilon$, where R is the achievable rate; it

Table A.1: Simulation parameters

Parameter	Value/range
Carrier frequency, f_c	3.5 GHz
Number of UEs	(50,65)
Critical cooperation range, r_c	5 m
Extended Cooperation range, r_e	25 m
Facility dimensions	120×50 m^2 [18]
Transmission power, P_{tx}	0 dBm
Bandwidth	100 MHz
NR slot duration	250 μs
Thermal noise power spectral density	-174 dBm/Hz
Receiver noise figure	9 dB
Interference	Independent intra-system interference
UE speed	1 m/s
Mobility model	Random waypoint (RWP)
Shadow fading standard deviation, σ	5.7 [18]
Path loss coefficient, α	2.55 [18]
Carrier frequency factor, ψ	2 [18]
Reference offset, β	33 [18]
De-correlation distance δ	20 m [19]
Discovery message periodicity	100 ms
Data message periodicity	10 ms
Data message size	100 kb
Simulation time	500 s

allows us to evaluate the achievable rate at the receiver side in respect to our desired target.

Figure A.4 presents the average slot occupancy. Intuitively, a good resource allocation scheme is one that ensures full occupation of the available slots (fully orthogonal allocation) before performing slot reuse. In each realization of the simulation, the total number of required slots, i.e., the load, fluctuates during the simulation time. The cause is the stochastic mobility and fading. Thus, it dictates whether or not a device is transmitting and how many slots the transmission is occupying. The slot occupation in Figure A.4 shows the average occupation over multiple simulation realizations. Therefore, none of the schemes reach 100% average percentage of slots occupied by only one UE.

Centralized coordination leads to the best orthogonalization at low to medium load (swarm size), i.e., ensuring the highest percentage of slots occupied by only a single UE and hence the least reuse. Our proposed schemes are closer to the centralized scheme than the sensing-based sidelink scheme

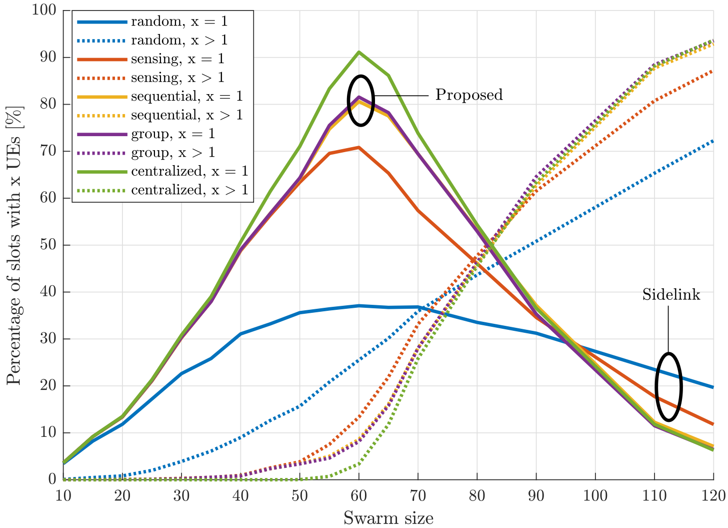

Fig. A.4: Slot occupancy (1 or more UEs) for different swarm sizes

and much closer than using the random sidelink scheme.

At higher load (swarm size), the sidelink random and sensing-based schemes have the highest percentage of slots with a single UE. The consequence is that the average number of UEs in the remaining slots becomes larger; it is seen that both the centralized and the proposed schemes work opposite to this, to have more slots with more users. This spreading out of resources among users, as we will see, leads to overall lower interference.

Figure A.5 shows the outage capacity based on simulations with swarm size of 50 and 65 UEs. The half-duplex problem leads to a certain percentage of transmission periods with zero rates for the random and sensing-based sidelink schemes. Besides, the lack of coordination in the sidelink schemes results in lower achievable rates at all outage probability levels when compared to the coordinated schemes. The largest difference is at the lower outage probability levels. At the 0.1% outage probability level, the coordinated schemes improve the achievable rate by a factor of 4 and 15 for swarm sizes of 50 and 65 UEs, respectively. At the 0.01% outage probability level, the random and sensing-based sidelink schemes have zero outage capacity due to the half-duplex problem. The coordinated schemes mitigate this issue and can achieve rates of 12 and 9 Mbps for swarm sizes of 50 and 65 UEs respectively. The proposed schemes reach the same mean achievable rate as the centralized scheme and have similar performance at all outage probability levels with a swarm size of 65 UEs. At the lower outage probability levels with a swarm size of 50 UEs, the group scheduling reaches higher achievable rates than the device sequential, but less than the centralized scheme which

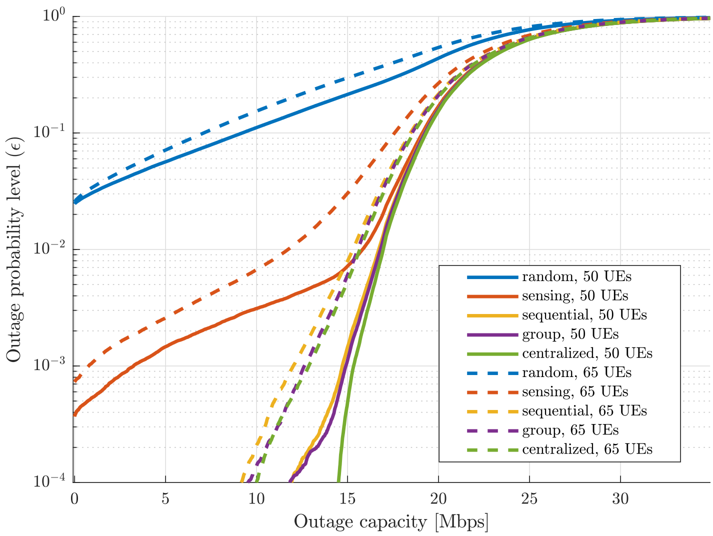

Fig. A.5: Outage capacity at swarm size of 50 and 65 UEs.

allocates fully orthogonal resources, thus avoiding interference completely.

The proposed schemes are evaluated in an industrial robotic swarm setting, but the schemes are generally applicable in any swarming scenario. Additional simulations are necessary to evaluate the performance in other scenarios. In e.g. a drone swarm scenario it should be considered that free space propagation might lead to higher potential interference, thus the extended cooperation range should be increased. Similarly, the higher speeds of aerial vehicles could lead to larger critical cooperation ranges. It is expected that in such a drone swarm, the required performance could only be met at lower swarm densities.

6 Conclusion and further work

Swarm robotics is likely to evolve towards decentralized systems in which highly reliable, high throughput and low latency communications will be a necessity. Current resource allocation schemes were not designed to meet the stringent requirements for collective perception and collision avoidance in mobile and dense swarms. We propose two coordinated resource allocation schemes for decentralized swarm communication that outperform baseline schemes in terms of achievable rate. The proposed device sequential and group scheduling allocation schemes give at least a 10 Mbps reachable rate increase over the sensing-based sidelink mode 2 scheme at the 0.1% outage probability level and significantly outperforms at the 0.01% outage probability level. They achieve almost the same performance as central scheduling.

The results clearly indicate that coordination is a requirement to meet reliability and throughput requirements. Therefore, in our future work, we will apply solutions to further performance improvement, and investigate the latency implications caused by the proposed resource allocation schemes.

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Part III

Challenges in Supporting Signaling for Cooperative Resource Allocation Over NR SL Mode 2

Challenges in Supporting Signaling for Cooperative Resource Allocation Over NR SL Mode 2

This part focuses on designing the signaling flow of control messages to enable device sequential and group scheduling functionality. The benefits of decentralized resource allocation in the previous thesis part; however, if the designing of control signaling diminishes all of them, the proposed cooperative schemes do not represent a suitable option for our stringent communication requirements. This part covers the analysis of the signaling design effect on the performance to identify the degree of impact of the different kinds of half-duplex problems and interference between control signals and data. It also provides insights into their cause and a whole perspective of these challenges to propose techniques to overcome them.

1 Motivation

Previously, we have determined that under the assumption of having error-free signaling, cooperative resource allocation benefits the outage capacity performance by comparing it to mode 2 and a centralized approach. The performance of the cooperative schemes was close to the centralized one until reaching the maximum resource pool occupation with orthogonal resources at 60 UEs swarm size. Beyond that value, there is a gap in outage capacity being the best performance for the centralized scheme since the overall knowledge allows the absence of half-duplex problems (at the target reliability), and interference is globally optimized by the central device in charge of the resource allocation. The design of the required control signaling to enable cooperative resource allocation y fundamental for the overall performance since the amount of control signaling messages might impact the latency of data transmissions. Moreover, control signaling messages are prone to experience half-duplex problems and interference with others of the same kind and data. Additionally, it is required that evaluations contain a higher degree of realism. Therefore, the system-level simulations should incorporate the modulation and coding scheme (MCS) to evaluate the failure probability of data receptions. The objective is to identify the performance gap between error-free and error-prone signaling to reaffirm the benefits of cooperative resource allocation despite the price to pay for its operation.

2 Objectives

The goals of this part of the theses are the following:

- Design a control signaling flow to enable cooperative resource allocation for device sequential and group scheduling schemes.
- Evaluate the effect of control signals exchange on the failure probability of device sequential and group scheduling schemes.
- Classify the different kinds of half-duplex problems and interference and their proportion to the overall failure probability.
- Incorporate techniques to mitigate the impact of half-duplex problems and interference with control signals.

3 Included Articles

The main findings of this part are included in the following article:

Paper B. Signaling Design for Cooperative Resource Allocation and its Impact to Reliability

Design and performance of the cooperative resource allocation control signaling. A review of the prior art about decentralized wireless communications is conducted. The system model for proximity communications to determine the problem in the resource allocation is presented. A full description of NR SL mode 2, device sequential, and group scheduling resource allocation schemes is provided. The control signal flow through the incorporation of new information to the DMs, and a new control are required to enable the cooperative resource allocation. It is done by UEs when sharing their resource allocation with others in proximity with a lower priority ID (i.e., device sequential). When groups are formed (i.e., group scheduling), UEs get it from the group leader. These procedures are explained in detail to provide all necessary details regarding schemes' functionality and particular behavior.

A new evaluation methodology is introduced to distinguish the different causes for half-duplex and interference. Thus, three techniques (e.g., retransmissions, non-overlapping, and piggybacking) are applied to mitigate some of them. The failure probability evaluation includes the impact of each proposed technique for data transmissions using system-level simulations. Additionally, a 3GPP KPI named as packet inter-reception (PIR) is evaluated to provide insights about latency performance of the schemes. The enhancement of the system-level simulator combines the functionalities introduced in Part II with the MCS dynamically adapted at the time of allocation together with the enhancement techniques.

4 Main Findings

UEs have sufficient discover probability

Both mode 2 and cooperative resource allocation schemes require DMs to exchange their respective heading direction and coordinates, which determines the instant they proceed with data transmission. We assumed that DMs are exchanged in a different resource pool, but they are not exempt from suffering half-duplex with data or control signaling (for the case of cooperative schemes). For that reason, it is necessary to provide sufficient probability to DMs so that UEs can discover others. Since our assumptions in Part II included the use of SPS transmissions, mode 2 as baseline scheme, and the mean period of DMs equal to the discovery period; the probability of a half-duplex problem does not allow a pair of UEs discover each other, denoted as $P(failedDM)$, is shown in equation III.1 as follows,

$$P(failedDM) = 1 - (1 - {P_1}^m)^g \tag{III.1}$$

Where P_1 is the probability that two, or more, out of g UEs, within extended cooperation range r_e, do not select resources at the same time instant for DM transmission, and m is the number of consecutive DM transmissions. If we consider that the minimum period of time established in mode 2 is 750 ms [1], UEs count with at least seven discovery periods (m = 7), providing UEs with sufficient discover probability as $P(failedDM)$ results significantly low.

Identify the type of half-duplex and interference plays an essential role in applying the correct enhancement technique(s)

Knowing the cause of half-duplex or interference represents a potential tool to explore specific techniques capable of mitigating their effect. In our use case, we identified three causes for half-duplex, three for interference, and one particular behavior in the group scheduling scheme. The half-duplex cases can be categorized as half-duplex data (i.e., two or more devices within critical cooperation range r_c, select the same time-frequency resources for data transmissions), half-duplex DM (i.e., two or more devices within critical cooperation range r_c, select resources at the same time instant, in the different resource pools, for DM and data transmissions), and finally, half-duplex RM (i.e., two or more devices within critical cooperation range r_c, select resources at the same time instant, in the different resource pools, for RM and data transmissions).

Focusing on interference, when UEs located within r_c perform harmful transmissions, we have inner interference. If those transmissions occur within r_e, it is considered outer interference, while when both happen simultaneously, we have mixed interference.

A particular behavior was found in the group scheduling scheme, where some UEs did not receive the resource selection messages RM from their respective group leaders. It would be caused by either a half-duplex problem or interference. According to the control signaling design, if a group member UE does not receive an RM, it is deprived of transmitting data since UEs do not have the autonomy to perform resource selection. Therefore, these cases will directly impact the scheme's failure probability performance.

All the half-duplex and interference types and their proportion to the failure probability are shown in Fig. III.1.

Three techniques are necessary to provide robustness to control signal messages

The identification of data transmission failures provides an important role in determining the portion each one has to provide robustness to the control signaling. Three enhancement techniques were added to avoid or mitigate the recurrence of some of the causes. These techniques are: *non-overlapping*, *piggybacking* and *RM re-transmission*.

The failure cause producing the biggest impact is no RM receptions occurring only in the group scheduling scheme. The fact that a UE does not receive the corresponding RM from its leader produces the non-transmission of data for the whole SPS period until the re-selection of resources takes place. Therefore, it experiences the highest failure probability value. To solve this problematic, we incorporated *RM re-transmissions* [2] consisting in sending negative acknowledgment (NACK)s to the leader, when the trigger time ends, until successfully received the RM. Indeed, UEs might experience some deprived data transmissions until getting the RM. However, Fig. III.2 shows

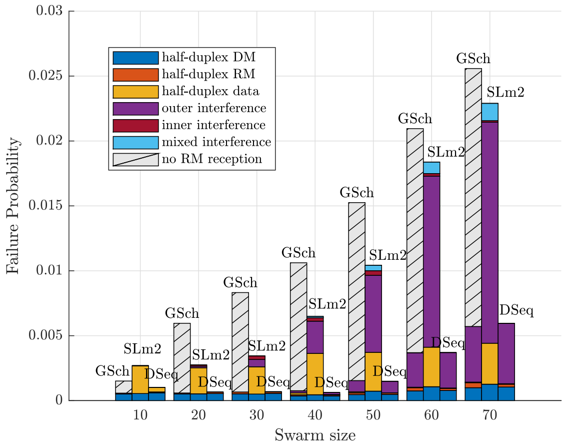

Fig. III.1: Data failure causes (half-duplex of DM, RM and data, inner, outer and mixed interference, and no RM reception) and their proportion in the overall failure probability for the three resource allocation schemes (SLm2, DSeq and Gsch). (Source: Paper B)

that almost all failures due to this problem were eliminated.

Next, interference represents a problem as the swarm size increases. The predominant type is outer interference and affects mode 2 way more than device sequential or group scheduling as depicted in Fig. III.1. The grid occupancy due to the higher swarm's size makes possible the presence of interference in all schemes beyond a swarm size of forty UEs. Even though the cooperative schemes handle interference by selecting the resource(s) that experience the lowest interference, the possible resource selection between group leaders (group scheduling scheme) and devices out of the r_e (device sequential scheme) might cause some transmissions to be harmful to others. To overcome this problem, we incorporated the *piggybacking* technique to the cooperative schemes, consisting of repeating the resource selection information. UEs append these information of its predecessors RMs (i.e., device sequential scheme) or group leaders sends new RMs containing information of its prior sent RMs (i.e., group scheduling scheme). It will provide extra information to UEs, in the cooperative schemes, for a more accurate resource selection. However, Fig. III.2 shows that it does not affect reducing either interference or half-duplex with RMs. It may be justified in the lack of long enough allocation sequences despite having large swarms up to seventy UEs in the device sequential scheme. For the group scheduling scheme, the effect of piggybacking is negligible since the interference occurs due to the lack of coordination among leaders whose UEs are out of their respective r_c.

Last but not least, it was found that some data transmissions experienced half-duplex with DMs in all resource allocation schemes. Previously, we have

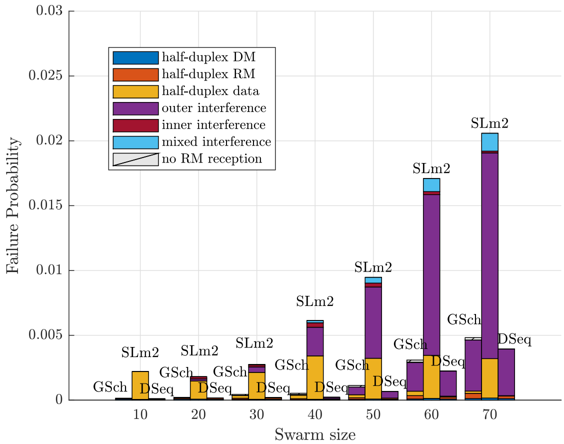

Fig. III.2: Data failure causes (half-duplex of DM, RM and data, inner, outer and mixed interference, and no RM reception) and their proportion in the overall failure probability for the three resource allocation schemes (SLm2, DSeq and Gsch) after applying non-overlapping, piggybacking and RM re-transmissions techniques. (Source: Paper B)

demonstrated that UEs count with sufficient discovery probability. However, experiencing a half-duplex between data and DMs directly affects the failure probability. To tackle this problem, we introduced the non-overlapping technique to all resource allocation schemes, using the information obtained during the sensing procedure. Specifically, avoid transmitting DM in slots where were detected the parameter *"resource reservation period"* in the sidelink control information (SCI) [1] within the sensing procedure. Fig. III.2 illustrates that the effect of the non-overlapping techniques almost eliminates the half-duplex cases between data and DMs. The remaining ones occur due to the large swarm size, which creates a more tolerant interference behavior within the sensing procedure.

Error-prone signaling cooperative schemes outperform mode 2

The performance of the cooperative resource allocation scheme is considerably reduced when evaluating the effects of the designed control signaling. However, they still outperform mode 2, as depicted in Fig. III.3. The only scheme fulfilling the stringent requirements is device sequential for a swarm size of ten UEs, compared to the approximately fifty-UE swarm size obtained when evaluating the outage capacity of error-free signaling in Part II. The results for error-free signaling in Fig. III.3 are quite different since this study incorporates and evaluates the MCS instead of the outage capacity. The failure probability evaluation also confirms the effects of the three techniques

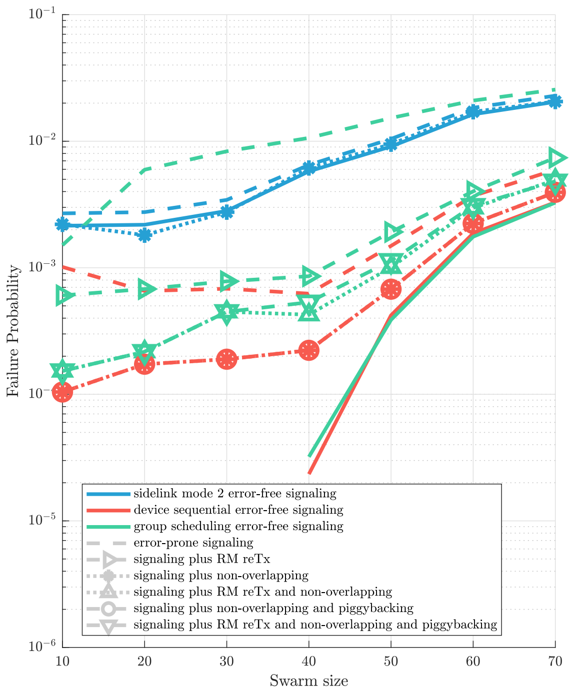

Fig. III.3: Failure probability at five simulation configurations for the three resource allocation schemes: error-free signaling, error-prone signaling, error-prone signaling with re-transmissions (only for group scheduling scheme), error prone with non-overlapping (re-transmissions), and error prone signaling with non-overlapping plus piggybacking (re-transmissions). (Source: Paper B)

explained previously, where the most beneficial for all schemes is the non-overlapping technique. At the same time, piggybacking has a negligible effect on cooperative schemes. RM re-transmissions are essential to the group scheduling scheme. Otherwise, it delivers the worst performance than mode 2.

Another important aspect is that a UE-centered cooperative resource allocation (i.e., device sequential scheme) requires mode control signaling exchange than group-centered resource allocation (i.e., group scheduling). The former provides UEs with an accurate knowledge of the resource occupancy so that they can properly choose their required resources. However, as the swarm size increases, the sequences get longer, and the performance worsens. Additionally, it is not enough to profit from the benefits of the piggybacking technique. On the other hand, group scheduling resource allocation is leader-dependable. So, it gets a bit closer to a centralized approach since any problem experienced by the local leader directly impacts the overall performance. Proof of this is the no RM reception and the cooperation between group leaders. Once it is covered, its performance is close to the device sequential scheme, which depending on the application, may provide the desired performance by using less control signaling.

5 Relation with part II

In Part II, we were focused on introducing proof of concept about the benefits cooperative resource allocation schemes can bring to decentralized proximity communications. The obtained results were promising since the gap between their respective performance was considered significant. However, incorporating the control signaling design, together with the MCS, reduces this gap and only fulfills the stringent requirements for a swarm size of ten UEs, but still decreases the failure probability by order of magnitude.

6 Recommendations and follow-up studies

Decentralized proximity cooperative resource allocation beyond 5G requires UEs to properly use the available time-frequency slots to provide an overall required performance when the communication requirements are stringent. When the schemes' performance evaluation includes the effects of the control signaling and three enhancement techniques, the cooperative schemes still outperform mode 2. Based on this study; the following recommendations are made:

- UEs require knowledge of their relatives located in proximity (i.e., both extended and critical cooperation ranges, r_e and r_c respectively). Thus, they require sufficient discovery probability.
- The way cooperative resource allocation takes place has an impact on the overall performance. When it is purely UE-centered (i.e., device sequential), the applied enhancement techniques directly impact the overall performance. However, in a group-centered approach (i.e., group scheduling), the application of techniques requires more exhaustive research on the resource allocation behavior (e.g., no RM receptions) since the group leader should cover these kinds of particular behaviors.
- The fulfillment of the stringent requirements needs the application of techniques that cope with half-duplex data transmissions (primarily for

mode 2) and all kinds of interference. Applying time and spatial diversity to the three schemes might be essential in fulfilling the stringent requirements for decentralized swarm communications.

References

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Paper B

Signaling Design for Cooperative Resource Allocation and its Impact to Reliability

C. Santiago Morejon, Rasmus Liborius Bruun, Troels B. Sørensen, Nuno K. Pratas, Tatiana K. Madsen and Preben Mogensen

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Abstract

Decentralized cooperative resource allocation schemes for robotic swarms are essential to enable high reliability in high throughput data exchanges. These cooperative schemes require control signaling with the aim to avoid half-duplex problems at the receiver and mitigate interference. We propose two cooperative resource allocation schemes, device sequential and group scheduling, and introduce a control signaling design. We observe that failure in the reception of these control signals leads to non-cooperative behavior and to significant performance degradation. The cause of these failures are identified and specific countermeasures are proposed and evaluated. We compare the proposed resource allocation schemes against the NR sidelink mode 2 resource allocation and show that despite signaling has an important impact on the resource allocation performance, our proposed device sequential and group scheduling resource allocation schemes improve reliability by an order of magnitude compared to sidelink mode 2.

1 Introduction

The density of connected devices is growing rapidly. Nowadays it is insufficient to have connectivity only in smartphones. Wireless connectivity is expanding to wearables, domotics, automotives, etc., to make our lives simpler, safer and more convenient. As connectivity becomes omnipresent, the basis for a new form of collaboration has been created. Nature has inspired many technological leaps, and the collaboration of simple entities is a well known phenomenon in the animal kingdom, where ants, birds, bees, fish and a plethora of other species have learned to benefit from collaboration, allowing them to unite efforts and enable them to achieve complex tasks. The behavior of swarming, flocking and schooling serves as inspiration for the collaboration which has become possible between connected electronic devices. The first use cases have already been envisioned, e.g:

- In manufacturing, swarms are envisioned to enhance production lines, by enhanced flexibility and adaptability enabled by better communication [1].
- In search and rescue flocks, drones are envisioned to cover land quickly and with short response time, thus vastly cutting the critical time to find lost persons in the debree of a collapsed building, people lost at sea, in a forest, etc. In such operations it is life critical to locate the missing persons as soon as possible [2].
- Within the agricultural industry, in [3] a monitoring and mapping system guides autonomous weeding robots. This system maps the field

by using a swarm of UAVs to patrol it. The system provides weed's presence identification and location of different intervention urgency areas.

- In domotics (smart home and office) the collection of connected smart devices (each with a distinct sensing, actuating or service function) will collaborate like the bee swarm maintaining the hive, to efficiently monitor the state of the building and provide an optimal indoor environment while minimizing the energy bill cost [4, 5]. The robot vacuum will operate where needed, but at the most convenient times and the heating, ventilation, and air-conditioning (HVAC) will be adjusted ad-hoc to provide the perfect indoor climate at all times of day and year [5, 6].
- In automotive, connected devices will be vital to maintain a streamlined transportation infrastructure where the transportation needs of humans, and goods can be met in the safest and most seamless way possible. The sensors around the transportation grid will provide real-time traffic updates to the active vehicles which will negotiate their optimal routes as they drive in dense platoons not unlike ants and migrating birds [7, 8].

These are just to mention a few of the present use cases. Undoubtedly, the most revolutionary applications of swarm robotics have yet to be discovered as technologies mature and become accessible. Common for the aforementioned use cases and the nature of swarms is the need for communication between devices within proximity. In theory, direct one hop communication between devices has the shortest possible latency and best utilization of time-frequency resources. Also, it provides good conditions to obtain high reliability which we define as the probability that a receiver successfully decodes a received message within an application's latency requirement. However, achieving these benefits will require smarter solutions. For that reason our efforts are concentrated on decentralized communication where all devices engage in communication on equal terms and no coordination from network or one specific device is needed for communications to take place. Additionally we are concerned with pushing beyond the current state of the art, thus focus on how to improve throughput and reliability at reduced latency.

1.1 Decentralized Wireless communication

Different solutions exist for decentralized wireless communications, however to achieve adoption and wide spread usage, standardization is indispensable. Standardized wireless communication technologies enable different manufacturers to produce compatible products. This aids competition and will result in larger supply of products at lower cost. The most known standards are governed by IEEE, Bluetooth SIG and 3GPP.

Bluetooth SIG governs the Bluetooth standard which is a personal area network technology. Bluetooth Classic refers to the original Bluetooth protocol stack which was originally meant as a wireless alternative to a cabled connection, e.g. between headset and phone. In version 4.0 of the Bluetooth Core Specification, the Bluetooth Low Energy protocol stack was introduced. Bluetooh Low Energy is incompatible with Bluetooh Classic and designed for low power consumption. Both Bluetooth stacks operate in the unlicensed 2.4 GHz Industrial, Scientific and Medical (ISM) band. The Bluetooh Mesh specification [9] was adopted in 2017 to allow Bluetooth technology to cater applications which include multiple device networks.

The IEEE 802.15.4 standard is a low-data-rate, low cost and low power physical and MAC layer specification [10]. It was originally conceived to enable low cost personal area networks between ad-hoc devices, and operates in the ISM bands between 0.8 and 2.4 GHz. IEEE also governs the 802.11 standard, which is a specification of protocols for wireless local area networks. The amendments 802.11a/b/g/n/ac/ax refer to WiFi networks, which connect computers and smartphones to the internet via an access point. However, 802.11s, 802.11p and 802.11bd are amendments directed at device to device applications. The 802.11s amendment enables mesh networking in which packets are routed according to one of the supported protocols. Dedicated short-range communication is supported by the 802.11p and the upcoming 802.11bd amendments. The target of these amendments is to enable vehicular communication in the 5.9 GHz Intelligent Transport Systems (ITS) band.

The main challenge that Bluetooth SIG and IEEE governed standards have is their operation in the unlicensed spectrum bands where they need to abide by either listen before talk or duty cycle restrictions [11, 12]. For this reason, these standards are vulnerable to interference and low spectral efficiency which limits their achievable throughput and latency performance [13].

In the United States, the 3.5 GHz Citizen Broadband Radio Service (CBRS) band with a bandwidth of 150 MHz was established in 2015 to allow shared commercial usage in the band [14]. Up to 70 MHz is licensed by census tract (limited geographical region) allowing factories, airports and the like to license the band and utilize it for a dedicated network. This licensing arrangement is interesting for future use cases of e.g. cellular technologies which already operate in this band in other parts of the world.

3GPP standardizes cellular communication. The concept of device-to-device communications appeared within 3GPP release 12, with the development of proximity services (ProSe). The most recent version of the standard is release 16. Among other things, it includes decentralized device-to-device communications in the form of NR sidelink resource allocation mode 2 (mode 2). The mode 2 resource allocation is explained in detail in section 2.

The main performance constraints of mode 2 are caused by the presence of half-duplex problems and multi-user interference [15]. Half-duplex refers to the limitation a transceiver has, since it is not able to receive and transmit simultaneously. The problem arise when two communicating transceivers transmit to each other simultaneously rendering both unable to receive. To overcome these issues, inter-UE coordination is being discussed for the upcoming release 17 [16]. Here the concept of cooperation/coordination is adopted as an option to be added on top of mode 2 which should aid in mitigating half-duplex and interference problems. Two coordination schemes are agreed upon: Inter-UE coordination scheme 1 and scheme 2. In the former, upon request, the receiving UE-A assists the transmitting UE-B in resource allocation by indicating a set of preferred/non-preferred resources for the transmitting UE-B; the latter allows the receiving UE-A to notify the transmitter that the resource selected by the transmitter results in expected/potential and/or detected conflicts.

The inter-UE coordination framework being introduced in 3GPP Rel.17 does not target swarm use cases where a group of UEs have to exchange information. In other words, the signaling is pair based and not efficient for use cases where a group of UEs requires coordination information.

The scope of this paper is to introduce and evaluate a cooperative inter-UE coordination scheme suitable for group coordination.

1.2 Cooperative communications

Consensus on the use of time-frequency resources is the basis of multi-user communications. In decentralized communication systems one way to achieve high throughput, high reliability and low latency is to reach consensus in the usage of time-frequency resources via cooperative resource allocation. Authors in [17] introduced two consensus communication protocols, the first a gossip-based (multi-hop message diffusion) and the second a broadcast (single-hop message diffusion) communication protocol. In both protocols, a set of UEs (validators) validates and commits the proposed action (vacant frequency band) made by the proposer UE. The consensus protocols have low latency and high reliability that could support mission-critical and real-time tasks as long as consensus decisions change infrequently. The validation process may take some time due to the number of validators, and conversely if this number reduces, reliability may suffer. Therefore, there is a need for a balance between reliability and latency. The main advantage of the consensus algorithm is its resilience to UEs with malicious intent.

In systems without "malicious UEs", the consensus procedure is no longer necessary since it is assumed that all nodes will follow the specified resource allocation procedure. Consequently, an optimal resource allocation scheme can be reached faster. Authors in [18] developed resource allocation algo-

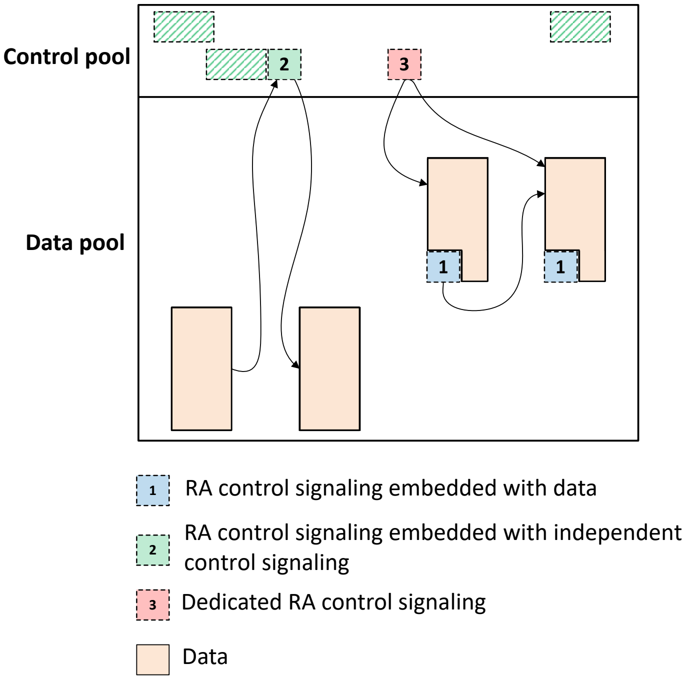

Fig. B.1: Methods to exchange signaling: i) Embedded with data (blue), ii) Embedded with independent signaling (green), and iii) Dedicated (red)

rithms inspired by a bio-swarming behavior. The presented methods rely on multiple iterations before they converge to an optimal resource allocation. In [19] the authors present a distributed resource allocation scheme which converges in quadratic time. The convergence is dependent on the number of devices, because each device is involved in execution of the algorithm.

Although these distributed consensus and resource allocation schemes achieve full alignment of the swarm members and an optimal resource allocation, the involvement of the majority of the swarm members in the allocation process is detrimental to the latency as the swarm size grows. Instead, it is desired that changes to the resource allocation can be performed locally among one or several sub-sets of swarm members, such that overhead in the form of control signals is limited. Mode 2 operates like this (a more detailed explanation is provided in Section 2), where control signals are embedded with the data transmissions and thus only reach nearby swarm members (illustrated by control signal method 1 in Fig. B.1).

In recent literature, cooperative extensions to the existing NR mode 2 standard have been suggested in an effort to address shortcomings in the current version. The continuous collision problem of the semi-persistently scheduled (SPS) transmissions is tackled in [20] by allowing a third UE to piggyback with its own transmission an indication that continuous collision is (likely) taking place in another resource (method 1 in Fig. B.1). It is a reactive scheme where collisions are resolved rather than avoided. The scheme depends on other UEs being able to assist.

In [21] authors introduce a counter in the SPS signaling indicating the time of reselection, i.e. as method 1 in Fig. B.1. Within each SPS transmission, a procedure is proposed to adjust the counters such that no UE will be reselecting in the same transmission time interval, thus mitigating SPS collisions. The procedure is proactive as it tries to mitigate future collisions, but the procedure is designed for low density swarms. Additionally, failures on the initial transmission are not handled.

The piggybacking of control signals to periodic safety messages in [22] indicates the future resource allocation of SPS transmissions (method 2 in Fig. B.1). The next SPS allocation is performed before the end of the current SPS transmission, allowing time to reselect the SPS in case of potential conflicts.

With the aim of addressing the mode 2 limitations (i.e. susceptibility to half-duplex and interference), in [23] we introduced two cooperative resource allocation schemes, device sequential and group scheduling, which follow the framework of 3GPP but have different resource allocation algorithms and cooperation schemes. The coordination scheme of both the device sequential and group scheduling approach allow coordination where message exchange is only required for devices in proximity and with immediate need for communication resources. The additional signaling required could partly be piggybacked to existing discovery messages (method 2 in Fig. B.1) and by the introduction of a dedicated control signal (method 3 in Fig. B.1). Under assumption of perfect exchange of control messages, the proposed schemes far outperformed mode 2 [23].

In this article we recapitulate the device sequential and group scheduling resource allocation schemes and additionally design the required signaling exchange to evaluate its impact on data reception reliability. We show how device sequential and group scheduling schemes provide significant performance improvement over the baseline despite introducing signaling overhead. Our evaluation focuses on the causes of data reception failures, thereby allowing a deeper analysis of the signaling design, its impact on the resource allocation, and the resulting data reception performance. Additionally, it provides us information to propose techniques to overcome such failures and evaluate their impact on the final data reception reliability. The specific contributions in this article are:

- Signaling design to enable distributed cooperation for the proposed device sequential and group scheduling cooperative resource allocation schemes.

– Evaluation of signaling overhead on the performance.

– A methodology of analysis for separating communication failures and identifying the most impacting causes, thereby deepening the understanding of performance differences and focal points for further enhancements.

– Techniques to enhance the signaling reliability and overall swarm application performance, based on the specific failure causes.

We continue with Section 2 presenting the assumptions, notation and the baseline mode 2 allocation scheme. In Section 3 we present the cooperative resource allocation schemes device sequential and group scheduling. Control signaling design for the cooperative schemes are presented in Section 4. Section 5 outlines the simulation setup and the simulation results and enhancement techniques are presented and evaluated in Section 6. Concluding remarks are made in Section 7.

2 System Model and Notation

Consider a system of N UEs engaging in proximity communication, enabled by their omnidirectional antennas and half-duplex radios. At any point in time, a UE is either not involved in proximity communication, and therefore not transmitting data messages, or the UE is involved in proximity communication, defined by UEs being within (a device-centric) critical communication range of r_c. We differentiate between *data messages*, defined as the information bits transmitted for the purpose of some swarm application, and *control signals*, defined as the transmitted bits which serves a supporting function not directly related to the swarm application. The proximity communication consists of transmitting and receiving multi-casted data messages of size x_d bytes with a d_p seconds periodicity to and from all UEs within proximity; i.e., a UE will transmit data at a rate of $t_d = x_d/d_p$ bytes per second during proximity communication. The need to transmit data messages is determined based on proximity: the *ready time* is the moment in time when a data message is ready from application layer. A maximum latency of l seconds can be tolerated from the ready time until the message is delivered at all intended destinations. Combined, the ready time and latency budget defines the deadline of the data messages. The data message becomes useless after the deadline and will be discarded. Some control signals might be exchanged regardless of proximity.

We follow the 3GPP system framework [24] where communication is based on Orthogonal Frequency Division Multiplexing (OFDM) on a frequency band of bandwidth B. The frequency resource is shared between

Table B.1: Notation

Symbol	Meaning
N	Total number of autonomous robots
W	Bandwidth for data transmissions
S	Number of slots in the lifetime of the network
r_e	Extended cooperation range
r_c	Critical cooperation range
n_s	Number of slots requested by a UE for its transmission
$\mathcal{N}$	Set of UE IDs $\mathcal{N} = \{1, 2, ..., N\}$
$\mathcal{S}$	Set of time slots $\mathcal{S} = \{1, 2, ..., S\}$
$\mathcal{C}$	Set of indices of candidate slots for possible resource allocation
	$\mathcal{C} = \{1, 2, ..., 40\}$ indicates the slots with indices 1 to 40
$\mathcal{R}$	Set of information about utilization of slots in $\mathcal{C}$
$\mathcal{R}_s$	Resource occupancy determined by sensing procedure
$\mathcal{R}_e$	Resource occupancy determined by exchange of control signals
$\mathcal{A}$	Slots allocated for requested transmission(s)
s	Indicates a unique slot in $\mathcal{S}$
o	Indication of the occupancy in a slot
d_p	Transmission periodicity
x_d	Size of data message in bytes
t_d	Data message data rate
p_{tx}	Transmission power
T	Thermal noise power
$g^s_{n,n'}$	Channel gain between UEs n and n' in slot s
$\gamma^s_{n,n'}$	SINR on transmission between UEs n and n' in slot s

UEs by time division multiple access (TDMA). The smallest allocation unit is called a slot and has duration d_s, which is configurable based on the selected numerology. For simplicity we adhere to numerology 2, the highest numerology available for frequency range 1, which results in the shortest slot duration. We refer to time slots by their index s in the set $\mathcal{S} = \{1, 2, ...S\}$, which spans the lifetime of the network. For simplicity we assume UEs to have the same transmission requirements and be time synchronized, i.e. following the 5G NR procedure explained in [25]. In the following sections we use the notation in Table B.1.

When a UE with id $n \in \mathcal{N} = \{1, 2, ...N\}$ generates data in a slot s, this data is associated with a group of receivers $\mathcal{N}' \subset \mathcal{N}$ where $n' \in \mathcal{N}' : n \neq n', \text{dist}(n, n') < r_c$. The function $\text{dist}(n, n')$ returns the euclidean distance between UEs n and n'. For simplicity, we assume every transmission is subject to the same transmission power p_{tx}. The channel gain on transmission from n to n' in slot s is given as $g^s_{n,n'}$ and the gain from interfering transmissions is given as $g_{k,n'}$ $\{k : k \in \mathcal{K} \subset \mathcal{N}, k \neq n, k \neq n'\}$. The channel gains are modeled as the combined effect of path loss and shadowing, where the shadowing component on different links is correlated.

When a slot is used for transmission, the SINR on a link between n and n' in slot s is calculated according to

$$\gamma^s_{n,n'} = \frac{p_{tx} g^s_{n,n'}}{T + \Sigma_{k\in\mathcal{K}} p_{tx} g^s_{k,n'}} \tag{B.1}$$

where T is the thermal noise power.

Based on the ready times and latency requirement, the 3-dimensional data transmission matrix can be obtained $\mathbf{D}_{N\times N\times S} = [\delta_{n,n',s}]$

$$\delta_{n,n',s} = \begin{cases} s + \lfloor \frac{l}{d_s} \rfloor, & \text{if } n \text{ generates data in slot } s \text{ which} \\ & \text{should be transmitted to } n' \text{ within} \\ & \text{latency } l \\ 0, & \text{otherwise} \end{cases} \tag{B.2}$$

The problem is to determine an allocation, indicated by the allocation matrix $\mathbf{A}_{N\times S} = [\alpha_{n,s}]$ where the maximum number of UEs can be supported in the swarm.

$$\alpha_{n,s} = \begin{cases} 1, & \text{if } n \text{ transmits in slot} \\ & s \\ 0, & \text{otherwise} \end{cases} \tag{B.3}$$

such that for each nonzero entry $\delta_{n,n',s}$ in $\mathbf{D}$, the corresponding transmissions can be determined as the nonzero entries of $\mathbf{A}$ in the corresponding row n and the columns in the interval $[s; s + \lfloor \frac{l}{d_s} \rfloor]$. We refer to this interval as the allocation interval, as it is the slot interval in which a UE can be allocated transmission resources for a given data packet. Let $\Delta_{\delta_{n,n',s}} = \{\alpha_{n,r} : r \in S, s <= r <= s + l\}$ be the set of slots n utilize for the transmission of data $\delta_{n,n',s}$ to n'. The combined SINR of the transmissions relating to the same data message is calculated as

$$\gamma_{\delta_{n,n',s}} = 2^{\frac{1}{K}\Sigma_{r\in\Delta_{\delta_{n,n',s}}} log_2(1+\gamma^r_{n,n'})} - 1 \tag{B.4}$$

which is also known as the mean instantaneous capacity method used to determine an effective SINR mapping. Thus a set can be defined as $\Gamma = \{\gamma_{\delta_{n,n',s}} : \delta_{n,n',s} \neq 0, n \in N, n' \in N', s \in S\}$ and the optimization problem is formulated as

where $\mathrm{bler}(x)$ is a mapping function which maps a certain SINR to a block error rate, following the physical layer abstraction given in [26]. The first constraint guarantees that the system failure probability does not exceed a required failure probability requirement, f_p. The second constraint ensures that no two UEs within critical cooperation range transmit simultaneously, thereby avoiding half-duplex problems.

The problem of determining the allocation matrix $\mathbf{A}$ (like the problem formulated in [27]) is NP-hard, thus no algorithm can be found to determine the optimal solution within polynomial time. Additionally, due to the potential overlap of allocation intervals of different UEs, in search of the optimal solution, the entire lifetime of the network should be considered. Therefore, it is not feasible to find an optimal solution to this problem, and instead we deal with heuristic methods to efficiently determine suboptimal solutions to the allocation problem in a decentralized manner. We note that these approaches limit the scope of each round of allocation such that only a subset of slots in $\mathcal{S}$ is considered. Furthermore, due to the decentralization of the system, the allocation decision can be delegated to each UE, which might have a limited knowledge about the allocation decisions of other UEs. We will see that knowledge of other UEs allocation decisions is important for the performance of the system, as it might help avoid half-duplex allocations and reduce interference. In the next section, the state of the art decentralized resource allocation algorithm of 5G NR is presented.

2.1 Baseline resource allocation scheme (Mode 2)

On the sidelink, UEs can transmit directly to each other by performing 5G NR sidelink resource allocation mode 2. Mode 2 [28] relies on the signaling exchanged in the sidelink control information (SCI). The SCI is transmitted as part of a data message as depicted by control signal method 1 in Fig. B.1. The SCI carries information which is necessary for decoding of the data transmission, but more importantly (in a resource allocation perspective) it indicates the periodicity of the transmission, i.e. the future resources reserved for this semi-persistently scheduled (SPS) transmission. SPS transmissions reduce the overhead of resource allocation by introducing predictability, which allow other UEs to avoid allocation of conflicting resources. In addition, the UEs can reuse the resource allocation of one data message of subsequent data messages. This is a key concept of mode 2 by which UEs autonomously allocate resources. For completeness, we summarize the two stages of mode 2 below.

Sensing stage

Sensing is performed on a *sensing window* which spans the bandwidth configured for mode 2 transmissions and a time span no longer than 1 s leading up to the selection stage. The goal of the sensing is to determine a set of candidate resources. Initially a set of candidate resources of size M_{total} is defined.

Resources are removed from the candidate set if a SCI received during the sensing window indicates that the candidate resource is reserved by another UE **and** the measured reference signal received power (RSRP) on the SCI is above a threshold. If the resulting candidate set is smaller than 20% of M_{total}, the threshold is increased by 3 dB and the discarded candidate resources are re-evaluated, i.e. re-introduced to the candidate set if the RSRP is below the threshold.

Selection stage

In the selection stage the resource allocation algorithm is performed. It consists of selecting the requested resource(s) randomly among the candidate resources. If the resources are reoccurring with a given periodicity, the SPS re-selection counter is initialized [29]. At each transmission using the allocated resource, the counter is decremented. Once the counter reaches zero, re-selection is performed according to the mode 2 resource allocation.

The advantage of mode 2 is the autonomy of the procedure. It is only affected by the information it is able to obtain during the sensing window, and the delay introduced by determining the candidate slots is fixed. The disadvantage is that the simple coordination might cause two UEs with close ready times to allocate overlapping resources, resulting in half duplex problems. Additionally, the random nature of the allocation can cause sub-optimal performance.

Following, we introduce our cooperative resource allocation schemes. Both were built to comply with the 3GPP sidelink framework and its possible extensions. The sidelink framework is different from the framework of ISM-band technologies, where listen-before-talk and duty cycle restrictions are essential bounds on the resource allocation. Therefore, mode 2 acts as the baseline to which we compare our proposed allocation schemes.

3 Proposed cooperative resource allocation schemes

The cooperation scheme refers to the distribution of the resource allocation and related functions. It answers the question of who will perform the resource allocation, when, and based on what information. As in Fig. B.1, we assume the bandwidth is divided into two adjacent frequency resource pools to accommodate control transmissions and data transmissions, respectively. The UEs are able to either transmit or receive in both resource pools simultaneously, but due to the half-duplex constraint, simultaneous reception and transmission is not possible. Section 4 will explain what types of signals are

Algorithm B.1 Resource allocation

Input: $\{(n_s, \mathcal{R} = \{\mathcal{R}_s \cup \mathcal{R}_e\}, \mathcal{C})_k\}, k = 1, 2, ..., K$
Algorithm:

for each k in descending order of number of UEs within *critical cooperation range* **do**
    $\mathcal{P} = \{(s, o)_i \in \mathcal{R}_k, o_i \neq \infty, s_i\ in\mathcal{C}_k, i = 1...|\mathcal{R}_k|\}$
    for $n = 1, 2, ..., n_{s,k}$ **do**
        $\arg\min_i o_i \in P$
        $\mathcal{A}_k \leftarrow \mathcal{A}_k \cup s_i$
        $\mathcal{P} \leftarrow \mathcal{P} - (s, o)_i$
    end for
end for

Output: $\{\mathcal{A}\}_k$

transmitted in the control pool. The control pool signals are intended for UEs within extended communication range of r_e m.

Both proposed resource allocation schemes described here share the same basic resource allocation algorithm (Algorithm) B.1). We differentiate between the *allocating* UE which is the UE executing the resource allocation algorithm, and the *requesting* UE(s), which is the UE(s) requesting an allocation from the allocating UE. The allocating and requesting UE can be the same UE. The input is the tuple $(n_s, \mathcal{R} = \{\mathcal{R}_s \cup \mathcal{R}_e\}, \mathcal{C})$ for each user k where n_s is the number of slots requested by the requesting UE. The set of candidate slots, $\mathcal{C} \subset \mathcal{S}$ is every slot within the allocation interval of the requesting UE with respect to a data message. The predictability of SPS transmissions will be utilized in the proposed schemes. A benefit of SPS transmission is that one resource allocation can be valid for multiple data message transmissions. Allocation of a SPS transmission is triggered at the *trigger time*. The trigger time happens when the number of UEs within proximity is incremented to one (no longer zero) or after the resource re-selection counter expires. The resource re-selection counter is defined in [30] and decrements at each data transmission. The resource pool occupancy is given in the set $\{\mathcal{R}_s \cup \mathcal{R}_e\} = \{(s, o) | s \in \mathcal{S} \text{ and } o \in \mathbb{R}\}$ where o_i is an indication of the occupancy defined as the strongest signal previously received from any of the UEs expected to transmit in slot s_i. If a slot s_i is occupied by a UE within critical cooperation range of the requesting UE, the corresponding o_i is set equal to infinity to avoid the half-duplex problem. $\mathcal{R}_e$ is provided by the allocating UE and n_s, R_s and S are provided by the requesting UE. R_s indicates the current resource utilization as observed by the requesting UE whereas $\mathcal{R}_e$ indicates the resource utilization obtained (through control signaling) by the allocating UE. If K UEs are requesting an allocation from the same allocating UE simultaneously, their inputs will be ordered according to their priority,

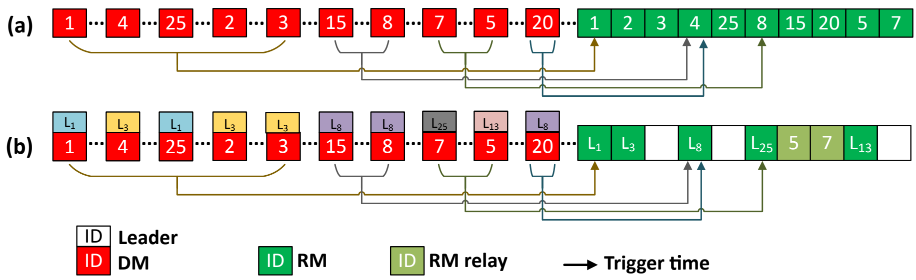

Fig. B.2: Relation between discovery messages (DMs) illustrated by red boxes and resource selection messages (RMs) illustrated by green boxes for (a) device sequential and (b) group scheduling schemes. ID is UE identification.

with $k = 1$ indicating the highest priority UE and $k = K$ the lowest priority UE.

Based on the resource occupancy from the requesting UE(s) and the received control signals, the resource allocation algorithm (Algorithm. B.1) allocates the resources for UE_k to avoid half-duplex problems and ensure the lowest interference from other UEs. If multiple requesting UEs are being assigned a resource allocation, the requesting UE with most potential half-duplex conflicts (most UEs in critical cooperation range) has resources allocated first. This greedy selection scheme is also know from greedy graph coloring algorithms. For each requesting UE, a set $\mathcal{P}$ of potential resources is initialized based on the resource pool occupancy observed by UE k. Resources are allocated based on the lowest occupancy in lines 4 and 5 of Algorithm B.1. In case multiple slots have identical minimum occupation in line 4, one will be randomly selected. A slot is allocated for UE k in line 5 and the corresponding entry is removed from set $\mathcal{P}$ in line 6. As a result, the output of the resource allocation algorithm is the set of allocated resources, $\mathcal{A}_k \subseteq \mathcal{C}_k$, for each of the requesting UEs.

3.1 Device sequential resource allocation scheme

This scheme consists of coordinated resource selection by following a sequence in which UEs independently perform resource allocation in prioritized order. In our design, the UE priority is based on their trigger time and a unique ID. The UE with earliest trigger time has highest priority, and in case multiple UEs have identical trigger time, the unique UE ID determines the sequence such that lower ID has higher priority.

In Fig. B.2 (a) the red boxes indicate the point in time when the trigger time is announced (in a discovery message discussed in Section 4.1). UEs 1, 4, 25, 2 and 3 have the same trigger time as indicated by the arrow pointing to the time slot for resource allocation. Due to the trigger time collision between

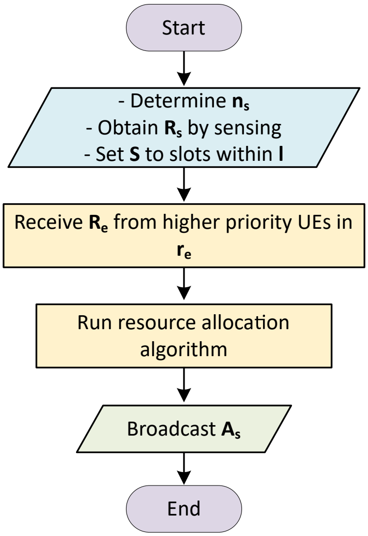

Fig. B.3: Device sequential coordination scheme for UE_i

the 5 UEs, they follow the prioritized order, which cause UEs 2, 3, 4 and 25 to perform resource allocation after their indicated trigger times (respectively a delay of 1, 2, 3 and 4 time slots). The coordination scheme for device sequential resource allocation follows the flow presented in Fig. B.3. A UE continuously monitor the trigger time and position of other UEs within the extended cooperation range r_c. Once the UE requires resources, it initiates the resource allocation scheme. After determining the number of resources necessary for the transmission, the UE-Awaits the resource selection from higher priority UEs within r_c and continues when either resource selection has been received from all higher priority UEs or the *resource selection delay* expires (further discussed in section 4). The resource selection delay is a configurable parameter. Then, the UE executes the resource allocation algorithm, providing itself with a resource allocation. The allocated resources is signaled by broadcast intended for every other UE within r_c.

The advantage of the device sequential scheme is the autonomy with which each UE is performing its own resource allocation while simultaneously coordinating with UEs in extended coorperation range. Additionally, the prioritization scheme, while important for the coordination, is also a way of providing differentiated service to the swarm member UEs. The potential drawback of the scheme is the additional resource allocation delay which might be incurred if the trigger time of multiple UEs within extended coordination range overlap, and the control overhead from the signals which indicate trigger time and selected resources between UEs.

3.2 Group scheduling resource allocation scheme

As implied by the naming, the group scheduling resource allocation scheme rely on local groups in which a group leader is executing the resource allocation algorithm and supplying the group members with resource allocation. Coordination happens within the group, but also between groups. For the latter, group leaders are either within extended cooperation range of, or have group members which collaborate with UEs in, another group. The group leader coordination is similar to the sequential scheme, where the prioritized order of allocation is determined by firstly group member trigger time (earlier trigger time is higher priority) and secondly the group leader unique ID (lower ID is higher priority). In Fig. B.2 (b) UEs 1 and 3 have been elected as leaders with IDs L_1 and L_3, respectively. Both leaders have group members with the same trigger time (UEs 1 and 25 for L_1 and UEs 2, 3 and 4 for L_3). L_1 has highest priority, thus performs resource allocation for its group members before L_3. The flow of the group scheduling resource allocation scheme is presented in Fig. B.4.

A UE continuously maintain membership of a group. It does so by periodically performing leader selection and broadcasting the choice of group leader. The candidate leaders are all UEs within r_e. Out of the candidate leaders, the leader is chosen as the candidate with most UEs within r_c. The unique UE ID will resolve any such that the candidate leader with the lowest ID UE will selected as the leader. Thereby, the group leaders are bound to be involved in swarm communication. Ahead of the trigger time, a UE informs its leader of its trigger time, the number of requested resources, the sensed resource occupation and the candidate slots. At the trigger time the leader executes the resource allocation algorithm after receiving any potential resource selection from higher priority leaders within r_e, or at latest when the resource selection delay has expired. The output from the resource allocation is signaled to the requesting UE and any lower priority leaders within r_e. Due to the range controlled leader selection procedure, the leaders of two collaborating UEs might be outside extended coordination range, potentially not being able to directly communicate. We refer to this as the *edge case*. In edge cases, the collaborating UEs need to forward the resource allocation received from their leader to allow the leaders to coordinate the resource allocation. Such forwarding is performed by UE 5 and 7 in Fig. B.2.

The advantage of the group scheduling scheme is that leaders are able to perform resource allocation for multiple UEs simultaneously and combining their allocation in a single control message, thereby reducing the amount of messages used for control signaling. Additionally, the group leader has more information for resource occupation as each group member and the group leader itself collects resource occupation information. The disadvantages relate to the additionally required control signals. The resource allocation must

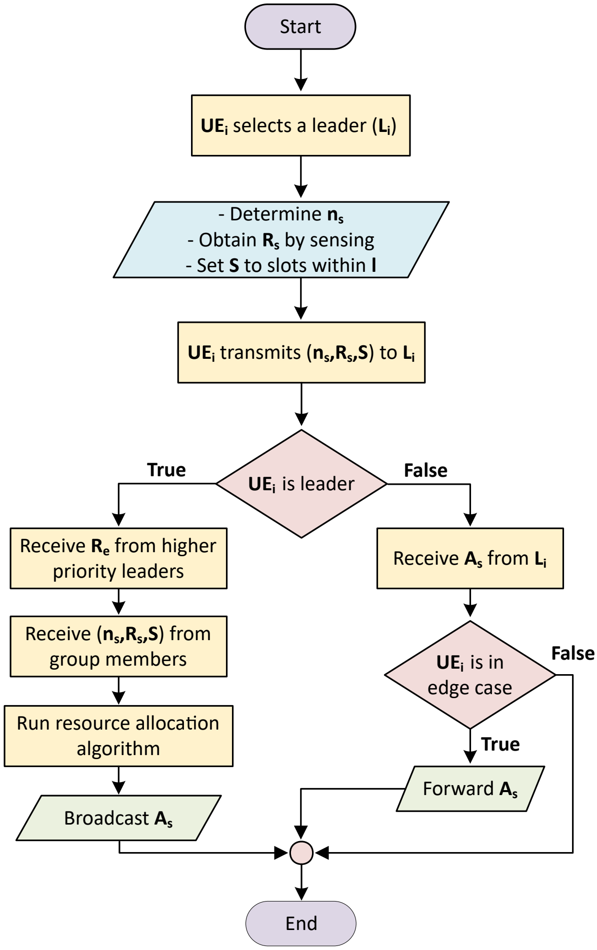

Fig. B.4: Group scheduling coordination scheme for UE_i

be signaled between leader and requesting UE. Failure to receive this signal will cause the requesting UE to be without a resource allocation. The requesting UE must provide information to the leader which incurs additional signaling overhead. Lastly, the edge case where coordinating leaders are out of direct communication range will cause a coordination delay and additional overhead.

4 Control signaling for cooperative schemes

The decentralized cooperative resource allocation schemes require additional control signaling exchanges compared to mode 2. In this section we establish

Table B.2: Message content necessary for the three resource allocation schemes

	Mode 2	Device sequential	Group scheduling
Discovery message (DM) content	• UE ID • Position & heading	• UE ID • Position & heading • Trigger time	• UE ID • Position & heading • Trigger time(s) • Leader selection • Sensed resource occupation (R_s) • Special forward indication
Resource selection message (RM) content	-	• Resources allocated by UE (A)	• Resources allocated to group members (A)
Data message	• Message periodicity • Application data	• Message periodicity • Application data	• Message periodicity • Application data

the control messages which will carry the control signals. For the cooperative schemes we utilize all three methods in Fig. B.1 (RA control signaling embedded with data, embedded with independent control signaling and dedicated) for exchanging control signals. A summary of the control signals and their control information for each resource allocation scheme is presented in Table B.2. The data message is identical for all schemes and simply include an indication of the periodicity of the message, making any receiver able to determine future resource reservation. The next subsections will elaborate on the discovery and resource selection message types.

4.1 Discovery message (DM)

The objective of DMs is for UEs to become aware of each others ID, position and heading direction. It is transmitted periodically with no exceptions. The DM is necessary regardless whether the resource allocation scheme is cooperative or non-cooperative, e.g. mode 2. Each DM is scheduled randomly within the discovery period.

For the device sequential and the group scheduling schemes the DMs are extended with information about the **trigger time**, when this is known by the UE. The UE can determine the trigger time either by estimating when another UE will be within r_c or when the re-selection counter reaches zero. We assume that the trigger time can be estimated far in advance and that the minimum value of the reselection counter is 750 ms as specified in [29]. A 100 ms discovery period would lead to each UE having at least 7 DM transmissions which results in sufficient discovery probability.

In the group scheduling scheme, the DM is extended with additional information. The leader selection is included in each discovery message such that leaders and collaborating UEs remain updated about the existing groups. When the trigger time approaches, the requesting UE will include the sensing result in its DM for the leader to use during resource allocation. Additionally, if UE-A identifies that its leader, L_A, and the leader, L_B, of a collaborating UE-B are out of direct communication range, UE-A will indicate in the DM the ID of L_B and the trigger time of UE-B. This allows L_A to determine the priority between the leaders and follow the coordination procedure. The size

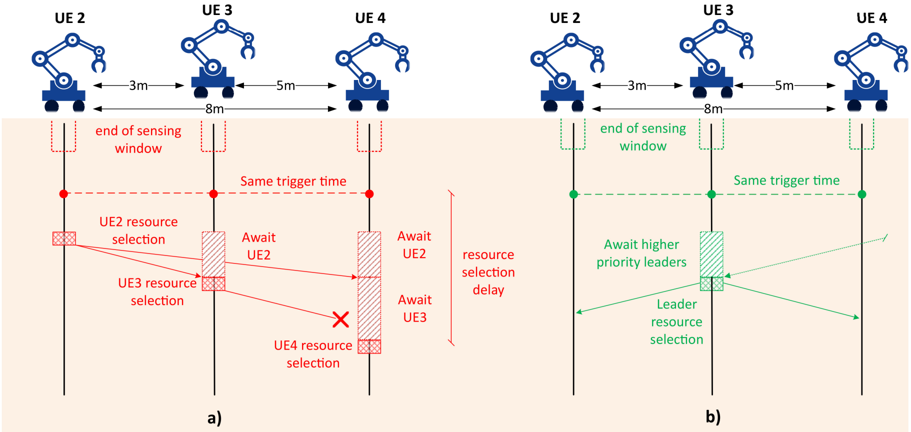

Fig. B.5: Control signaling exchange for (a) device sequential and (b) group scheduling

of DMs are enlarged by up to tenths of bytes due to the extensions needed by the cooperative schemes.

4.2 Resource selection message (RM)

This control signal is exclusive to the cooperative resource allocation schemes. Its function is to carry information about the allocated resources for future data transmissions. Hence there is a direct connection between RM transmission and the trigger time indicated in the DMs. Compared to the non-cooperative scheme, the RM represents an additional overhead. However, it is transmitted only once per SPS period. Fig. B.5 presents the RM transmission sequence diagram for each of the cooperative resource allocation schemes. The particularities of RMs for device sequential and group scheduling schemes are the following.

Device sequential

At the trigger time a UE allocates resources and transmit its RM unless one of the two following conditions are true:

1. there are UEs with higher priority (lower unique ID) within r_e with the same trigger time (e.g. UE 3 waits for UE 2's RM in Fig. B.5 (a)), or

2. there are UEs within r_e, with earlier trigger time, which are pending to perform resource allocation (e.g., UE 8 is waiting for UE 25's RM in Fig. B.2 (a)).

Therefore, upon reception of RMs from higher priority UEs or when the predefined resource selection delay has expired, the UE will proceed to send its RM. Even though the delay to perform resource allocation scales linearly with the number of higher priority UEs in the sequence, it is bound by the resource selection delay. Resource allocation commences once the resource selection delay expires (e.g., resource selection delay expires for UE 4 and it performs its resource allocation as illustrated in Fig. B.5 (a)).

Group scheduling

RMs are transmitted from the group leaders to their respective group members at the trigger time. If two or more leaders within r_e have inferiors with the same trigger time (e.g. the leader, UE 3, waits for higher priority leaders resource allocation in Fig. B.5 (b)), they must follow the sequential procedure explained in Section 4.2. In cases where multiple group members have been given resources simultaneously (e.g. UEs 2, 3, and 4 in Fig. B.5 (b)), the group leader combines the selected resources in one RM. This is beneficial in dense scenarios since it reduces the load of control signals in the control resource pool in comparison to the device sequential scheme. For the special forwarding procedure (edge case), group member UEs should forward the RMs (e.g. UEs 5 and 7 in Fig. B.2 (b)) between leaders to enable leader-cooperation and hence, avoid half-duplex problems when allocating resources within their respective groups. The delay to perform resource allocation in the group scheduling scheme scales with the number of leaders within r_e of each other. In addition, the special forwarding procedure introduces the delay of up to two additional transmission times. However, initiation of the resource allocation is bounded by the configurable resource selection delay.

5 System Level Evaluation

We consider an application for collective environment perception, in which robots within a proximity of $r_c = 5$ m must establish real-time high-throughput communication at high reliability for cooperative behavior, e.g. collision avoidance among robots and with external objects. This scenario is not unlike collective perception and cooperative collision avoidance use cases from vehicle to anything (V2X) envisioned by 3GPP in [31]. Specific requirements for this scenario are a 10 Mbps throughput where message latency does not exceed 10 ms at a reliability of 99.99 % [31].

The robots are driving in a rectangular indoor factory building. Each robot moves according to the random waypoint mobility model in which the robot moves at fixed speed between random points within the factory. The 3GPP non-line of sigth indoor factory with sparse clutter and low base station (InF-SL) pathloss model from [32] is used for modeling the pathloss on links. UE antennas are omnidirectional. As multiple links are in use, we impose correlation on the shadowing component. The shadowing is computed according to the method in [33] where integration over a Gaussian random field enforces a 20 m de-correlation distance and 5.7 dB standard deviation. Fast fading is not explicitly modeled, but included in the link layer model.

Regarding 5G NR parameters we select numerology 2, dictating a $d_s = 0.25$ ms slot duration. The data channel bandwidth is 100 MHz whereas the control data is carried on the smallest configurable sidelink sub-channel of twelve sub-carriers resulting in a 7.2 MHz bandwidth. The lowest modulation and coding scheme (MCS) for sidelink has modulation order 2 and coderate $\frac{120}{1024}$, leaving at most 196 bits for the control messages. The MCS for the data transmission is dynamically adapted at the time of allocation. For each robot within r_c, the signal to interference and noise ratio (SINR) is measured on the most recent transmission. The worst SINR is used to determine the modulation and coding scheme from [34, Table 5.1.3.1-2] which can attain a 0.01 % target block error rate (BLER). The link level, hence the mapping from SINR to BLER, is modelled using a set of BLER curves generated from separate link level simulations [26]. The link level simulation includes all physical layer processing according to 5G NR. The required number of slots n_s are calculated based on the selected MCS, assuming that the transport block is bit padded to an integer number of slots. We do not differentiate between data and control signal transmission in the link level modeling which makes the control link performance slightly optimistic due to the much lower transmission bandwidth, i.e. 100MHz compared to 7.2MHz. Simulations parameters are listed in Table E.2.

5.1 Key performance indicators

The main key performance indicator is reliability - the probability that a data message is received within the latency constraint. We measure it in the form of failure probability. The target 99.99% reliability corresponds to a 10^{-4} failure probability. As a complementary key performance indicator we capture the packet inter-reception (PIR) metric defined by 3GPP in [35]. It indicates the time in between successive packet receptions and is important for applications where regular updates are required. Multiple reasons might cause a reception failure, e.g. half-duplex errors arise when a UE is transmitting and therefore not able to receive a data transmission. We differentiate between whether a UE is transmitting a data message (half-duplex data), a discovery message (half-duplex DM), or a resource selection message (half-duplex RM).

Interference is another source of data reception failure. We differentiate between interference caused by UEs within r_c, denoted *inner* interference, and interference by UEs outside r_c, denoted *outer* interference. When UEs within and outside r_c simultaneously cause interference we denote it as *mixed* interference.

Lastly, when a group member has not received the resource selection message from its leader (no RM reception), it cannot perform a data transmission which will cause data reception failures at the receivers.

5.2 Simulation configurations

For the evaluations, five configurations were performed.

1. **Error-free signaling** in which every control message is received at every intended receiver.
2. **Error-prone signaling** according to the prevailing signal conditions.
3. **Signaling plus the RM re-transmission technique** in which in addition to 2) the RM re-transmission technique is utilized in the group scheduling scheme to mitigate data failures caused by failure to receive RMs.
4. **Signaling plus the RM re-transmission and the non-overlapping technique** in which in addition to 3) the non-overlapping technique is utilized to schedule DM in time slots where no incoming data transmissions are expected.
5. **Signaling plus the non-overlapping and piggybacking techniques** in which in addition to 4), the piggybacking mechanisms are enabled for the cooperative RA schemes.

The mobility trace of each swarm size was reused for all five configuration to allow direct comparison between the configurations. A 1000 seconds simulation time allows the robots to traverse the facility multiple times causing various collaborative configurations. Simulations parameters are listed in Table E.2.

6 Simulation Results

The control signaling exchange has a direct impact on the data exchange performance. It is fundamental to fulfill two conditions. First, the random selection of DM transmission must not coincide with the reception of data transmissions since it will cause half-duplex problems (hald-duplex DMs). Second, RMs failure probability should be sufficiently low such that it does not inhibit the performance of the cooperative schemes.

Table B.3: Simulation parameters

Parameter	Value/range
Carrier frequency, f_c	3.5 GHz
Swarm size (number of UEs)	$[10, 20, 30, 40, 50, 60, 70]$
Critical cooperation range, r_c	5 m
Extended Cooperation range, r_e	25 m
Facility dimensions	120×50 m^2 [32]
Transmission power, P_{tx}	0 dBm
Data channel bandwidth	100 MHz
Control channel bandwidth	7.2 MHz
Resource selection delay	1.25 ms
NR slot duration	250 μs
Thermal noise power spectral density	-174 dBm/Hz
Receiver noise figure	9 dB
Interference	Independent intra-system
UE speed	1 m/s
Mobility model	Random waypoint (RWP)
Pathloss model	InF-SL [32]
Propagation condition	Non line of sight
De-correlation distance δ	20 m [33]
Discovery message periodicity	100 ms
Data message periodicity, d_p	10 ms
Data message size, x_d	100 kb
Data message latency requirement, l	10 ms
Simulation time	1000 s

6.1 Reliability analysis and enhancement techniques

In Fig. B.6 we present the failure probability and the causes at various swarm sizes for the three resource allocation schemes group scheduling (GSch), mode 2 (SLm2) and device sequential (DSeq).

Failure to receive RMs in the cooperative resource allocation schemes can result in non-cooperative resource allocation. In the group scheduling scheme, a group member UE is dependent on receiving the RM from its leader. Failure of this RM reception will result in failure to transmit data for the entire SPS data transmission period (grey hatched bars in Fig. B.6). To address this problem the *RM re-transmission* technique was incorporated. It enables the group member to send a non-acknowledgment (NACK) to its leader indicating that re-transmission of the RM is necessary. It might take several NACKs for successful reception of RM. Fig. B.7 illustrates how failures caused by no RM receptions diminishes.

The second largest failure cause (at small swarm sizes) is half-duplex failures caused by transmission of discovery messages (blue bars in Fig. B.6).

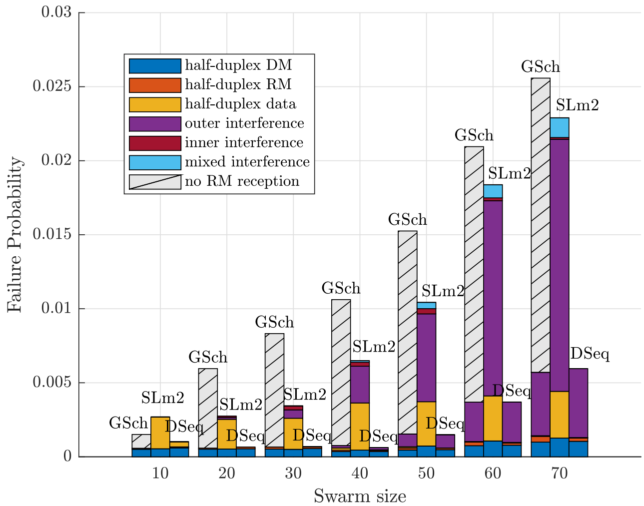

Fig. B.6: Failure probability and the causes of data transmission failures (half-duplex of DM, RM and data, inner, outer and mixed interference, and no RM reception) for three resource allocation schemes (SLm2, DSeq and GSch)

The random transmission of DMs has a significant impact on total failure probability of the cooperative resource allocation schemes. Mode 2 is similarly affected by the half-duplex DM. To counteract this problem we propose the *non-overlapping* technique. It utilizes the information about the current SPS transmissions acquired by UEs during the sensing procedure. The SPS transmission slots acquired by other UEs are not considered as possible options for the transmission of DMs to reduce potential half-duplex problems. Fig. B.8 depicts the near disappearance of half-duplex DM failures.

Additionally, a few half-duplex problems occur in receiving data due to simultaneous data transmission (yellow bars for Gsch in Fig. B.6) even at small sizess. This indicates that leaders were not cooperating. In the 40 UE swarm size, the device sequential scheme also experiences half-duplex failures to receive data due to simultaneous data transmissions (half-duplex data). This is an indication that some UEs failed to follow the sequential procedure. These described issues lead to the application of the *piggybacking* technique for the respective resource allocation schemes. Piggybacking builds on repeating the resource selection information by appending it to other RMs. It is done as follows in the two cooperative schemes:

- *Device sequential:* When a UE receives RMs from its predecessors, it includes this information in its respective RM, so that if UEs that follow the sequence did not receive previous RMs, they can recover them.

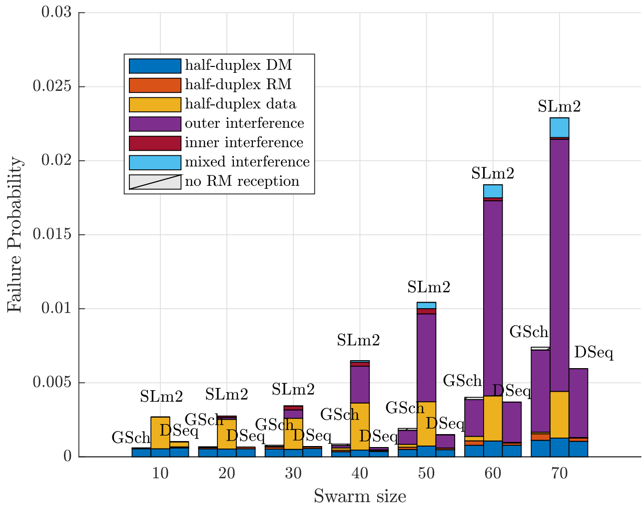

Fig. B.7: Failure probability and the causes of data transmission failures for three resource allocation schemes after enabling RM re-transmissions

- *Group scheduling:* When the group leader sends an RM to a group member UE, it includes the information of prior transmitted RMs. It allows group member UEs an additional chance to receive its resource allocation when the leader schedules other inferiors

Fig. B.9 illustrates that the effect of the piggybacking is negligible. This is a sign that the allocation sequences are not long enough even at swarm sizes of 70 UEs for the piggybacking technique to have an effect.

At large swarm sizes, outer interference becomes the main cause of failure. We plan to address it in our future work.

Even without the improvement techniques enabled, the device sequential RA scheme outperforms mode 2. At small swarm sizes the main difference lies in mode 2 having a considerable number of half-duplex data failures. The half-duplex failures caused by transmission of RMs in the cooperative schemes constitute a minor performance impact. As swarm size increases, interference becomes a dominant failure cause. The lack of cooperation and the resource selection procedure of mode 2 (described in 2.1) result in UEs experiencing data reception failures caused by high interference coming from UEs outside cooperation range (outer interference), UEs inside cooperation range (inner interference), or both (mixed interference).

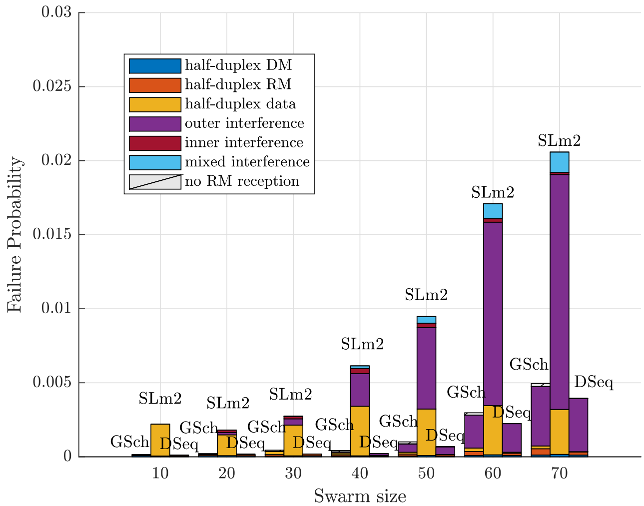

Fig. B.8: Failure probability and the causes of data transmission failures for three resource allocation schemes after enabling RM re-transmissions and non-overlapping techniques

6.2 Reliability performance with enhancements

Fig. B.10 shows the failure probability for different swarm sizes in simulations with the following configurations:

1. **Error-free signaling** in which every control message is received at every intended receiver.
2. **Error-prone signaling** according to the prevailing signal conditions.
3. **Signaling plus the RM re-transmission technique** in which in addition to 2) the RM re-transmission technique is utilized in the group scheduling scheme to mitigate data failures caused by failure to receive RMs.
4. **Signaling plus the RM re-transmission and the non-overlapping technique** in which in addition to 3) the non-overlapping technique is utilized to schedule DMs in time slots where no incoming data transmissions are expected.
5. **Signaling plus the non-overlapping and piggybacking techniques** in which in addition to 4), the piggybacking techniques are enabled for the cooperative RA schemes.

Mode 2 (blue lines in Fig. B.10) reaches failure probability below 10^{-2} until swarm size of 50. The failure probability of mode 2 is barely affected by the

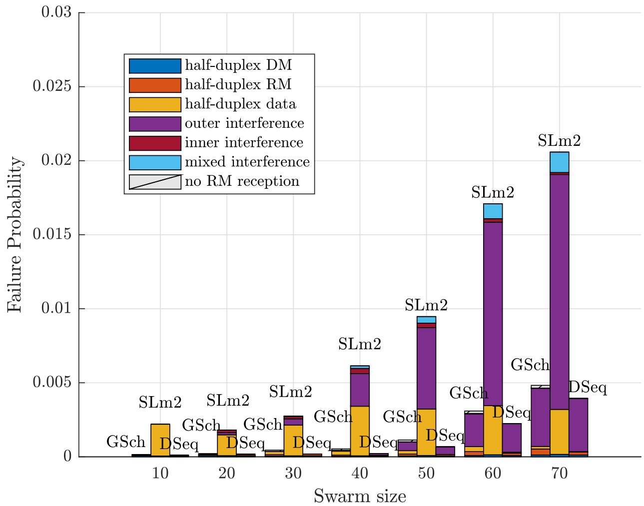

Fig. B.9: Failure probability and the causes of data transmission failures for three resource allocation schemes after enabling RM re-transmissions, non-overlapping and piggybacking techniques

simulation configuration. The highest failure probability is observed in the error prone signaling configuration, where in addition to half-duplex data and interference, errors were caused by half-duplex DM. Enabling the non-overlapping technique brings the error probability of mode 2 down to the level of error free control signaling.

Device sequential resource allocation is affected by the enhancement techniques. With error prone signaling the failure probability below 10^{-3} can be maintained until swarm size of 40. Enabling the non-overlapping technique further reduces the failure probability and allow it to maintain failure probability below 10^{-3} until 50 UE swarm sizes. The piggybacking technique has no impact. The device sequential scheme is able to meet the 10^{-4} failure probability target at 10 UE swarm size when all enhancement techniques are enabled. With error-free signaling, the device sequential scheme experiences no failures at swam sizes smaller than 40 UEs.

Group scheduling with error prone signaling has the highest failure probability of all schemes and configurations due to the impact on non-received RMs. However, enabling RM re-transmissions reduces the failure probability by an order of magnitude and makes the performance comparable to the device sequential scheme in the error prone signaling configuration. Enabling non-overlapping further reduces the failure probability of the group scheduling scheme maintaining the failure probability below 10^{-3} untill swarm size of 50. With all features enabled the failure probability of group scheduling is

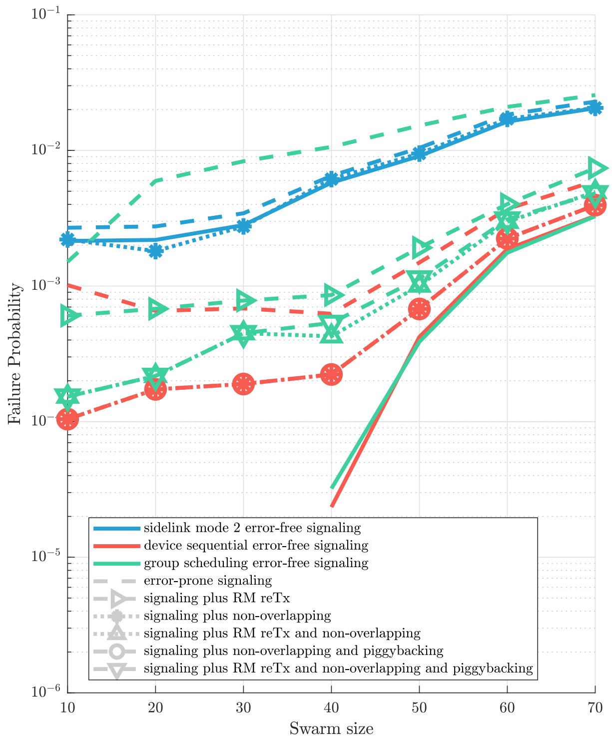

Fig. B.10: Failure probability for the resource allocation schemes at the five simulation configurations: error-free signaling, error-prone signaling, error-prone signaling with re-transmissions (only for group scheduling scheme), error prone with non-overlapping (re-transmissions), and error-prone signaling with non-overlapping plus piggybacking (re-transmissions)

still slightly higher than that of device sequential. With error free signaling, the group scheduling performance is as good as device sequential.

6.3 Packet inter reception (PIR)

Fig. E.17 (a) and (b) show the complementary cdf of the PIR for respectively 20 and 70 UE swarm size simulations. At both loads a PIR less than or equal to 10 ms is most frequent. This is expected, as the SPS period is exactly 10 ms, thus successive successful receptions of data messages in the same series of SPS transmissions will result in a 10 ms PIR. A PIR lower than 10 ms can occur as a result of re-selection of SPS transmission, and the same goes for PIR between 10 and 20 ms. However, PIRs longer than 20 ms are caused

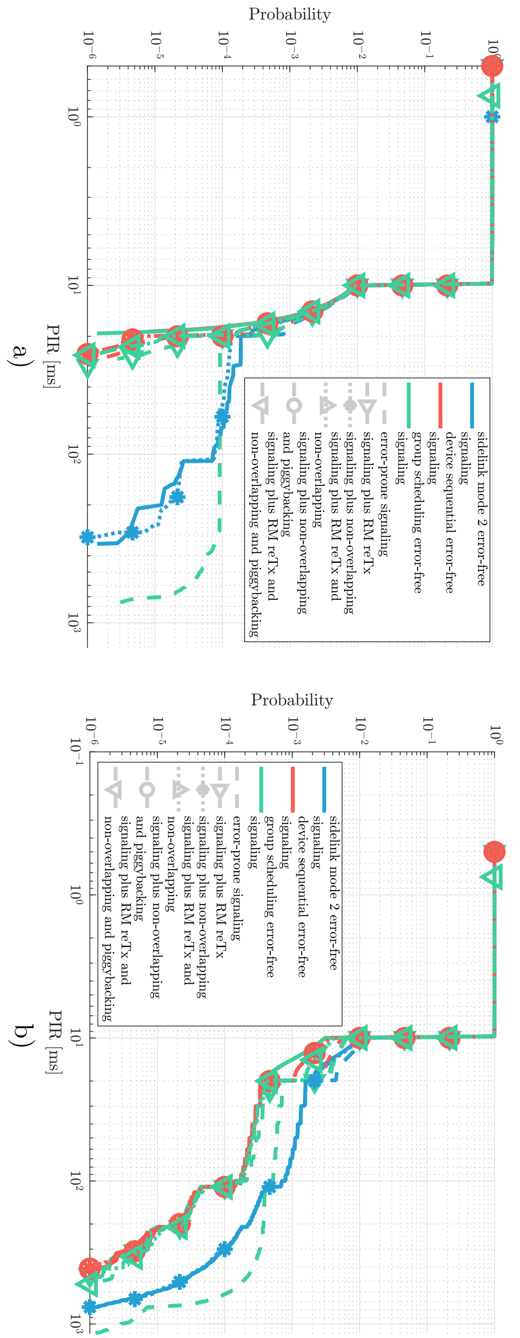

Fig. B.11: Packet inter reception (PIR) at swarm sizes of 20 UEs (a) and 70 UEs (b) for all simulation configurations by reception failures. The configuration with the highest failure probability also experience the longest PIR, regardless of allocation scheme. At 20 UE swarm size, the PIRs exceed 20 ms with a probability less than 10^{-3}. Only mode 2 and the group scheduling configuration with error prone signaling experience 30 ms, corresponding to 2 successive reception failures. At 70 UE swarm size all configurations experience PIRs greater than hundreds of milliseconds. The cooperative schemes perform similar in configurations with RM-retransmissions enabled and outperform mode 2 at both swarm sizes.

7 Conclusion

5G NR sidelink mode 2 is the current baseline resource allocation scheme for swarm communication. However, the autonomy of mode 2 and its random resource allocation algorithm is an impediment for its ability to accommodate the growing demand for high performance in dense swarms. We proposed two cooperative resource allocation schemes - *device sequential* and *group scheduling* - each representing a different coordination scheme.

We evaluate the proposed resource allocation schemes against baseline mode 2 in a series of comprehensive system level simulations. Despite the increased signaling overhead necessary in the coordinated schemes, they still represent an order of magnitude reduction in failure probability when compared to mode 2.

The methodology of identifying distinct causes of data failure provided valuable insight. Three enhancement techniques, respectively, resource selection message re-transmissions, non-overlapping allocation of discovery messages and piggybacking, were designed to address the data transmission failures caused by the error prone control signaling. Resource selection message re-transmission and non-overlapping allocation of discovery messages proved to significantly reduce failure probability in the coordinated schemes, whereas piggybacking did not introduce any significant gain.

The proposed resource allocation schemes, their associated control signaling and enhancement techniques provide a good trade-off between control overhead and performance in terms of latency and reliability. However, in order to achieve the stringent 99.99% reliability requirement additional interference management techniques are necessary. In our future work we will explore techniques to improve the reliability at larger swarm sizes.

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Part IV

Robustness and Time and Spatial Diversity for Enhancing Reliability of Cooperative Resource Allocation Over NR SL Mode 2

Robustness and Time and Spatial Diversity for Enhancing Reliability of Cooperative Resource Allocation

1 Motivation

Achieving stringent reliability, throughput, and latency requires the application of enhancement techniques for both mode 2 and cooperative resource allocation schemes. The two previous parts covered the proof of concept and signaling design for cooperative resource allocation schemes and its comparison with mode 2. Even though the effects of the control signaling were possible to minimize, it was feasible to fulfill the stringent requirements of up to ten UEs when using the device sequential scheme. Since the minimum throughput is 10 Mbps, data transmissions may require several slots. Thus, the effective signal-to-noise-plus-interference ratio (SINR) [1] should be adequately high to allow target UE receivers to decode the transmitted data. One, several, or all slots may experience either half-duplex problems or interference, making a successful reception impossible. Currently, if a UE does not incorporate full-duplex capability, receiving data in a slot that experiences half-duplex is impossible. However, the latest 3GPP release 17 [2] incorporated resource allocation cooperation in the form of inter-UE coordination (IUC). It consists on providing IUC information from the receiver UE to its transmitter. It indicates the set of candidate slots the receiver considers the best to receive data from that transmitter. This approach's disadvantage is the need of additional control signaling messages compared to our proposed cooperative resource allocation schemes. An example of the number of control signal messages of n UEs in need to transmit data by using IUC (mode 2) or cooperative resource allocation schemes (device sequential and group scheduling) is presented in Table IV.1.

Table IV.1: Number of control signaling messages (Num. Messages) to achieve cooperative resource allocation in NR SL mode 2 IUC scheme 1, device sequential and group scheduling. (Source: Paper E)

RA Scheme	Num. Messages
Mode 2 IUC scheme 1	n(2n-2)
Device sequential	n
Group scheduling	1

Therefore, cooperative resource allocation schemes represent an important option to alleviate the grid congestion due to control signal messages flow in the dedicated resource pool that may cause half-duplex problems.

Another option to overcome half-duplex problems is performing data re-transmissions [3] but at the cost of increasing the grid's occupancy. It is crucial to consider the aspects HARQ re-transmissions involve, such as NACK reception and time employed for the first transmission to take profit of HARQ's advantages rather than them becoming disadvantages.

Interference-wise, as the swarm size increases, UEs tend to be closer to each other, and the amount of data transmissions creates interference in all its kinds (e.g., inner, outer, and mixed). The adoption of directional antennas and beam selection represents a suitable solution to diminish or eliminate them, if possible, as UEs will be using the antenna(s) pointing at the direction of the target receiver/transmitter. Important elements to consider are the angle of the horizontal and vertical half power beam width (HPBW), the manner UEs proceed with beam selection, and how UEs behave in case they are deprived of transmitting data (i.e., group scheduling scheme).

Finally, incoming data failure receptions due to half-duplex and interference can be avoided or recovered using the previously introduced techniques. However, they do not guarantee following ones within the SPS period will have a similar fate. Suppose robustness is incorporated into the communication links by using link adaptation [4]. In that case, UEs can reduce the MCS index to decrease the value of the minimum required SINR to then successfully decode data.

Our goal is that a large swarm can operate with stringent communication requirements. Then, the application of enhancement techniques that eliminate or at least considerably reduce interference and allow UEs to recover failed data receptions due to half-duplex problems represent promising solutions.

2 Objectives

The objectives of this part of the thesis are the following:

- Incorporate time diversity to all resource allocation schemes while considering the time UEs to perform the first and the subsequent re-transmissions.
- Provide robustness to the D2D links that experienced data reception failures to minimize their presence until the semi-persistent period ends.
- Eliminate the interference coming from UEs located in the extended cooperation range (r_e) and minimize the one at the critical cooperation range (r_c) by incorporating directional antennas and beam selection to each UE.
- Provide group scheduling resource allocation scheme with an alternative to eliminate the presence of deprived transmissions that prevent it from profiting from the benefits of the proposed enhancement techniques, impacting the scheme's reliability directly.

3 Included Articles

The main findings of this part are included in the following article:

Paper C. Decentralized Cooperative Resource Allocation with Reliability at Four Nines

Effect of HARQ and link adaptation by aggregation (LAAG) into schemes performance. This article discusses the impact of sidelink's HARQ and link adaptation into both mode 2 and cooperative schemes. A detailed explanation of how HARQ operates is provided. It includes the description of the chosen slot configuration to enable feedback and the use of NACKs to trigger re-transmissions. Moreover, the explanation of our proposal to link adaptation by aggregation is provided. It consists of randomly allocating additional slot(s) after a data failure reception, such that the MCS index is reduced for the subsequent data transmissions until the SPS period ends. Additionally, it includes the description of the effective SINR value used at the receiver to map it to the MCS curves to determine if data was either or not received.

The evaluation of the impact of both techniques includes the analysis of different swarm sizes of the mean resource occupancy, the failure probability, and latency. The latter is done by using the PIR KPI defined by 3GPP as the time between consecutive data packet receptions. The analysis is conducted by applying the techniques separately and simultaneously to provide a fair comparison of their individual and combined effect.

Paper D. New Radio Sidelink with Beam Selection for reliable Communication in High-Density Robotic Swarms

Directional antennas and beam selection into mode 2. A discussion is carried out of mode 2's resource selection procedure and its consequences on partial overlap (i.e., some slots belonging to the same data transmission experience half-duplex) and full overlap (i.e., all slots belonging to the same data transmission experience half-duplex). The antenna deployment adopted follows the configuration for a type 2 vehicle specified by 3GPP consisting of placing four patch antennas on each face of the robot's chassis. Each antenna produces a beam that covers the corresponding azimuth sector. With sufficient discovery probability, the beam selection builds on the context information (i.e., coordinates, heading direction, and speed) given in DMs. The evaluation covers the performance obtained when transmitter and receiver beam selection were enabled simultaneously and separately. It includes the effect of beam selection into the effective SINR reflected on the failure probability. It also provides an accurate characterization of the reduction of each error type by progressively applying beam selection for different swarm sizes. It is possible by evaluating the average failure per NR slot (i.e., the sum of per UE number of slots experiencing failures divided by the product of the swarm size and the number of slots in the simulation time).

Paper E. Robust Decentralized Cooperative Resource Allocation for High-Dense Robotic Swarms by Reducing Control Signaling Impact

Eliminate the presence of deprived transmissions (group scheduling scheme) and employ directional antennas and beam selection into device sequential and group scheduling schemes. This article considers the presence of a few deprived data transmissions in a group scheduling scheme, impacting the failure probability performance directly. A new *"rebel sub-mode"* is proposed to prevent group members from being deprived of transmitting data when they have not received RMs from their respective group leaders. Additionally, directional antennas and beam selection are applied to device sequential and group scheduling schemes to compare their performance against mode 2. The evaluation contemplates the impact of the progressive application of the enhancement techniques (HARQ,LAAG, and beam selection) on the error-prone signaling performance until enabling all of them simultaneously for different swarm sizes. It covers the techniques' impact on reducing each of the data failures causes when evaluating the average failure per slot for each resource allocation scheme.

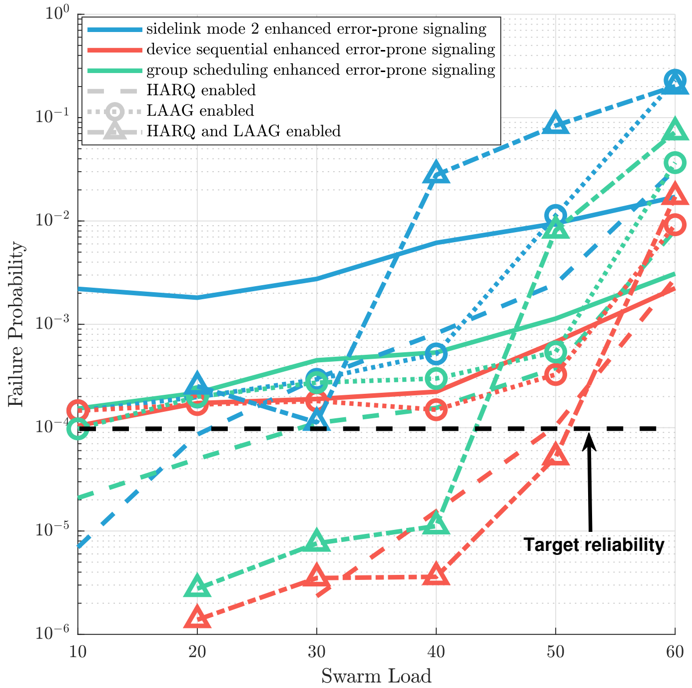

Fig. IV.1: Sidelink mode 2, device sequential and group scheduling failure probability for: error-prone signaling, signaling with HARQ, signaling with LAAG and signaling with HARQ and LAAG enabled. (Source: Paper C)

4 Main Findings

HARQ benefits are complemented by LAAG

The difference between both techniques lies in HARQ focusing on re-transmitting the failed transmission and making it successful before the latency constraint ends. On the other hand, LAAG builds on making the subsequent data transmission more reliable by randomly allocating additional slot(s). Therefore, the only implementation of LAAG will not recover a failed transmission; hence, the failure probability will be impacted. However, upcoming transmissions within the SPS period will benefit, and failures might be avoided. Fig. IV.1 shows how HARQ allows fulfilling the stringent requirements compared to the error-prone signaling performance up to close to fifty UEs for device sequential scheme. Nevertheless, LAAG does not produce such an effect since its focus is on subsequent transmissions. Therefore, when enabling both, the best performance is obtained in the cooperative schemes but not in mode 2. A likely explanation is that recovering the failed transmission with HARQ and making subsequent transmissions robust allow cooperative schemes to use slots efficiently since their fundamental purpose is to avoid half-duplex and harmful interference. This behavior is not straightforward to mode 2 as its random resource selection produces the presence of more re-transmissions, increasing the resource occupancy and, therefore, providing the worst performance.

In our simulations, we selected a first transmission window time of one-third of the latency target (i.e., 3.33 ms). The reason behind it lies in providing UEs sufficient slots to perform a successful first shot transmission and enough time for one or several re-transmissions, if necessary.

When analyzing the two extremes, giving a short period to the first shot transmission will make UEs fail it as the swarm size increases. A considerable re-transmission window will make it more likely that at least one is successful. However, since re-transmissions are randomly allocated, they will likely experience half-duplex problems. Conversely, UEs counting with enough space to perform a successful first shot transmission can be problematic because they will put all the odds in the first transmissions, and the few options to perform re-transmissions might cause a failed transmission. Therefore, there would seem to be a need to give sufficient room to perform re-transmissions while not shrinking the first shot transmission window to avoid the constant need for a re-transmission(s).

Antenna's HPBW of 65 degrees is the best option

As introduced before, the chosen configuration for the directional antennas was the type 2 vehicle specified by 3GPP. It contemplated using four directional antennas, each covering a 90^o horizontal azimuth sector. It was hypothesized that the first intuitive choice would be a 90-degree HPBW such that the whole azimuth sector can be covered. However, 3GPP has established a value of 65^o to the patch antenna HPBW. For that reason, we wanted to compare which of the two options provides the higher gain at the boresight and the lowest at the edges since it will provide both higher SINR at the desired direction and interference reduction to other sectors. Fig. IV.2 illustrates the 360^o antenna pattern of an isotropic antenna (used in previous studies), and our named 3GPP-wide patch.

Results show that the 3GPP antenna pattern (red) is the most suitable option for our use case. It provides a higher gain between $\pm\ 45^o$ from the boresight, and at those values, it has the same gain as the 3GPP-wide. Beyond that, the gain significantly reduces. It allows UEs to increase the SINR of the desired transmission at the transmitter or receiver side while reducing the interference coming from UEs located within other azimuth sectors.

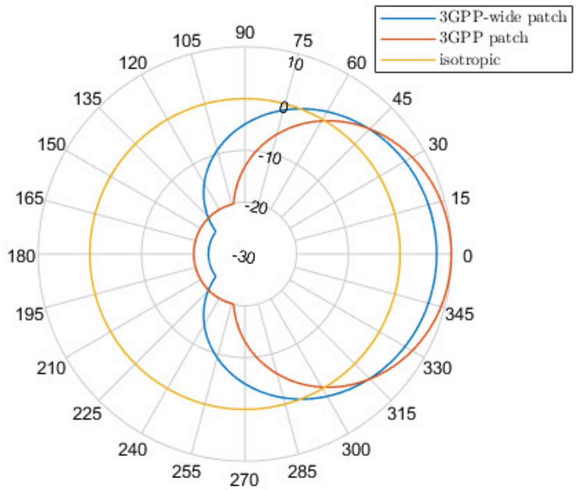

Fig. IV.2: Antenna pattern for 360^o azimuth angles when adopting isotropic, 3GPP modeled patch antenna element and 90-degree 3GPP modeled patch antenna element (3GPP-wide patch). (Source: Paper D)

Rebel sub-mode allows group scheduling scheme to outperform mode 2
Despite RM re-transmissions significantly reducing the number of no RM receptions, the presence of few cases directly affects the scheme's performance. Fig. IV.3 shows the presence of few no RM reception cases which increases with the swarm size. A deprived transmission translates to multiple failed data transmissions as the group member UE will not perform any transmission within the SPS until resource re-selection occurs.

Once noticing this particular behavior, the introduction of the *rebel sub-mode* allows UEs to avoid these cases since if a group member does not receive an RM from its leader, it proceeds to allocate slot(s) randomly. The downside of this approach is that some half-duplex problems might occur, but with HARQ, it would be possible to recover those failures. Therefore, group scheduling performance will improve as the average failure rate does not show failures coming from this issue, as depicted in Fig. IV.4. The significant impact of this enhancement will be reflected in the failure probability's lower percentiles included in the next point.

Beam selection considerably reduces the number of half-duplex of data transmissions and interference
Beam selection allows UEs to increase the SINR of each desired transmission

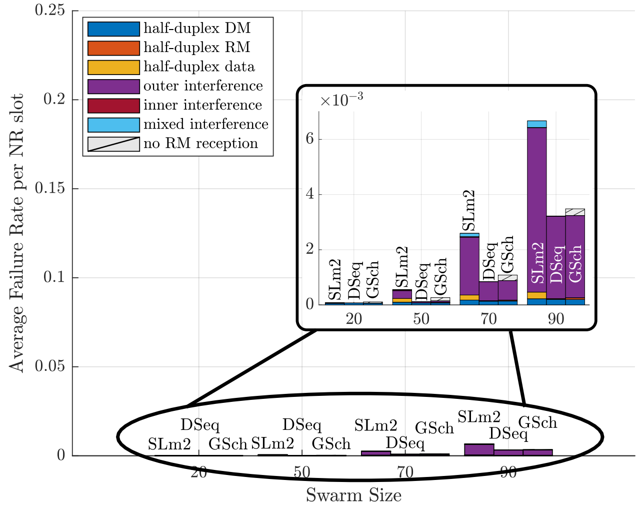

Fig. IV.3: Average failure rate per NR slot when all enhancement techniques are disabled for the three resource allocation schemes: mode 2, device sequential, and group scheduling (rebel sub-mode disabled), for four swarm sizes. (Source: Paper E)

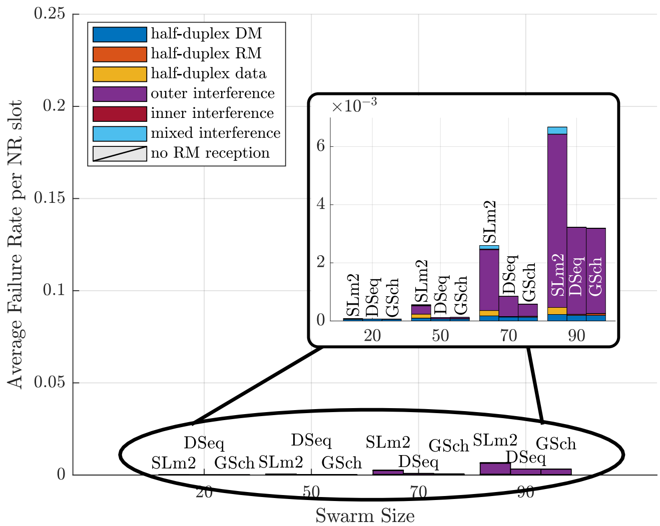

Fig. IV.4: Average failure rate per NR slot when all enhancement techniques are disabled for the three resource allocation schemes: mode 2, device sequential, and group scheduling (rebel sub-mode enabled), for four swarm sizes. (Source: Paper E)

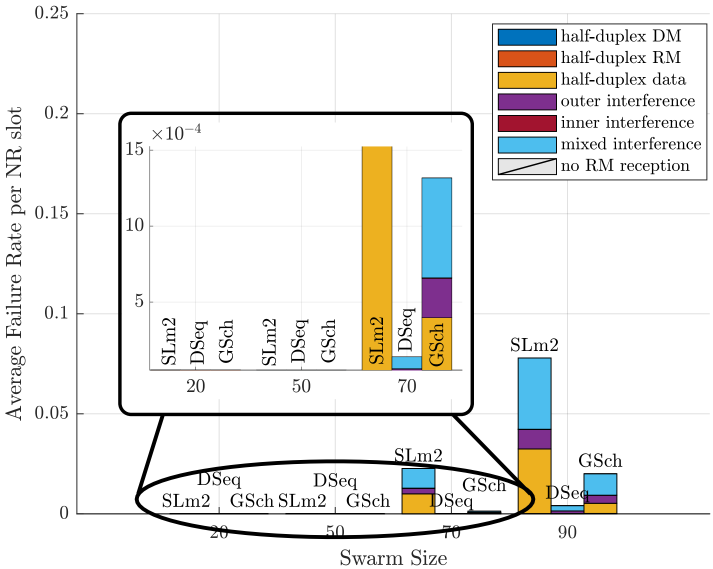

Fig. IV.5: Average failure rate per NR slot when all enhancement techniques are enabled for the three resource allocation schemes: mode 2, device sequential, and group scheduling (rebel sub-mode enabled), for four swarm sizes. (Source: Paper E)

while reducing it when coming from interferers. Since each 100 kbit data transmission is likely to use more than one slot, we determine the effective SINR (γ_{MIC}) of K allocated slots by using the mean instantaneous capacity method. It is computed as,

$$\gamma_{MIC} = 2^{\frac{1}{K}\sum_{k=1}^{K} log_2(1+\gamma_k)} - 1 \tag{IV.1}$$

The effective SINR is mapped to the set of BLER curves for the given MCS. Separate link-level simulations were used to obtain the BLER curves by adopting all physical processing established for 5G NR [5]. Then, it is possible to determine if data was successfully received or not. Even though one or some slots experienced half-duplex problems, if the γ_{MIC} is sufficiently high, the data transmission can be received. However, if all slots for the same data transmission experienced half-duplex, the γ_{MIC} will be zero, and it will surely be a failed transmission.

Therefore, enabling transmitter and receiver beam selection represents a promising solution since the SINR increases at the transmitter and receiver sides, and the interference is reduced at the receiver side. Fig. IV.5 shows that when enabling all enhancing techniques, the average failure rate reduces by order of magnitude in all schemes, being the lowest value for device sequen-

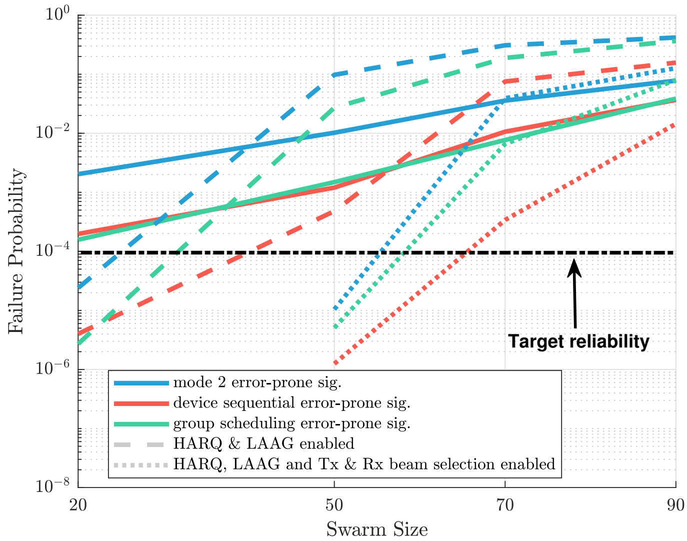

Fig. IV.6: Failure probability achieved at three configurations (error-prone signaling, HARQ & LAAG enabled, and HARQ & LAAG plus Tx & Rx beam selection enabled) for the four swarm sizes. The 10^{-4} requirement is indicated by the dashed black line. (Source: Paper E)

tial. At a larger swarm size, mode 2 is experiencing a half-duplex of data transmissions and outer and mixed interference due to its random resource selection. Few cases of the same kind were found in group scheduling due to the misalignment between leaders since the swarm is dense, and it is more likely to have such cases.

In Fig. IV.6, we present the failure probability performance for each scheme when gradually enabling the enhancement techniques. First, only the error-prone signaling followed by the incorporation of HARQ and LAAG to finally add transmitter and receiver beam selection. It is straightforward that cooperative resource allocation schemes outperform mode 2. Beam selection benefits allow all schemes to fulfill the stringent requirements at a large swarm size, but device sequential goes further than mode two and group scheduling. The reason behind group scheduling's performance is that in our simulation environment, UEs move at 1m/s, and the resource reselection maximum time is at 1.5 s. Then, conditions such as edge cases and uncoordinated leaders might persist for several SPS periods as the swarm becomes dense, being those failures harmful since the effective SINR does not reach the required minimum value. Even though the average failure rate in group scheduling is significantly lower, the randomness of mode 2's resource selection alleviates the persistence of such behavior and, thus, the similar performance when the swarm overpasses seventy UEs.

Receiver beam selection represents the best option for decentralized proximity communications, and it is complemented by transmitter beam selection
The previous point presented the benefits of simultaneously enabling transmitter and receiver beam selection. Here, we want to address why receiver beam selection is more beneficial than transmitter beam selection. Since our scenario is based on proximity communications for a swarm of robots, the scenario is likely to follow a groupcast nature. The reason lies in the scenario's particularity. Since communication is based on proximity, one UE's transmission is likely to reach several receiver UEs. Depending on the locations of the target receiver(s), the transmitter will be required to select one or more beams to reach them, being the latter a source of interference. In contrast, one receiver UE is more likely to receive one transmission at a time. Thus, it uses one beam, making the interference effect at the non-active beams negligible. Fig. IV.7 shows mode 2's failure probability when transmitter and receiver beam selection is enabled separately and simultaneously. Below a swarm size of 30 UEs, both perform equally since the density is not large enough to generate harmful interference in the case of transmitter beam selection. Beyond this value, a difference in performance starts to be noticeable, being receiver beam selection capable of coping approximately ten more UEs than transmitter beam selection. Therefore, the combination of both allows UEs to boost the SINR at both communications edges, making it possible to support more UEs, as presented in the previous point.

Cooperative resource allocation schemes require significantly less control signal messages than mode 2 IUC
When the Ph.D. project started, 3GPP release 16 was the latest. It did not include IUC and hence it was not implemented in our system-level simulator. Nonetheless, we compared the number of control signal messages between mode 2 IUC and our proposed cooperative resource allocation schemes to get a perspective on the degree of resource pool occupancy, giving a hint about the overall performance. In [3], it is specified that IUC request only works for unicast. However, within our analysis, we assumed the possibility that a UEs can broadcast IUC requests to all the UEs located within critical cooperation range r_c. As a reminder, IUC occurs when the transmitter UE sends an IUC request to a receiver UE, getting as reply the IUC information containing the set of resources it considers the best candidates to have a successful reception. If we recall the content of Table IV.1 and expand it to the case where IUC can be broadcasted as presented in Table IV.2.

It is clear that even though the number of messages is reducing when assuming IUC request broadcast, the number of control signaling messages is still significantly higher compared to our proposed cooperative schemes.

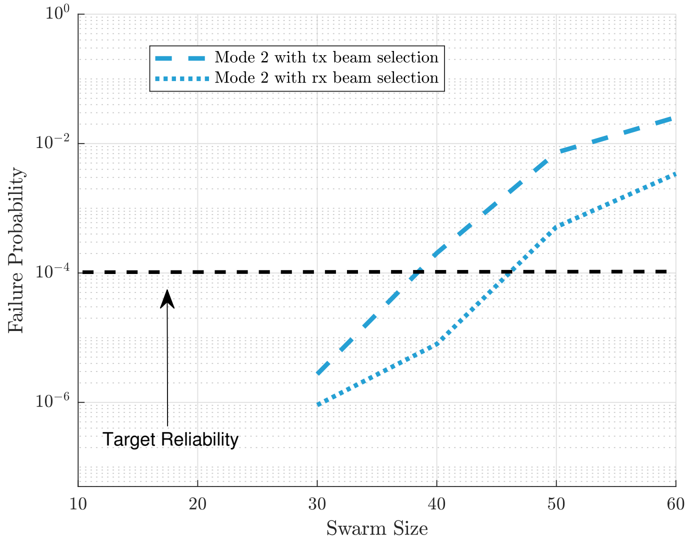

Fig. IV.7: Failure probability achieved at mode 2 with Tx & Rx beam selection enabled separately for the four swarm sizes. The 10^{-4} requirement is indicated by the dashed black line. (Source: Paper D)

Table IV.2: Number of control signaling messages (Num. Messages) to achieve cooperative resource allocation in NR SL mode 2 (IUC request unicast and broadcast), device sequential and group scheduling. (Source: Paper E)

RA Scheme	Num. Messages
Mode 2 IUC request unicast	$n(2n-2)$
Mode 2 IUC request broadcast	n^2
Device sequential	n
Group scheduling	1

Fig. IV.8 shows how this number increases with the number of UEs within r_c.

The difference is reflected in the resource occupancy of the separate resource pool use to transmit the control signaling. Most importantly, it might create half-duplex problems between data and IUC request and information messages as their reception probability tends to be reduced with the increment of swarm members. Indeed, the benefits of our cooperative schemes are not straightforwardly granted. Issues like uncoordinated leaders, edge cases, and no RM receptions affect group scheduling's reliability. However, when considering a device-centric cooperative resource allocation (i.e., device sequential scheme), the benefits are undoubted and represent the best choice when the swarm size is considerably large.

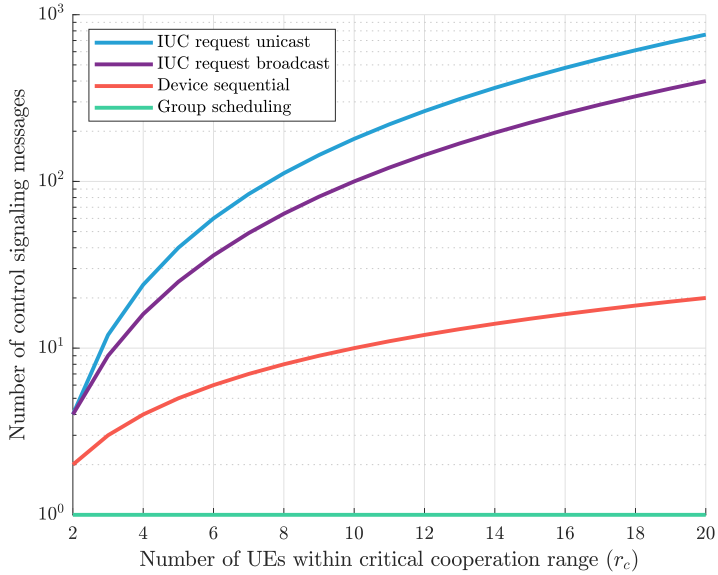

Fig. IV.8: Number of control signaling messages to achieve cooperative resource allocation for mode 2 (IUC request unicast and broadcast), device sequential, and group scheduling for different sizes of UEs located within their respective r_c.

5 Relation with part III

In Part III, we concluded that when evaluating the signaling design impact on the performance, only ten UE could satisfy the stringent requirements when using the device sequential scheme. Therefore, incorporating enhancement techniques is necessary to increase the number of UEs fulfilling the stringent requirements. Thus, HARQ, LAAG and beam selection represented a suitable solution.

6 Recommendations

The studies presented in this part indicate the significant benefits of our proposed cooperative resource allocation compared to mode 2's performance. They benefit from HARQ, LAAG, and beam selection to fulfill the stringent communication requirements for larger swarms. Based on the obtained results, the following recommendations are made:

- If the resource availability is a limitation, the achievement of cooperative resource allocation by using our proposed schemes represents the best choice as they require far less control signaling messages compared to mode 2 IUC.

- Adopting a groupcast resource allocation has to be carefully studied to identify unusual behaviors that limit the desired performance if the goal is to support large swarms. At lower reliability percentiles, it is necessary to consider tiny details that may cause few data failure receptions (e.g., RM receptions).
- When the swarm is small, the best choice would be to adopt a group scheduling scheme. It provides comparable performance to device sequential and mode 2 when enabling all enhancing techniques, with the difference of using the lowest amount of control signaling messages of the three. It represents an important aspect when considering the UE's power consumption (KPI that does not been part of any study of this Ph.D.). Nevertheless, if the required swarm size is large, the best choice is the device sequential scheme because it provides the best performance, but at the cost of sending more control signal messages, but significantly less than mode 2 IUC.

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Paper C

Decentralized Cooperative Resource Allocation with Reliability at Four Nines

C. Santiago Morejon, Rasmus Liborius Bruun, Troels B. Sørensen, Nuno K. Pratas, Tatiana K. Madsen, Ji Lianghai and Preben Mogensen

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Abstract

Decentralized cooperative resource allocation schemes for robotic swarms represents an alternative to infrastructure-based communications across different commercial, industrial and environmental protection use cases. The cooperative communication schemes, device sequential and group scheduling in [1], have shown superior performance in comparison to 5G NR sidelink mode 2, but have also shown performance issues due to signaling overhead and signaling induced failures. In this paper we introduce different techniques that reduce the failure probability of data packet transmissions and the packet inter-reception (PIR) time. We evaluate two techniques, respectively, of incremental redundancy using hybrid automatic repeat request and link adaptation by aggregation, as well as their combination for our decentralized cooperative resource allocation schemes and sidelink mode 2. Our results show that the introduced enhancements, allow to double the amount of supported swarm members while achieving four nines reliability when compared to the case where the same enhancements are applied to the sidelink mode 2.

1 Introduction

Robots will replace humans in even more complex operations of future industrial production. For that purpose, proximity communication will play a vital role in enabling cooperation between collaborating robots. Proximity communication involves collective perception of the environment by sharing video streams. These require a 10 Mbps data rate, with a maximum latency of 10 ms, and a reliability of 99.99 % (equivalent to a 10^{-4} transmission failure probability) as mentioned in [2]. Even though the perception is collective, each individual robot will be governed by a control loop. This control loop is vulnerable to variations in the arrival timing of the input [3], and these timing variations should be kept at a minimum.

To address these requirements, in [4] two decentralized cooperative resource allocation schemes were proposed. In [4] it was shown that these scheme were able to outperform the baseline resource allocation scheme defined for New Radio (NR) sidelink, termed as NR Sidelink Mode 2, by an order of magnitude. The proposed techniques in [1] addressed the issues related to the control plane signaling associated with the resource allocation, in particular control plane signaling blocking reception (half duplex) of user plane data and unsuccessful reception of control plane signaling.

However, even with the proposed enhancements in [1], these two resource allocation schemes were not able to achieve the targeted performance requirements, as in [1] it was shown that after the control plane issues have been addressed, the next performance bottleneck occurred in the user plane.

The aim of this paper is to introduce user plane focused enhancements

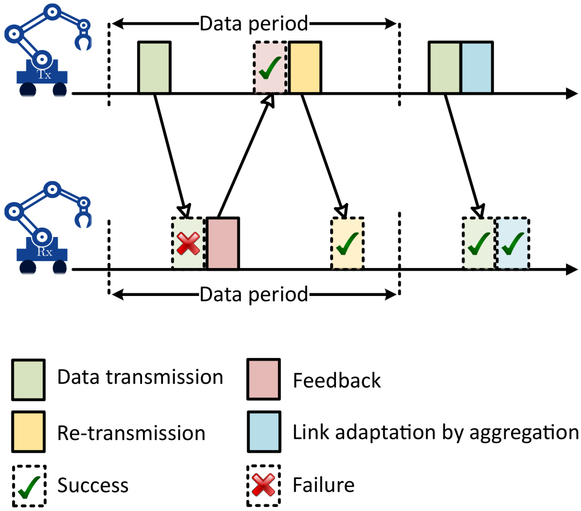

Fig. C.1: Data failure reception recovered by HARQ or incremental robustness to subsequent transmissions given by link adaptation by aggregation for UEs sharing high-throughput data

that enable the proposed resource allocation schemes to reach 99.99 % reliability. In addition, we also evaluate the time variations of the control loop input by using the packet inter-reception (PIR) metric, which was defined in 3GPP [5] as the time in between successive packet receptions.

One well known and widely utilized technique to improve reliability on a per-transmission basis is hybrid automatic repeat request (HARQ). In HARQ, forward error correction is combined with re-transmissions (illustrated by yellow boxes in Figure C.1) to flexibly adapt the redundancy in the transmission to cope with the current channel conditions.

To maintain the reliability of subsequent transmissions, link adaptation is utilized. It controls the modulation and coding scheme (MCS) (illustrated by blue boxes in Figure C.1) to meet the configured average block error rate in dynamic channel conditions [6].

In this paper we show how HARQ and link adaptation can be adapted to the scenario and evaluate the impact to reliability and PIR in proximity communications. Specifically, the contributions of this paper are:

- Augmentation of the decentralized resource allocation schemes with HARQ and link adaptation by aggregation to reach the four nines reliability
- Characterization of the PIR to validate the suitability for control loop operation

In Section 2 we explain the HARQ and link adaptation by aggregation techniques in detail. The simulation setup is briefly described in Section 5 and the results and evaluation follow in Section 6. Concluding remarks are made in Section 7.

2 Failure causes and enhancement techniques

Resource allocation is a complex task with impact on communication. The performance of the resource allocation is determined by the available information (obtained through passive or active means) and how the information is being utilized (the algorithm and computation power available). Resource allocation is an NP-hard problem [7] and often appear in a context where time is a limiting factor. Thus, an appropriate solution is dependent on the specific context. We briefly summarize the considered resource allocation schemes from [1, 4] in the following.

Sidelink mode 2

The baseline scheme is the current procedure for autonomous decentralized resource allocation in 5G NR called sidelink mode 2. In this procedure, a UE (term used for the communication module attached to a robot) senses the assigned communication resources (resource pool) during the sensing window prior to resource allocation. It then excludes resources from the candidate set based on reoccurring semi-persistently scheduled (SPS) transmissions for the upcoming allocation based on the reference signal received power level (RSRP). However, 20 % of the potential resources must remain in the candidate set. The occupied resources with lowest RSRP may be re-included into the candidate set to meet this criteria. The transmission resource is chosen randomly from the set of candidate resources.

In proximity communication, beside exchange of application data (be it video or any other high data rate stream), discovery between robots (UEs) is paramount, and performed by periodic transmission of discovery messages (DM) in a resource pool dedicated for control-type transmissions. The discovery messages include at least position and heading information but can be optionally extended.

Device sequential [4]

Device sequential resource allocation takes advantage of cooperation between UEs in the resource allocation phase. In addition to sensing ongoing SPS transmission from other UEs, each UE includes in their DM the time at which they will initiate resource allocation, denoted by the *trigger time*. Thereby, UEs in proximity will be aware of others' intentions to allocate resources,

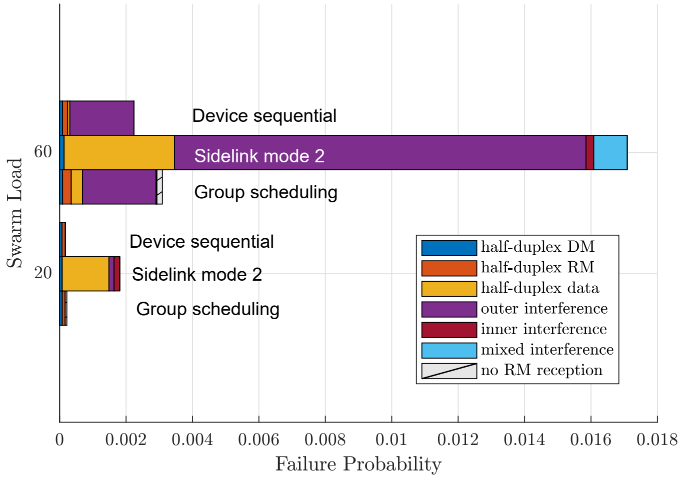

Fig. C.2: Failure probability and the causes of data transmission failures (halfduplex of DM, RM and data, inner, outer and mixed interference, and no RM reception) for three resource allocation schemes with enhanced (error-prone) signaling

and the UEs can follow a sequential procedure of allocating a resource, and publishing the allocation immediately by transmitting a resource selection message (RM) in the control resource pool. Upon reception, the next UE in the sequence proceeds. This cooperative procedure allows UEs to select the resource they seem best fit without relying on a random procedure.

Group scheduling [4]

Group scheduling resource allocation builds on the idea to save signaling and build a wider information base by letting local group leaders collect sensing results and perform resource allocation for multiple group members simultaneously. This scheme implies the addition of a leader selection phase. We found in [1] that the required signaling could be contained in the discovery messages with negligible impact on DM reliability. When the leaders need to cooperate, they do so by following the sequential procedure of transmitting the RM, which contains the resource allocation assigned to group members.

2.1 Failure causes

Figure C.2 shows the causes of data reception failure and their prevalence in each resource allocation scheme without utilization of enhancement techniques for 2 swarm loads (20 and 60 UEs) following the methodology presented in [1]. Half-duplex issues caused by communicating UEs simulta-

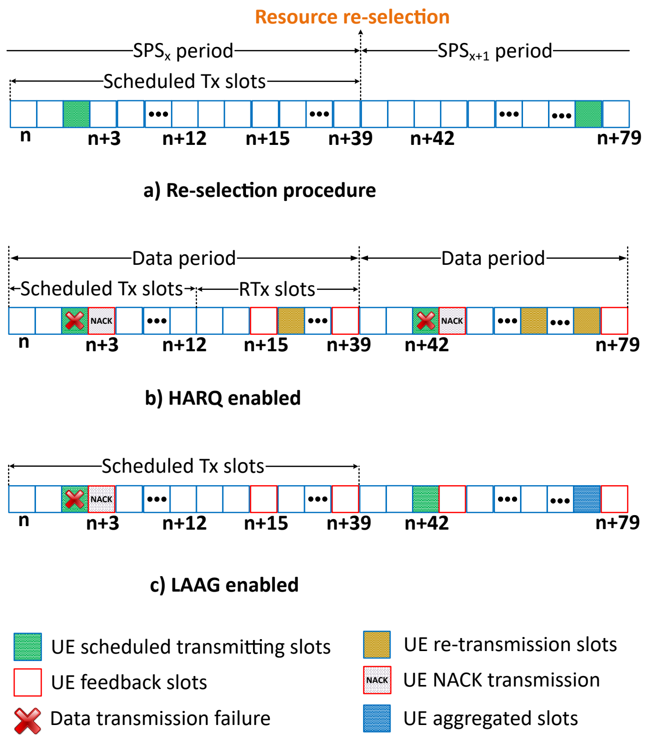

Fig. C.3: Resource utilization a) during resource re-selection, b) with HARQ enabled and c) with LAAG enabled

neously transmitting data is consistently a cause of failures for the sidelink mode 2 resource allocation scheme. Half-duplex issues caused by transmission of control messages (DMs and RMs) account for only a small part of the failures for all schemes. In dense swarms, interference from other data transmissions become the main cause of reception failures for all schemes. Specific to the group scheduling resource allocation scheme is the non-reception of RMs from the leader. This failure cause was greatly reduced by the RM re-transmission technique introduced in [1].

The PIR metric will be impacted by data reception failures. During the SPS transmissions the PIR - in absence of failures - will be equal to the 10 ms period of data transmission. PIR can exceed 10 ms due to 3 reasons. When SPS transmissions are reconfigured, the PIR will deviate from the 10 ms in case the SPS resource is re-selected. This behavior can be observed in Figure C.3 (a) where the UE re-selects the transmission resource from the third slot (n+2) in SPS period x to the second last slot (n+78) in SPS period $x+1$. This will cause a PIR greater than 10 ms. However, the latency requirement is still fulfilled because it is measured relative to the data period.

The second reason for PIRs above 10 ms is data reception failures which triggers re-transmissions, and the third reason is the combination of the former.

In the following, we will introduce techniques with the potential to tackle the reception failures and elevate the performance of the data transmission to meet the four nines reliability requirement in proximity swarm communication.

2.2 Enhancement techniques

The mitigation techniques rely on feedback from the receiving to the transmitting UE. 5G NR provides flexibility to customize the slot configuration such that the feedback channel (PSFCH) is included [8]. Specifically, the higher layer parameter sl-PSFCH-Period-r16 (defined in [8]) can be set to 0 (feedback disabled), 1 (feedback in all NR slots), 2 (feedback in every second NR slot), or 4 (every fourth NR slot). Within each feedback slot the receiver UE can send a negative-acknowledgment (NACK) to its transmitter. We have chosen a periodicity of 4 NR slots for our implementation as shown in Figure C.3 (b) and (c).

NR HARQ re-transmissions

The purpose of hybrid automatic repeat request (HARQ) is to improve reliability at the expense of redundant information added to a transmission or as additional transmissions. In [1] we introduced the *trigger time* as the time at which a UE needs to perform a resource allocation and the data period of 10 ms starts. To avoid the fact that resources are allocated in slot(s) at the end of the data period, and hence do not give enough room to perform re-transmissions, we have divided the data period when the HARQ re-transmissions are enabled into two: scheduled Tx slots and RTx slots. Scheduled Tx slots compose one-third (13 slots as depicted in Figure C.3 (b)) of the total data period where resources are allocated to perform the first data transmission attempt. If receiver UEs were not able to decode the transmitted data or have not received data within the scheduled transmission window (deprived transmission explained in [4]), they proceed to send a NACK in the following feedback slot (marked by red outline in Figure C.3 (b)). Once the transmitter UE receives the NACK, it randomly selects a slot(s) within the RTx slots to perform a re-transmission. If this re-transmission is not successfully received, the procedure repeats while there are available slots in the RTx slots period.

In our implementation we introduce HARQ with soft combining. It uses chase combining with a combining efficiency factor $\eta = 1$. The resulting

SINR, γ_{CC}, is calculated as

$$\gamma_{CC} = \sum_{i=0}^{R} \gamma_i \cdot \eta^R \tag{C.1}$$

where R is the number of re-transmissions and γ_i is the SINR of the ith (re-)transmission (the original transmission has index 0).

Link adaptation by aggregation

Link adaptation by aggregation (LAAG) works by allocating additional resource(s) when a UE fails one of its SPS data transmissions. When a data transmission failure happens, the receiving UE proceeds to send a NACK in the following available feedback slot (see Figure C.3 (c)). After the transmitting UE successfully received this NACK, it proceeds to autonomously (i.e. without cooperation) allocate additional resource(s), allowing it to utilize a lower MCS index for the subsequent transmission (slot n+78 in Figure C.3 (c)) and until SPS resources are re-configured. This increases the robustness for subsequent data transmissions and the receiver will be able to decode the data at lower SINR. Successful reception of the transmission with additional resources is dependent on the effective SINR of the aggregated transmission. In our implementation, we determined the effective SINR, γ_{MIC}, by using the SINRs of each resource combined by the mean instantaneous capacity (MIC) [9] calculated as,

$$\gamma_{MIC} = 2^{\frac{1}{K}\sum_{k=1}^{K} log_2(1+\gamma_k)} - 1 \tag{C.2}$$

where K is the number of resources and γ_k is the SINR of the k^{th} resource.

3 System level evaluation

We went beyond our system level simulator development presented in [1] by implementing the two previously introduced techniques and the evaluation of PIR and resource occupancy. Resource occupancy is defined as the average number of UEs occupying a single time-frequency resource.

The simulation models an indoor factory in which UEs move around following the random way-point model. The pathloss follows the 3GPP indoor factory model found in [10]. In addition we applied correlation to the shadow fading component by following the technique proposed by [11]. When UEs get within a 5 meter distance of another UE, they initiate the proximity communication in which multi-cast is utilized for message exchange. Each UE selects the modulation and coding scheme (MCS) such that a 100 kbit data

Table C.1: Simulation parameters

Parameter	Value/range
Carrier frequency, f_c	3.5 GHz
Swarm size (number of UEs)	$[10, 20, 30, 40, 50, 60, 70]$
Critical cooperation range, r_c	5 m
Extended Cooperation range, r_e	25 m
Facility dimensions	120×50 m^2 [10]
Transmission power, P_{tx}	0 dBm
Data channel bandwidth	100 MHz
Control channel bandwidth	7.2 MHz
NR slot duration	250 μs
Thermal noise power spectral density	-174 dBm/Hz
Receiver noise figure	9 dB
UE speed	1 m/s
Mobility model	Random waypoint (RWP)
Pathloss model	InF-SL [10]
De-correlation distance δ	20 m [11]
Discovery message periodicity	100 ms
Data message periodicity	10 ms
Data message size	100 kb
sl-PSFCH-Period-r16	1 ms
Scheduled Tx slots window	3.33 ms
RTx slots window	6.67 ms
Simulation time	1000 s

message can be transmitted with an expected block error rate (BLER) of 0.01 % at the estimated SINR-conditions.

Table E.2 presents the simulator settings. For the evaluations, simulations with the following four configurations were performed:

1. **Enhanced (error-prone) signaling** in which the successful reception of data messages was enhanced by the techniques of RM re-transmissions, non-overlapping and piggybacking as presented in [1]

2. **Signaling with HARQ enabled** in which in addition to 1) the HARQ technique is utilized

3. **Signaling with LAAG enabled** in which in addition to 1) the link adaptation by aggregation technique is utilized

4. **Signaling with HARQ and LAAG enabled** in which both HARQ and LAAG are enabled in addition to 1)

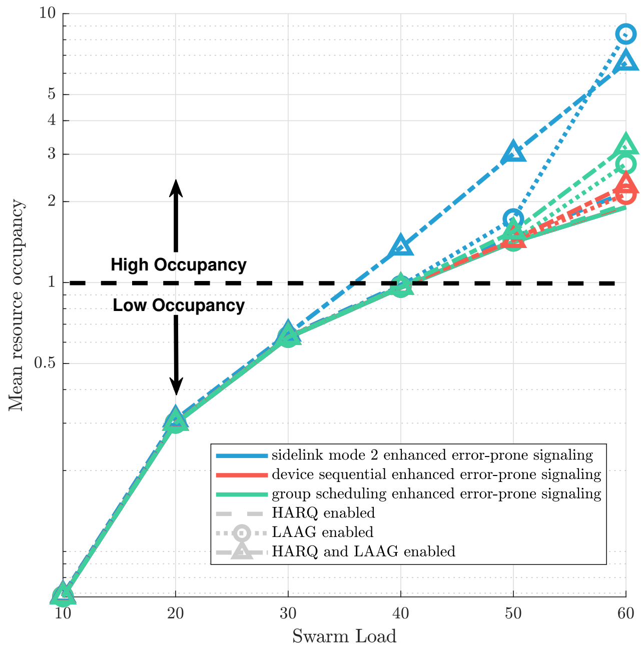

Fig. C.4: Mean resource occupancy for swarm load from 10 to 70 UEs. Mean occupancy below one is considered low

4 Simulation results

The resource occupancy is illustrated in Figure C.4. We see that swarm loads below 40 UEs correspond to low resource occupancy, i.e. in average less than one UE per resource, while swarm loads of 40 and above result in high resource occupancy. The mean resource occupancy is negligibly affected by the mitigation techniques at low occupancy. At high swarm load, LAAG has the strongest impact on resource occupancy. We observe that at high occupancy, LAAG causes sidelink mode 2 to allocate more resources than the cooperative schemes.

The transmission failure probability as a function of swarm load obtained in simulations is shown in Figure E.16. The transmission failure probability is the probability that a single transmission of a 100 kbit data message cannot be delivered within the 10 ms latency requirement. With the enhanced error-prone signaling alone we observe how the transmission failure probability, and hence the reliability of both cooperative schemes, are consistently better than the baseline sidelink mode 2. With increasing swarm load the transmis-

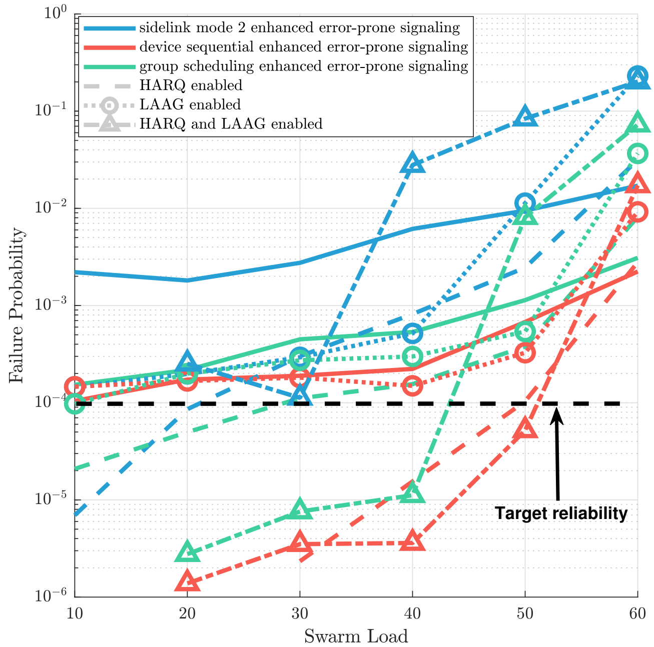

Fig. C.5: Sidelink mode 2, device sequential and group scheduling failure probability for: error-prone signaling, signaling with HARQ, signaling with LAAG and signaling with HARQ and LAAG enabled

sion failure probability increases for all schemes, and the gap between the cooperative schemes and sidelink mode 2 remains. Between the cooperative schemes, device sequential has slightly lower transmission failure probability at lower swarm loads, this advantage remains as swarm load increases. The plot of the device sequential scheme with HARQ and all schemes with HARQ and LAAG enabled starts at swarm load of 30 and 20 devices respectively due to the logarithmic y-axis and absence of errors at lower device loads.

Enabling HARQ is advantageous at low swarm load for all schemes. Interestingly, the relative performance gain is lowest for the group scheduling scheme. The likely explanation for this behavior is failure of reception of RMs from the leader due to the reduced number of scheduled Tx slots, which deprives the transmission from a group member and cause HARQ to be redundant to the RM re-transmission. For the sidelink mode 2 and group scheduling schemes, the four nines reliability requirement can be met until swarm load of 20 and 30 UEs respectively. Device sequential performs better, exceeding the reliability target for an additional 20 UEs. HARQ is the best configuration until swarm loads of 30 UEs for the device sequential scheme. At high occupancy the HARQ technique is detrimental to the transmission failure probability.

At the lowest swarm loads LAAG has negligible impact on the cooperative schemes, but reduces the transmission failure probability of sidelink mode 2 to the level of the cooperative schemes. Interestingly, the LAAG seems to dominate the impact on transmission failure probability, leaving all resource allocation schemes at the same performance until swarm load of 30 UEs. This can be explained by the fact that aggregated resources are allocated autonomously regardless of resource allocation scheme and when MCS is lowered, the autonomously selected resources will quickly dominate the resources selected by the resource allocation schemes. The difference is seen at higher swarm loads, where sidelink mode 2 transmission failure probability drastically increases at 50 UEs swarm load and the failure probability of the cooperative schemes increases at 60 UEs swarm load.

With HARQ and LAAG enabled simultaneously, the group scheduling sees an additional reduction in transmission failure probability at low swarm loads and gives the best performance for the scheme until swarm load of 40 UEs. For device sequential the combination of HARQ and LAAG is the best configuration at swarm loads of 40 and 50 UEs. For sidelink mode 2 the performance at low loads is ambiguous as the failure probability increases from 10 to 20 UEs but then drops from 20 to 30 UEs. Still, the four nines reliability target is only met at 10 UEs swarm load. The complementary effect at low swarm loads turns into a destructive effect a higher swarm loads where the combination of the two techniques perform worse than either of the techniques alone. The destructive effect can be explained by the reduction in scheduling Tx slots imposed by the HARQ, which limits LAAG and quickly saturates resources with transmissions leaving little time for reception.

PIR for two representative swarm loads is depicted in Figure E.17. As expected, the majority of PIR is exactly at one data period of 10 ms. Consistently, it is the configuration at the given swarm load with the highest transmission failure probability (in Figure E.16) which also experience the longest tail (in Figure E.17). This implies that when failures are introduced, they are likely to happen persistently in some UEs rather than sporadically. This is contrary to the conclusion of [12] where they show that transmission failure probability and PIR are only weakly correlated for random transmissions. Our observation is likely coupled with the SPS transmissions, and hence higher determinism in our scenario. At all swarm loads it is a variant of the sidelink mode 2 scheme which exhibits the highest transmission failure probability. Between the cooperative schemes, device sequential experiences both the lowest transmission failure probability and lowest PIR.

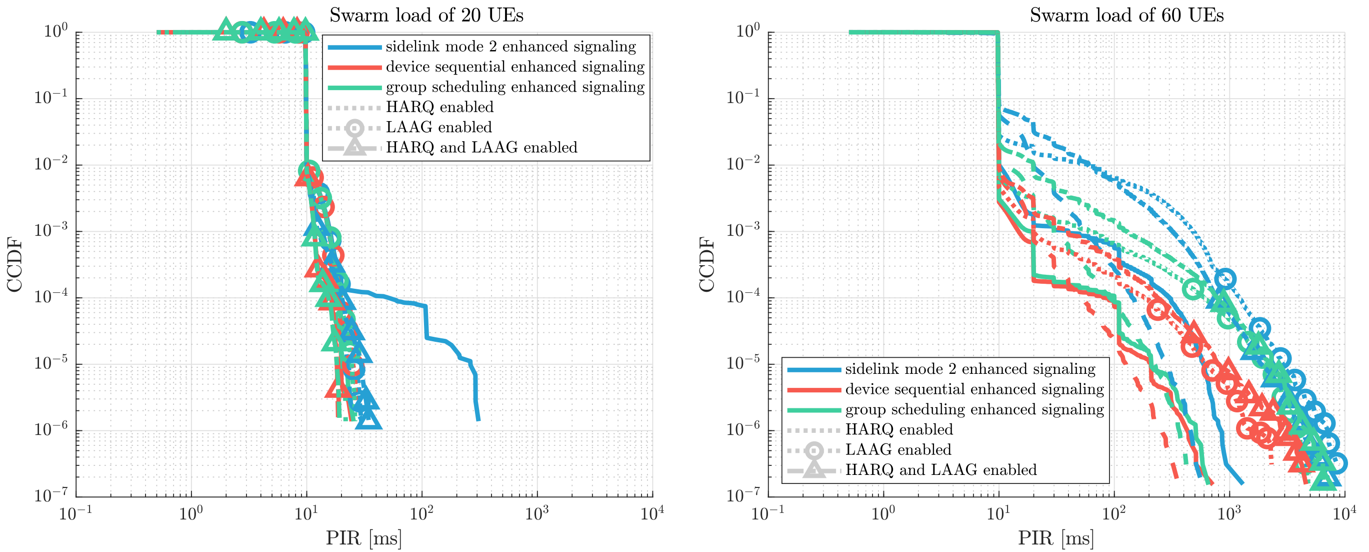

Fig. C.6: Packet inter-reception for swarm loads of 20 and 60 UEs for each of the resource allocation schemes for: error-prone signaling, signaling with HARQ, signaling with LAAG and signaling with HARQ and LAAG enabled

5 Conclusion

With the techniques of HARQ and link adaptation by aggregation (LAAG) we are able to reach the four nines reliability at more than twice the load of what is achievable with the sidelink mode 2 when using our proposed cooperative resource allocation schemes.

HARQ has the greatest impact at low swarm loads where resource occupancy is low. LAAG is more helpful at higher swarm loads. When resource occupancy becomes excessive, the techniques do not improve reliability and thus should be enabled in dependence of load.

The best PIR is coupled with the combination of techniques at a given load. At 20 devices, enabling both HARQ and LAAG has lowest transmission failure probability and also lowest PIR. At 60 devices the HARQ technique results in lowest transmission failure probability and shortest PIR. The growth of the PIR tails is correlated with the transmission failure probability, implying that an increased transmission failure probability is caused by additional successive failures in a subset of UEs rather than evenly across all UEs.

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Paper D

New Radio Sidelink with Beam Selection for Reliable Communication in High-Density Robotic Swarms

C. Santiago Morejon, Rasmus Liborius Bruun, Filipa Fernandes, Troels B. Sørensen, Nuno K. Pratas, Tatiana K. Madsen and Preben Mogensen

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Abstract

Swarm production robots, an enabler for Industry 4.0, are expected to establish direct communication links between each other based on proximity. The 3GPP's New Radio sidelink is a candidate technology to enable such communication links. However, when operating in autonomous resource selection mode (mode 2), sidelink communications are prone to half-duplex and interference problems, the severity of which increases with the swarm's density. In this paper, we study how beam selection by use of directional antennas can help reduce the impact of these problems and thus improve the reliability of packet reception. We evaluate the effect of directional antennas when applied at the transmitter and receiver, both separately and simultaneously, for increasing swarm density. Our evaluations show that these enhancements let mode 2 achieve twice the swarm density for a 99.99% reliability target, compared to the case where these enhancements are not applied.

1 Introduction

The fourth industrial revolution currently underway (Industry 4.0) seeks, among many other aspects, to change how the traditional linear and centralized production is carried out. The linear and centralized production depends on sequential manufacturing, where production modules are connected to a centralized controller. This framework makes it difficult to have flexibility and reconfiguration capacity [1]. Swarm-based production is a suitable solution to these limitations since it will allow the production processes to be flexible and reconfigurable by separating the linear and centralized production into production modules distributed across the factory [1]. Such a framework demands stringent communication requirements among the production modules, including high reliability, high throughput, and low latency [2] [3]. Wireless communication can fulfill such requirements if direct communication links between the swarm devices in close proximity are allowed. Such direct connectivity started with the concept of proximity services (ProSe) in the 3GPP release 12, and in the latest release 17 with a focus on Vehicle-to-everything (V2X) use cases [4] [5].

In [6] we introduced the use case of a swarm of robots moving within an indoor factory. Robots in proximity (i.e., within *critical cooperation range* of radius r_c) exchange high throughput data at 10 Mbps with a maximum latency of 10 ms and reliability of 99.99%. We define reliability at the packet reception level as the percentage of packages successfully received. We assumed that robots had perfect knowledge of the positions and heading direction of robots located in *extended cooperation range* of radius r_e ($r_e > r_c$). In [7] we introduced the error-prone signaling by exchanging periodically position and heading direction in the form of *discovery messages* (DMs) among robots within r_e. These DMs are randomly allocated in a separate resource pool.

Mode 2 in conjunction with HARQ and link adaptation by multiple slot aggregation fulfills the stringent requirements for a swarm size up to twenty (20) robots [8]. For bigger swarms, the presence of half-duplex problems (i.e., devices selecting the same time-frequency resources for their transmission and are unable to hear each other transmissions) and interference (i.e., when devices do not intend to communicate) cause the reduction of the effective SINR ending up in data failure receptions.

Antenna diversity techniques represent a suitable solution to mitigate interference and increase the effective SINR. The selection of beams produced by directional antennas is an alternative to beamforming [9]. In [10] authors used a unmanned aerial vehicle (UAV) equipped with directional antennas to reduce the number of handovers for better reliability and lower latency. Authors in [11] used a switching system and directional antennas on a vehicle showing a considerable improvement of the reference signal received power (RSRP) and reference signal received quality (RSRP) values.

In this paper, we evaluate the impact of directional antennas and beam selection in three different settings: (i) Transmitter only; (ii) receiver only; and (iii) Transmitter and receiver beam selection. The contribution of the paper is to show how directional antennas and beam selection can significantly increase the reliability of communication between swarm production robots for mode 2. We show that the use of directional transmit and receive antennas allow mitigating swarm interference and indirectly the effect of half-duplex problems, which would otherwise restrict the use of mode 2 at more dense swarms.

In Section 2 we explain and analyze the mode 2 limitations (i.e., half-duplex and interference) for our use case in detail. In Section 3 we present the system model with all the assumptions and procedures that robots follow when adopting transmitter beam selection, receiver beam selection, and the combination of both. Section 4 outlines the simulation setup and results evaluation. Concluding remarks are made in Section 5.

2 NR sidelink mode 2 resource allocation

A UE (name adopted for the communication component incorporated in a robot) in need for data transmission must follow two procedures when using NR SL mode 2: *sensing* and *resource selection*. We assume that before these two procedures take place, UEs are time-synchronized (i.e., adopting the NR SL synchronization procedure explained in [12]). In ***sensing***, UEs scan the channel within a time window of a maximum of one-second [13], extended through the configured bandwidth, to determine the suitable candidate slots in time and frequency. The *sensing* considers the reception of the

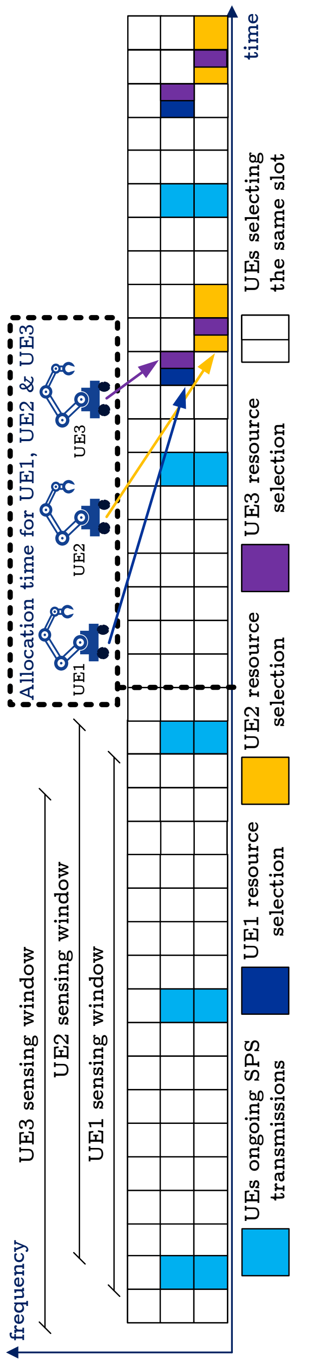

Fig. D.1: Mode 2 sensing and random Semi-Persistent (SPS) resource allocation procedures for 3 UEs (UE1, UE2 & UE3) located within each r_c

sidelink control indicator (SCI). It determines the slot's occupancy by other UE's semi-persistent (SPS) transmissions and non-SPS future transmissions. A UE considers a future slot occupied (and therefore not part of the candidate slot set) if either the *"resource reservation period"* field or the frequency and time resource assignment fields in the SCI indicate that slot during the targeted resource selection period and the *RSRP* value is above a pre-defined threshold. However, if less than 20% of all slots are candidate slots, the pre-defined *RSRP* threshold increases by 3dB. This approach continues until reaching 20%. During the ***resource selection*** procedure, the UE selects randomly from the set of candidate slots the number of required slots. When the UE establishes an SPS, then these slots will be used for the UE's SPS transmission following the SPS period. To avoid persistent collisions with other UE's transmissions, the UE applies a resource re-selection counter [14] to control when it should select new resources for its SPS.

Fig. D.1 shows the *sensing* and *resource selection* procedures, where it is assumed the absence of non-SPS traffic. UEs 1, 2, and 3 are located within their critical cooperation range r_c. They have different sensing windows to detect ongoing SPS transmissions (light blue slots). The empty slots (white slots) are considered candidate slots. UE1 selected one slot in the case shown, while UE2 and UE3 selected two. From these selections, it occurs that some UEs selected the same slot. UE1 and UE3 (half navy blue, half purple) and UE2 and UE3 (half yellow, half purple). However, UE2 is the only one selecting its second slot (yellow).

2.1 Analysis of half-duplex problem and interference

The uncoordinated nature (i.e., the lack of coordination between the UEs) of mode 2 in the resource selection is the cause of either a half-duplex problem or interference.

Half-duplex problem

As introduced in Section 1, UEs are unable to transmit data between them if they select the same time-frequency slots. Depending on how many slots each UE needs to transmit its data, half-duplex may impact one or several data segments. UE1 and UE3 in Fig. D.1 are an example where all data segments experience half-duplex (i.e., full overlap), one and two slots, respectively. In the case of UE2, one of the two allocated slots experiences half-duplex (i.e., partial overlap). Additionally, since the resource selection is semi-persistent, the half-duplex problem persists not only during the allocation time shown in Fig. D.1 but until the resource re-selection procedure occurs, affecting mode 2's reliability performance.

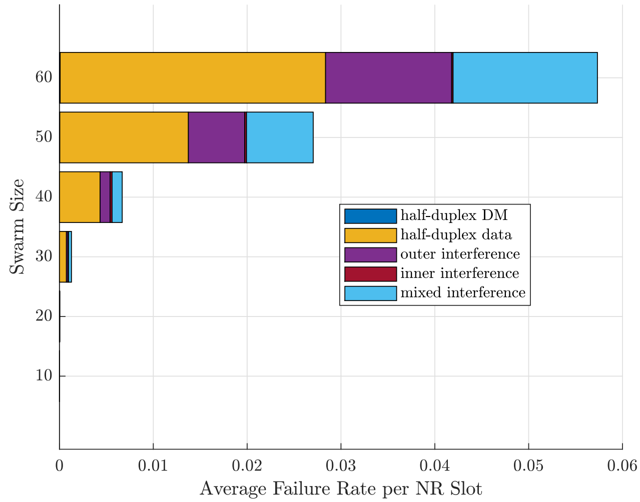

Fig. D.2: Mode 2 average failure rate per NR slot and its different causalities (half-duplex and interference) for different swarm sizes

Interference

Interference is caused by the harmful transmissions originating from UEs located within r_c (inner-interference) or r_e (outer-interference) of the transmitting UE. The presence of both indicates a mixed interference. These transmissions affect the SINR of the desired transmission at the receiver. In our use case it grows proportionally with the size of the swarm since the indoor facility becomes more populated.

Fig. D.2 shows mode 2's average failure rate per NR slot and its causes when HARQ and LAAG are enabled [8]. The considerable reduction of slots experiencing half-duplex between data and DMs comes from the non-overlapping technique [7] which makes use of the detection of SPS transmissions during the sensing procedure to discard them as candidate slots, in the separate resource pool, for DM transmissions. As the swarm size increases, it is seen that more slots are prone to experience interference (in their different forms) and half-duplex problems. Half-duplex data transmissions (yellow bar portions) represent the predominant cause of slots failure receptions. When looking at the interference behavior, it is more likely that the interference source location is mixed (light blue bar portion). The reason lies in the randomness in mode 2's resource selection. Therefore, if we assume that each UE uses directional antennas and beam selection, the effective SINR can be increased to mitigate the effect of the presence of half-duplex problems in one or few data segments as well as reduce the interference. Each

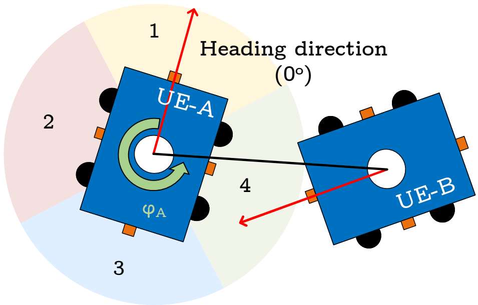

Fig. D.3: Generic antenna selection based on the UE's angle calculation of neighbors within r_c and position of interference sources. One patch antenna (orange square) is located on each face of the robot

data segment is transmitted in one NR slot.

In our previous studies, the antenna mounted at the robots has been assumed to be isotropic, radiating the transmitted power equally in all directions. This makes good sense given the omni-directional communication links in the specific scenario. However, by increasing the number of robots in a swarm, this also contributes to the increasing interference in the system.

3 System model

3.1 Antenna deployment

In our system model, we assume that each UE follows the configuration of a type 2 vehicle [15]. Therefore we assume that each UE has four patch antennas, each covering one of the four faces of the robot's chassis (orange squares in Fig.D.3). Each patch antenna produces a beam covering one of the four 90-degree horizontal azimuth sectors. Each sector has a fixed identifying number since it is referred to the robot's face that follows its heading direction, which always corresponds to sector 1 (yellow sector in Fig. D.3). Sectors 2, 3 and 4 follow an anti-clockwise (red, blue and green sectors respectively in Fig. D.3) with reference to sector 1. The antenna numbering corresponds to the sector it covers.

3.2 Beam selection assumptions

While broadcasting/listening to DMs is done with simultaneous activation of all UE's beams, data transmission is reserved for the UE's transmission beam that best suits a specific target receiver UE(s). Therefore, a beam selection for transmission is required. Instead of relying on a typical power-based beam selection [16], this work proposes to leverage the context information [17] (e.g., coordinates, heading direction, and speed) of all neighboring robots in r_e. It lets UEs map their current and near-future locations to determine which ones will enter the critical cooperation range r_c and become target UEs for data transmission. The DMs' periodicity would lead to having sufficient discovery probability [7] providing UEs enough time to proceed with the beam switching. Based on the mapping, the transmitter selects the beam which exhibits the highest gain in the relative horizontal orientation (i.e., ϕ angle) towards the target receiver. An analogous process is repeated for beam selection for data reception. In Fig. D.3 transmitter UE–A faces UE–B at horizontal angle ϕ_A, in the direction of beam number 4, and hence only this is selected for transmission.

If only transmitter beam selection occurs, we assume that UEs combine the output of the four patch antennas to form an isotropic receiver antenna. In this case, the transmitter can select one or up to four beam(s) depending on the estimated locations of their desired receiver(s). Similarly, we assume that all UEs have an isotropic transmitter antenna and select the receiver beam that faces its transmitter for receiver beam selection only. Compared to the transmitter beam selection case, it is more likely that receiver beam selection selects only one beam. However, UEs can select more than one beam in cases where they receive data from two or more transmitters. Finally, both procedures apply if transmitter and receiver beam selection is enabled simultaneously.

3.3 Antenna Element Radiation Pattern

Contrary to the isotropic antenna, the patch radiation power pattern, $A_{dB}(\theta, \phi)$, is not uniform in space. This function expresses how the patch spatially distributes its power through the spherical coordinates (θ, ϕ) in the vertical and horizontal planes. This function and its parameters are specified by 3GPP in [18] where the values of θ and ϕ can be between $[0^o, 180^o]$ and $[-180^o, 180^o]$ respectively. The correspondent linear gain $g(\theta, \phi)$ is determined as,

$$g(\theta, \phi) = 10^{\frac{A_{dB}(\theta,\phi)}{10}} \tag{D.1}$$

Since the robot has four 90-degree sectors, a patch antenna covering the whole sector with the highest possible gain is the best option to be taken.

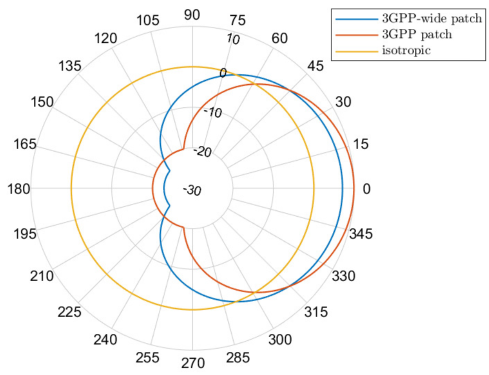

Fig. D.4: Antenna pattern for 360^o azimuth angles when adopting isotropic, 3GPP modeled patch antenna element and 90-degree 3GPP modeled patch antenna element (3GPP-wide patch)

For that purpose, we compare two values for vertical and horizontal HPBW, 65^o (defined in [18]) and 90^o. We name them as 3GPP patch and 3GPP-wide patch, respectively. Their antenna pattern is shown in Fig. D.4 together with the one of an isotropic antenna. It is noticeable that both patch antennas have the same beam gain at $\pm 45^o$, but as moving to the boresight, the 3GPP patch has a higher gain. Therefore, we use the 3GPP patch model.

The vertical angle θ is fixed to 90^o since all UEs have the same height meaning that antennas can see each other facing to the horizon, thus effectively $g(\theta, \phi) = g(\phi)$. The horizontal angle ϕ changes according to the source transmitter and/or target receiver position.

3.4 Signal-to-Noise-plus-Interference Ratio at the Receiver

Transmitter and receiver beam selection can work separately or simultaneously. The SINR (γ_k) of each of the K allocated slots can be obtained by using the maximum ratio combining (MRC) technique that uses all the N received signal elements as follows,

$$\gamma_k = \sum_{z=1}^{N} \left(\frac{\frac{p_{tx}}{M} * \left(\sum_{j=1}^{M} \sqrt{g(\phi_{t_j})} \right)^2 * g_l * g(\phi_{r_z})}{\sum_{i=1}^{I} \left(\frac{p_{tx_i}}{M_i} * \left(\sum_{j=1}^{M_i} \sqrt{g(\phi_{t_{i_j}})} \right)^2 * g_{l_i} \right) + n} \right) \tag{D.2}$$

Where $(p_{tx}, g(\phi_{t_j}), g_l)$ and $(p_{tx_i}, g(\phi_{t_{i_j}}), g_{l_i})$ are the values of transmission power, beam gain at each active transmitter beam, and path loss $(1/g_l)$, (all linear values) for the transmitter UE and i^{th} UE interferer(s) respectively. The beam gain at each active receiver beam is represented by $g(\phi_{r_z})$, while n is the additive white gaussian noise (AWGN).

UEs can activate M beams, from 1 to 4, with transmitter beam selection. To radiate the same transmission power regardless of the number of active beams, each time more than one beam activates, the transmission power is reduced proportionally in each of the individual beams. We assume that the transmissions from the individual beams combine coherently (voltage summation). For the case of two beams, this implies that for a position exactly in between the beams, the effective radiated power is twice the transmission power of each of the beams in that specific direction (beam gain); for other "less extreme" cases, the effective transmission power is closer to the proportional reduction, in this case, half the maximum transmission power (i.e., only one of the beams contributes significant power).

UEs can activate N beams, from 1 to 4, with receiver beam selection. It is more likely that only one beam is selected. Selecting more receive beams is generally a bad strategy since it makes the receiver more sensitive to half-duplex problems within the critical cooperation range r_c (i.e., transmissions from several transmitters within their critical cooperation range will collide in reception). If a UE needs to receive data from transmitters that don't see each other within their respective r_c, it makes sense to activate more beams.

To determine the effective SINR (γ_{MIC}) of K allocated resources (slots) we use the mean instantaneous capacity method adopted in [8]. It is computed as,

$$\gamma_{MIC} = 2^{\frac{1}{K}\sum_{k=1}^{K} log_2(1+\gamma_k)} - 1 \tag{D.3}$$

When a UE needs to transmit data, it chooses the MCS to send a data message (each 10 ms) in K allocated slots with an expected BLER of 0.01 %. In case that one of the K allocated slots experiences a half-duplex problem (e.g., with DMs or other data transmissions), the receiver will get a spectral efficiency $(log_2(1+\gamma_k))$ in equation D.3) equal to zero $[bps/Hz]$ on that slot. Even though the presence of a half-duplex problem represents a data loss, if the combined γ_{MIC} is sufficiently high for the selected MCS, the receiver will still be able to decode the data message. However, if all K allocated slots experience half-duplex problem, the receiver won't be able to decode the data message (for sure).

4 Simulation setup and Evaluation

We implemented directional antennas and beam selection functionality to our system-level simulator in addition to the HARQ and LAAG introduced

Table D.1: Simulation parameters

Parameter	Value/range
Carrier frequency, f_c	3.5 GHz
Swarm size (number of UEs)	$[10, 20, 30, 40, 50, 60]$
Critical cooperation range, r_c	5 m
Extended Cooperation range, r_e	25 m
Facility dimensions	120×50 m^2 [18]
Transmission power, P_{tx}	0 dBm
Data channel bandwidth	100 MHz
Control channel bandwidth	7.2 MHz
NR slot duration	250 μs
Thermal noise power spectral density	-174 dBm/Hz
Receiver noise figure	9 dB
UE speed	1 m/s
Mobility model	Random waypoint (RWP)
Pathloss model	InF-SL [18]
De-correlation distance δ	20 m [20]
Shadowing standard deviation σ	5.7 dB [20]
Discovery message periodicity	100 ms
Data message periodicity	10 ms
Data message size	100 kb
sl-PSFCH-Period-r16	1 ms
Scheduled Tx slots window	3.33 ms
RTx slots window	6.67 ms
Number of antenna elements	4
HPBW	65^o [18]
Simulation time	500 s

in [8]. The simulator models proximity communications for moving robots (UEs) within an indoor factory by adopting a random waypoint mobility model. The 3GPP non-line of sight indoor factory with sparse clutter and low base station (InF-SL) path loss model [18] was selected to model the path loss on the links. Furthermore, we enforced shadowing correlation by using the methodology presented in [19]. We set up a de-correlation distance (δ) of 20 meters, and shadow standard deviation (σ) of 5.7 dB. Proximity communication occurs when UEs have 5 meters (or less) distance between them. Simulation parameter settings are presented in Table E.2.

Our evaluations consider four configurations which are the following:

1. **NR sidelink mode 2 (Baseline)** in which, in addition to all mode 2's features, the non-overlapping technique (explained in Section 2.1) is enabled to avoid half-duplex between DMs and data.

2. **NR sidelink mode 2 with transmitter beam selection (Tx)** in which in

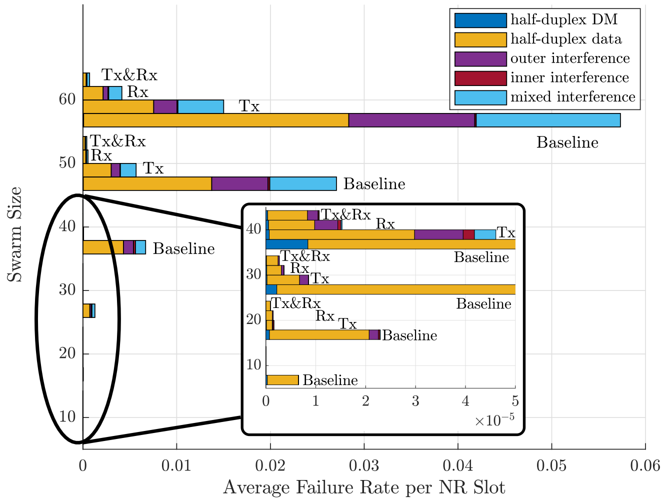

Fig. D.5: Average failure rate per NR slot at four configurations. *Baseline* represents NR sidelink mode 2 (baseline) while *Tx beam selection*, *Rx beam selection* and *Tx&Rx beam selection* represent each of the beam selection configurations

addition to 1) transmitter beam selection is enabled.

3. **NR sidelink mode 2 with receiver beam selection (Rx)** in which in addition to 1) receiver beam selection is enabled.

4. **NR sidelink mode 2 with transmitter and receiver beam selection (Tx&Rx)** in which both transmitter and receiver beam selection are added on top of 1).

We evaluate the four configurations in terms of the KPI of failure probability, defined as the probability that the reception of a 100 kbit message was not successful within the 10 ms latency constraint. Thus, failure probability is (1 - reliability probability), meaning that the 99.99% reliability requirement translates to a 10^{-4} failure probability.

Fig. D.5 illustrates the average failure rate per slot (i.e., sum of per UE number of slots experiencing failures / (swarm size * number of slots in the simulation time)) of the three-beam selection configurations (*Tx, Rx and Tx&Rx* bars) in comparison to the baseline mode 2 (*Baseline* bars). The baseline scheme only has a few slots experiencing half-duplex and interference at a swarm size of 10 UEs. Other configurations don't experience any failure since the different forms of beam selection eliminate the need to apply HARQ and LAAG, which reduces the number of slots used per transmission. Lower slot occupancy, in turn, causes fewer half-duplex problems. As

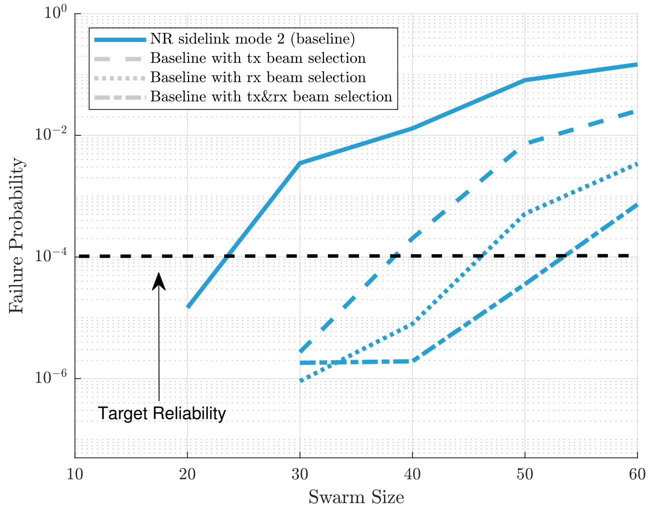

Fig. D.6: Failure probability achieved at four configurations. The 10^{-4} requirement is indicated by the dashed black line.

the swarm size increases, the number of slots experiencing interference (i.e., inner, outer, or mixed) increases considerably. In turn, this requires further HARQ re-transmissions and the use of aggregated slots, hence higher resource pool occupation. The result is that the average failure rate per slot increases exponentially for the baseline scheme with increasing swarm size. Beam selection configurations significantly reduce the number of slots experiencing transmission failures. Still, the resource pool occupancy increase doesn't guarantee that re-transmissions and aggregated slots will be free of failures due to the randomness of the resource selection. But at the same time, the boost of the SINR and the interference reduction allow UEs to reduce the need of HARQ re-transmissions and aggregated slots, hence reducing the resource pool occupancy.

Fig. E.16 shows the failure probability values of the four configurations at the target reliability requirement. None of the configurations encountered data reception failures (i.e., γ_{MIC} mapped to the selected MCS) at the 10 UEs swarm size during the simulation. Then, lines start at 30 and 20 UEs swarm size for all beam selection configurations and the baseline, respectively. The baseline meets the reliability requirement until a swarm size of 20 UEs. Enabling transmitter beam selection increases the supported swarm size by ten (10) UEs. Therefore, it is clear that the vast majority of the half-duplex problems in the baseline don't affect all the slots of the same data message. Then, the increment of the SINR of the non-affected slots boosts the effective SINR,

γ_{MIC}, making the reception successful. The receiver beam selection provides better performance than the transmitter beam selection supporting more than ten (10) additional UEs in the swarm. The groupcast nature of the scenario is the cause of it. The receivers are more likely to receive a transmission from one transmitter at a time, using one beam, and the interference coming at the non-active beams is eliminated. The transmitter is more likely to target multiple receivers, which will require the selection of more beams and increase the interference in the scenario. It becomes more critical as the swarm size increases since the transmitters are more likely to activate more than one beam at a time. The best performance (i.e., obtain the lowest failure probability) occurs by enabling simultaneous transmitter and receiver beam selection, supporting swarm sizes of more than double that of the configuration without beam selection.

5 Conclusions

In this paper, we evaluated three configurations when using directional antennas and beam selection to reduce the failure probability of NR sidelink mode 2. The combination of transmitter and receiver beam selection provided the best performance to achieve four nines reliability at more than twice the swarm size achieved for baseline sidelink mode 2. The boosting of the signal-to-noise-plus-interference ratio (SINR) at each allocated slot together with the interference reduction makes the effective SINR sufficiently high to decode the data message regardless of the presence of *half-duplex* (i.e., when transmissions partly overlap). When the swarm size grows even further, the high-occupation of the resource pool produces more *half-duplex* cases with fully overlapping transmissions, in addition to more segments with partial overlap. Even though transmitter and receiver beam selection is beneficial, they are not enough to keep the target failure probability when the swarm size goes beyond 50 UEs. Therefore, the application of resource management techniques is necessary. A way to achieve it is by incorporating coordination within the resource allocation, which is the focus of our future work.

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Paper E

NR Sidelink for Dense Robotic Swarms: Towards High Reliability on Cooperative Resource Allocation by Enabling Interference Management Techniques

C. Santiago Morejon, Rasmus Liborius Bruun, Filipa Fernandes, Troels B. Sørensen, Nuno K. Pratas, Tatiana K. Madsen and Preben Mogensen

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Abstract

High throughput, low latency, and high reliability in proximity communications for swarm robotics can be achieved using decentralized cooperative resource allocation schemes. These cooperative schemes minimize the occurrence of half-duplex problems, reduce interference, and allow a significant increase in the achievable swarm density, but requires additional signaling overhead, which makes them potentially more prone to performance degradation under realistic operation conditions. These conditions include both data, signaling, and their interdependence evaluated jointly. The negative impact of the signaling errors requires incorporating enhancement techniques to realize the full potential of the cooperative schemes. Particularly, in this paper and for this purpose, we evaluate the effects of HARQ, LAAG and beam selection by using directional antennas in the cooperative schemes, and compare performance with 3GPP NR sidelink mode 2 (including signaling) using the same techniques. Additionally, we include a comparison of the required number of control signals between sidelink mode 2 IUC and cooperative schemes, and introduce a decentralized rebel sub-mode behavior in our group scheduling scheme to further improve the performance at the 99.99 percentile. The simultaneous use of all these enhancement techniques in our cooperative schemes considerably reduces the impact of signaling errors and thereby increases the supported swarm size compared to sidelink mode 2.

1 Introduction

Industrial factories' production of goods is changing thanks to the fourth industrial revolution (I4.0). It aims to change the traditional linear, sequential, and centralized production, which lacks flexibility and reconfiguration capabilities [1]. A swarm-based production, based on simple agents collaborating between them, can perform the same task as a highly specialized one [2] and add more flexibility for increased efficiency. To perform the tasks (e.g., manufacturing tasks or enabling production flows), either production robots or AMRs can be used [3], turning factories into an unstructured environment with manufacturing systems and routing of goods changing dynamically [4]. automated guided vehicle (AGV) is an example of efficient warehouse systems where humans are either replaced by robots or collaborate closely with them [5]. The use cases above set new requirements for communication technologies with higher throughput, lower latency, and higher reliability than current wireless systems can offer [6–8]. Besides the challenges from radio propagation effects in industrial environments, causing outages for wirelessly commuted robots [9]. Their displacement across a large factory produces frequent handovers or link breakage due to uncovered areas [9], increasing latency and affecting the communication's reliability. Reliability is directly linked to latency since it can be defined as the receiver's successful reception probability within the application's latency requirement. D2D communication represents a suitable option to fulfill the new requirements by overcoming the problems mentioned above and providing connectivity in places where the network's coverage does not reach or where there are frequent handovers [9]. It provides one-hop communication improving the overall network capacity [10], spectrum and energy efficiency, and reducing transmission latency [11]. D2D deployed in the licensed spectrum can attain QoS, reflected on controlled interference, better energy consumption rate, and better spectrum utilization, in comparison to unlicensed bands which are unregulated and uncoordinated irrespective of network traffic increment [10, 12–14]. For the licensed spectrum, 3GPP supports two sidelink-transmission modes for D2D. They consist in allocating time-frequency resources for D2D links, either by devices having the network's assistance (i.e., sidelink mode 1 [15]) or by doing it autonomously (i.e., sidelink mode 2 [15]). We will use sidelink mode 2 (mode 2) as a reference in our study, and assume the same basic procedures for our cooperative schemes. Section 2 explains in more detail mode 2.

Our main focus is on the data exchange or communication, between robots, and how to allocate resources for their transmissions subject to given constraints. Robots move around the facility to perform different tasks through having a collective perception of the environment. Data exchange considers stringent communication requirements by means of high throughput at 10 Mbps with a maximum latency of 10 ms and 99.99% reliability [16]. We proposed the incorporation of cooperative capabilities into the resource allocation by following two approaches [17]. The first one uses a priority-based sequential order to allocate resources among robots in need to exchange data. It is denoted as a device sequential scheme. The second one considers the formation of groups among robots where they designate one as a group leader in charge of allocating resources for itself and all group members. It is named group scheduling scheme. Section 3 explains both schemes in more detail. In [18] we formulated the optimization problem of determining the resource allocation matrix $\mathbf{A}_{N_r \times S_l}$, where $\mathrm{N_r}$ corresponds to the maximum number of robots that can be supported in the swarm and $\mathrm{S_l}$ to the set of time slots that spans the swarm's allocation period. This problem, i.e., trying to determine an allocation supporting the maximum number of robots subject to interference constraints that guarantee throughput and latency, is an NP-hard problem [19]. Instead, we use heuristic methods to efficiently determine the sub-optimal solutions to decentralized resource allocation by using cooperative resource allocation.

The design of the control signaling for the cooperative resource allocation was evaluated by using the failure probability KPI (i.e., probability of unsuccessful reception of a 100 kbit message within 10 ms latency). The results showed that a swarm size of ten robots just met the 10^{-4} failure probability (equivalent to 99.99% reliability) requirement when using the device sequential scheme; increasing the swarm size further requires enhancing techniques. One highly used technique is hybrid automatic repeat request HARQ which was introduced by 3GPP in [20] and adopted within the standard in high speed packet access (HSPA), release 7 [21] [22]. Another well known and utilized technique by 3GPP is link adaptation [23] which is based on outer loop power control (OLPC) [24]. Our approach uses link adaptation by allocating additional time-frequency resources, denoted as link adaptation by aggregation LAAG, to add robustness. Incorporating both techniques [25] allowed to increase the swarm size up to twenty, forty, and fifty robots when using mode 2, group scheduling, and device sequential, respectively. Further increase in the swarm size needs techniques to handle interference due to half-duplex problems, where communication is attempted on the same resources (when robots exchange data) and uncoordinated transmissions when they do not.

One approach that could further enhance the solution put forward in this paper would be the application of network coding principles [26, 27]. For example, upon receiving the transmitted packets of the surrounding peer robots, a robot could perform a re-transmission where it would combine (e.g., apply an XOR) these different packets and potentially its packet. This would allow the surrounding robots that could not receive some of the packets to recover these. However, this type of solution can require multiple re-transmissions and tight coordination between the robots. Therefore, achieving all this within the tight deadline of the targeted setting would be challenging. So the inclusion of network coding principles has been left for future work.

On the other hand, directional antennas and beam selection represent a suitable technique for our use case since it minimizes the detrimental effects of half-duplex problems and generally improves the SINR. For example, directional antennas equipped in a UAV [28], unmanned ground vehicle (UGV) [29], or a car [30] reduced the number of handovers, achieve a robust long-range communication link, or increase the RSRP and RSRP, respectively.

We have seen the benefit of cooperative resource allocation schemes over mode 2 [17, 18], HARQ and LAAG applied to mode 2 and cooperative schemes [25], and directional antennas to mode 2 [31] knowing that interference is a limiting factor for D2D. In order to increase swarm sizes further in this paper, we show how our proposed cooperative schemes can benefit from the same enhancement techniques and outperform mode 2 when directional antennas and beam selection are used to reduce interference. Specifically, our contributions are:

- Review of mode 2 and our cooperative schemes, with detailed explanations of the enhancement techniques.
- Comparison of the number of required control signaling messages to

achieve coordinated/cooperative resource allocation between mode 2 IUC and cooperative schemes.

– Demonstrating the superiority of device sequential and group scheduling over mode 2.

– Detailed analysis of how HARQ, LAAG, and beam selection impact the failure probability.

– Enhancement of the group scheduling scheme compared to [25] that improves failure probability at 99.99 percentile.

The rest of this paper is organized as follows: Section 2 introduces our use case and provides an explicit characterization of mode 2. The explanation extends to our proposed cooperative resource allocation schemes in Section 3. Section 4 presents the HARQ and link adaptation as well as our system design for directional antennas and beam selection and its applicability for device sequential and group scheduling. Section 5 outlines the simulation setup, followed by results and an evaluation of them in Section 6. Finally, conclusions, final remarks, and future work are presented in Section 7.

2 3GPP 5G NR sidelink mode 2

Our use case contemplates the deployment of a swarm of robots within a rectangular indoor factory to perform several tasks. They move at a constant speed between random waypoints uniformly and randomly placed across the factory. Each robot incorporates a UE to transmit and receive data to/from other pairs. Since the focus of our studies was on D2D communication, there are no route planning and collision avoidance, meaning that robots can pass through each other [17].

Data exchange occurs when robots are close to each other, i.e., within *critical cooperation range* r_c (orange dotted circle in Fig. E.1). Robots identify the presence of others within r_c by acquiring the knowledge of their position and heading direction when exchanging *discovery messages* (DMs) within *extended cooperation range* r_e (green circle in Fig. E.1). It is larger than r_c ($r_e > r_c$).

Data and discovery information are generated semi-persistently (i.e., robots generate new data after a predefined period) using a simplified model [32]. Therefore, we assume the absence of non-SPS traffic. For simplicity, we adopt no misalignment in data generation, contrary to [33]. We assume that data and discovery messages are exchanged in different resource pools.

Focusing on data transmissions, mode 2 requires UEs to follow two procedures: ***sensing*** and ***NR slot selection***.

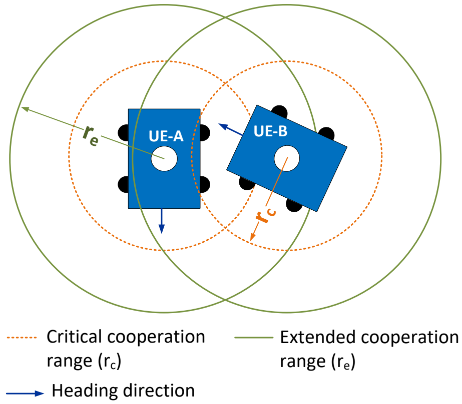

Fig. E.1: Two UE-centric proximity ranges to exchange discovery messages (r_e) and data (r_c).

2.1 Sensing

UEs monitor the channel for a preconfigured period defined as *sensing window*. It can have a maximum value of one-second [15] across the configured bandwidth. The monitoring consists of determining the set of candidate time-frequency NR slots through the SCI reception. The objective is to determine if a slot is suitable for the UE data transmission. Therefore, two parameters need to be evaluated. The first one is the *"resource reservation period"*, which, if present, indicates that the slot is being utilized by other UE's SPS. The second one is the RSRP. It indicates if the received signal's power is sufficiently high to be considered interference depending on whether it is above or below a predefined threshold. If the set of candidate slots does not meet the 20% of the total within the sensing window, the predefined RSRP value increases by 3dB to re-evaluate until reaching 20%.

2.2 NR slot selection

Once the set of candidate slots is obtained, the UE determines the number of slots required for its data transmission. Then, the slot selection proceeds either *uncoordinated* or *coordinated*.

Uncoordinated NR slot selection

A UE randomly selects the number of required slots among the ones in the set. Since the UE traffic is periodic, an SPS transmission is performed in the selected slot(s). The time the UE holds the slot(s) reservation is determined by the re-selection counter [34]. A drawback of this scheme is the potential presence of half-duplex problems (i.e., UEs choosing the same slot(s), making it impossible for simultaneous transmission and reception of data) due to the randomness in the process. A full overlap of slots happens when all required selections match; otherwise, it is a partial overlap. In [35], the authors propose a solution to tackle this kind of issue. They described and analyzed the probability that a vehicle losses several consecutive CAMs from one of its neighbors and proposed an extension to LTE sidelink mode 4, which significantly alleviated it. However, CAMs carry a significantly smaller amount of data compared to our use case. Moreover, 3GPP recently introduced a re-evaluation feature in release 17 [36] to reduce the half-duplex impact on performance. It contemplates the sensing and checking of SPS transmissions and UE's previous reserved slot(s). It occurs within a predefined amount of slots. It allows UEs to evaluate their selection and make a new one if half-duplex problems occur. Executing a re-evaluation and re-selection may also impact latency, as it is not guaranteed the absence of half-duplex problems. Fig. E.2 illustrates the UE-A's re-selection procedure when it detects a full overlap (one slot required) with UE-B.

Coordinated NR slot selection

It is known as IUC and was introduced in 3GPP release 17 [36]. It consists of two schemes that allow coordinated slots selection to avoid half-duplex problems. They were named as *scheme 1* and *scheme 2*. *Scheme 1* consists of sharing the set of preferred or non-preferred slots after a IUC trigger (e.g., UE-B needing to know which resources to use to reach UE-A successfully) occurs. It can be either a transmitter's IUC explicit request received by the receiver (i.e., option 1) or other conditions (i.e., option 2), for example, SCI request or higher-layer signaling. *Scheme 2* contemplates transmitter UE indicating the selected slots for its transmission in the SCI. The receiver UE indicates the expected/potential conflicts on that slot(s) selection such that the transmitter UE can perform a slot(s) re-selection. IUC entails the use of transmissions for IUC trigger/IUC information. In our use case, enabling IUC will create a more congested resource pool in addition to the potential presence of half-duplex problems and interference (i.e., UEs transmitting in the same slot but not intending to exchange information). Fig. E.3 shows IUC between UE-A and UE-B by using *scheme 1* (a) or *scheme 2* (b).

The latest mode 2 in 3GPP release 17 has proved that coordination among UEs resource allocation is the key to increasing its performance. Since IUC messages are exchanged between a pair of UEs, applying it to our use case represents that UEs require the exchange of a lot of IUC messages among their relatives located within r_c. Unfortunately, the design does not contemplate using only one IUC message for a whole group of UEs. Additionally, as coordination is not free-granted, having a more congested resource pool is the price. For that reason, our decentralized resource allocations schemes

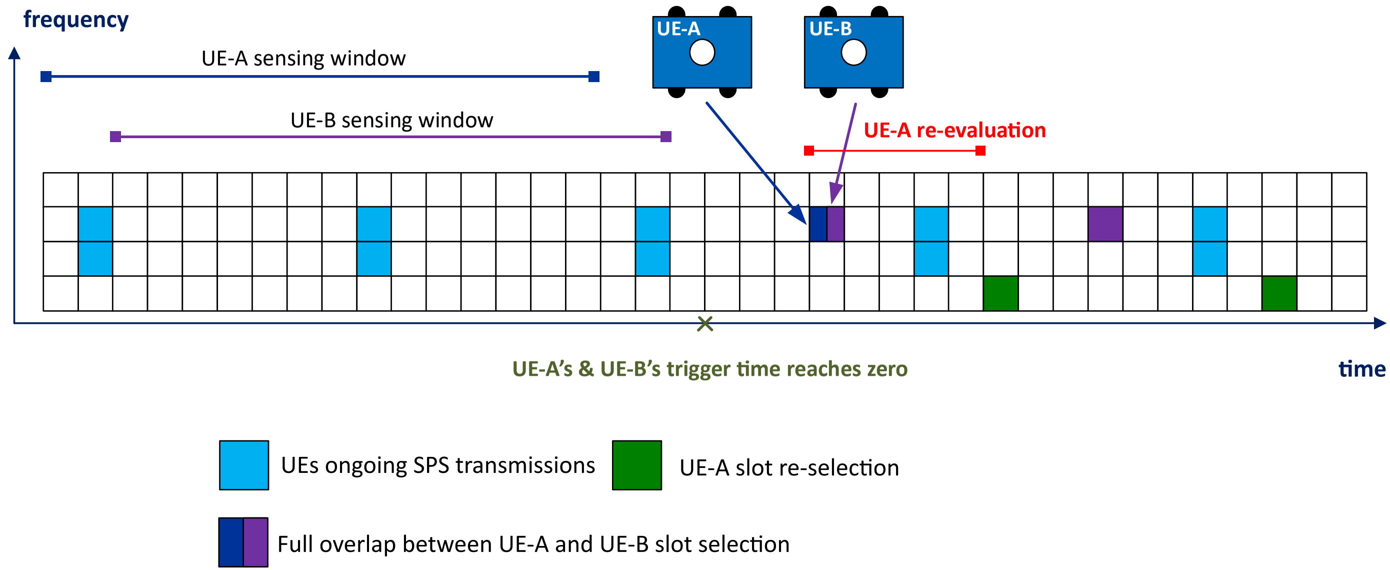

Fig. E.2: Uncoordinated NR slot selection followed by re-evaluation procedure by UE-A to re-select a slot after noticing a half-duplex occurred with UE-B selection.

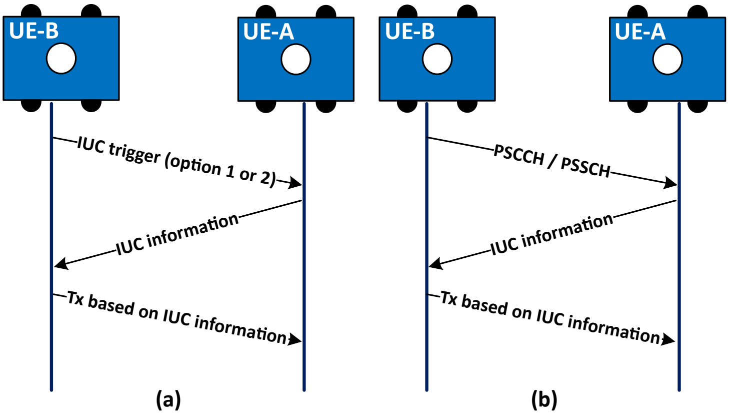

Fig. E.3: Coordinated NR slot selection through IUC schemes 1 & 2 between two UEs.

in [17] represent a suitable option for this use case since they are based on mode 2's design.

3 Cooperative resource allocation schemes

Cooperative resource allocation schemes were designed to achieve the most likely usage of all available slots by exchanging the least possible cooperative message signaling. It is achievable by determining: who (which UE performs the resource allocation), when, and what information is required for those decisions.

Cooperation requires the use of a new control signal in addition to the *discovery message* (DM) that includes UE's coordinates and heading direction [18]. It is denoted as *resource selection message* (RM) and contains information about the selection of resources a UE made for its data transmission. Then, to answer the questions posed, we proposed the inclusion of the *trigger time* parameter in the DMs. Trigger time is the time estimated by a UE when another will be within its r_c or when the re-selection counter reaches zero to proceed with the selection of resources. Once the selection is made, this information is shared in the RMs to all UEs within r_e. Our proposal considers performing the resource allocation in sequential order or by a group leader. For the latter, the incorporation of the *leader selection* parameter is required in DMs. We named these two approaches as ***device sequential*** and ***group scheduling*** schemes respectively.

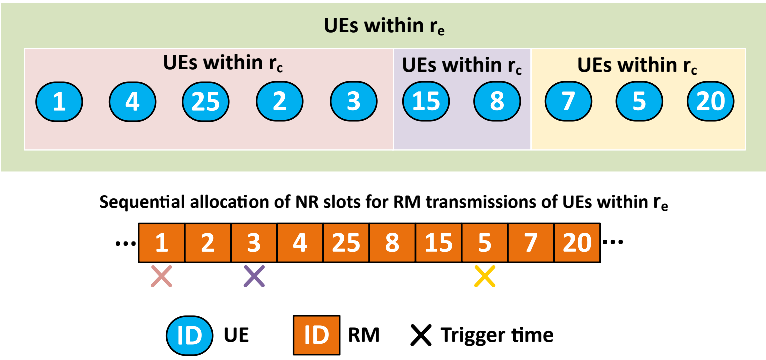

Fig. E.4: Resource allocation by using device sequential scheme for devices within r_c and r_e.

3.1 Device sequential scheme

This scheme contemplates UEs prioritizing their slot selection by evaluating in the first place the trigger time since it determines which UE(s) has a higher priority to allocate slot(s). If several UEs coincide with their trigger time, they place the priority order by following the sequential order of their unique IDs. In this case, the lower unique ID represents a higher priority. In our example in Fig. E.4, all UEs have the same r_e such that they exchange DMs (green box). The colored boxes (pink, purple, and yellow) indicate the group of UEs having the same trigger time, while the colored crosses indicate the exact time the resource allocation needs to occur (i.e., RMs need to be transmitted). The earliest trigger time is for UEs 1, 4, 25, 2, and 3. They follow the sequential order for slot selection 1, 2, 3, 4, and 25. UEs' 8 and 15 trigger time falls in the same slot UE 4 performs its allocation; therefore, they need to wait until UE 25 performs its allocation. Finally, once both UEs allocate their respective slots, trigger time for UEs 5, 7, and 20 occurs, following the respective sequential order. A UE will not await the allocations of its higher priority ones indefinitely; therefore, the *resource selection delay* parameter is included to start the slot(s) selection when its value reaches zero. Additionally, two scenarios may happen if a UE changes its r_c (e.g., UE5 moves closer to UEs 15 and 8). First, UEs 15 and 8 already made their resource selection and shared it with all UEs within r_e, meaning that UE 5 is aware of it and can proceed to select its resources and send its RM. The second scenario contemplates that UEs are within a resource re-selection phase. Then, UE 5 adds to the sequence of UEs 8 and 15, and it will be the first of the three to allocate resources and send the RM.

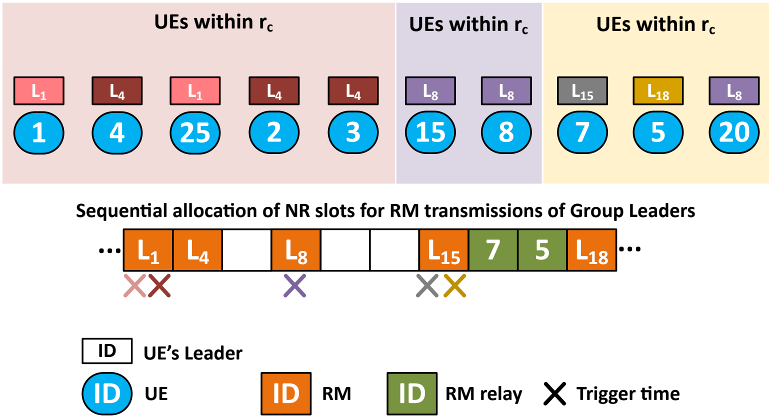

Fig. E.5: Resource allocation by using group scheduling scheme for devices within r_c and/or r_e.

3.2 Group scheduling scheme

Unlike device sequential, group scheduling scheme builds on forming a group of UEs led by a chosen leader (i.e., group leader) who collects sensing results and simultaneously allocates slots for all group members. The group leader selection follows the evaluation of two steps: (a) determining which UE, within r_e, has the most UEs within its r_c, and (b) determine which UE has the lowest unique ID in case several UEs within r_e have the same value at (a). A group leader may also need to coordinate with other leaders present in its r_e or group members collaborating with UEs belonging to other groups. Group leader coordination follows a similar approach as the device sequential scheme by prioritizing leaders resource allocation based on first its trigger time and second its unique ID. After inter-leaders cooperation occurs, each group leader performs the resource allocation for its group members at their respective trigger times. Doing so requires two conditions. The first is group members sharing the number of slots they need, the results of the sensing phase, and the trigger time with their respective leaders well in advance. The second includes group leaders receiving resource allocation from higher priority leaders within its r_e. In our example shown in Fig. E.5 UEs 1, 4, 25, 2, and 3 share the same r_c and trigger time (pink and orange crosses) but do not have selected the same group leaders (e.g., not necessarily share the same r_e). UEs 1 and 25 have L_1 leader who has higher priority than UEs 4, 2, and 3 denoted as leader L_4. Hence, leader L_1 performs resource allocation at the trigger time followed by leader L_4 in the next slot. Leaders L_{15} and L_{18} need assistance from their group members to allocate resources. In this case, UE 7 notifies UE 5 its received RM from L_{15} to be forwarded to L_{18} for its resource allocation.

Table E.1: Number of control signaling messages (Num. Messages) to achieve cooperative resource allocation in NR SL mode 2, device sequential and group scheduling

RA Scheme	**Num. Messages**
Mode 2 IUC scheme 1 unicast request	n(2n-2)
Mode 2 IUC scheme 1 broadcast request	n^2
Device sequential	n
Group scheduling	1

It could occur that in all schemes, DMs experiment half-duplex with data messages (in all schemes), or UEs do not receive RMs coming from either high priority UEs or group leaders (cooperative schemes). To solve these issues, in [18] we introduced three techniques named as *non-overlappping*, *piggybacking*, and *RM re-transmissions*. *Non-overlapping* makes use of the sensing phase such that UEs avoid transmitting DMs in slots where an SPS transmission occurred to prevent potential half-duplex problems. *Piggybacking* refers to repeating the information received in RMs to append it into its RM. In the group scheduling scheme, it may happen that one or several group members were unable to receive the RMs coming from their leader. *RM re-transmissions* allows group members receive them by randomly re-transmitting a new RM in case a group member sends a NACK.

Both device sequential and group scheduling resource allocation schemes represent a beneficial alternative to IUC, since they provide a considerable reduction of control signaling, which directly impacts the schemes' performance. For example, in a group consisting of n UEs, located within their respective critical cooperation range r_c, we determine the number of control signal messages required for mode 2 IUC scheme 1 and the cooperative schemes. 3GPP established unicast IUC request for mode 2 [36]. We named it as Mode 2 IUC scheme 1 unicast request. With the purpose of giving a fair degree of comparison, we assumed that mode 2 IUC is capable to broadcast IUC request. The number of control signal messages required for mode 2 IUC scheme 1 and the cooperative schemes is presented in Table E.1.

4 Enhancement techniques for cooperative schemes

HARQ and link adaptation techniques have been part of previous 3GPP releases and have evolved within time. Following, we present howHARQ has been adapted to mode 2 due to the network's absence, and our assumptions and procedure link adaptation follows by allocating additional resource(s) in our named link adaptation by aggregation LAAG technique.

4.1 Hybrid Automatic Repetition Request (HARQ)

HARQ builds on adding redundant information or performing more transmissions of the same data to increase communication reliability [37]. Our approach contemplates transmitting the same data repeatedly until it is successfully decoded at the receiver or the data period of 10 ms ends. Therefore, it is necessary to answer the following question: when should the first transmission be performed after the beginning of the data period? If it is done as early as possible, there will be enough time for additional re-transmissions at the cost of over occupying some portions of the data period of each UE when the swarm size increases. Additionally, they may be prone to perform more re-transmissions, expanding the resource occupancy, and hence, there might be higher interference or half-duplex problems. Our assumption contemplates a window of 30% of the data period (3.33 ms) for the first transmission while the remaining time is assigned for possible re-transmissions.

In 3GPP release 16, the mode 2's NR slot configuration to support HARQ was introduced [15]. It consists of reserving one of the fourteen OFDM symbols to the physical sidelink feedback channel (PSFCH), as shown in the zoomed slot structure in Fig. E.6. The slot's structure periodicity is determined by the higher layer parameter *sl-PSFCH-Period-r16* defined in [38]. It is set to one of four possible values 0, 1, 2, and 4 that correspond to feedback disabled, feedback in all NR slots, every second NR slot, and every fourth NR slot, respectively. We have chosen the value of 1 to this parameter to allow all NR slots to be capable to transmit the PSFCH.

The PSFCH serves to make the transmitter notice the unsuccessful data reception by receiving an acknowledgement (ACK) or negative acknowledgment (NACK). This information is included in the 2^{nd} stage SCI carried by the physical sidelink shared channel (PSSCH). Our approach considers the PSFCH carrying a NACK. The example shown in Fig. E.6 presents how a data transmission coming from UE-A is not received by UE-B (orange slot with a red cross). UE-B sends a NACK in the PSFCH to make UE-A aware of the failure (purple slot). Once UE-A notices the failure, it proceeds to re-transmit data (blue slot), successfully received. If a data failure reception occurs again, the procedure repeats while there is still time remaining in the data period.

At the receiver, each re-transmission is combined with previous transmissions by adopting soft combining. It uses chase combining [39] to obtain the resulting SINR of each re-transmission.

4.2 Link adaptation by aggregation (LAAG)

WhileHARQ focuses on making a failed data transmission successful, LAAG targets increasing the robustness of following data transmissions by allocat-

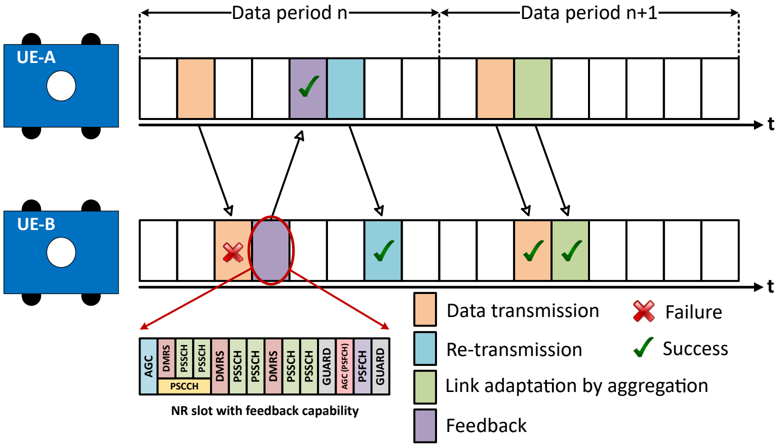

Fig. E.6: NR slot with feedback capability used to perform HARQ and LAAG techniques when there is a data failure reception in a data period.

ing additional slot(s). It is done by using the feedback procedure HARQ has. Once a transmitter UE fails one transmission within the SPS period, it receives the first NACK from the receiver in the PSFCH, as detailed in Section 4.1. This NACK serves as a trigger of a UE's autonomous resource selection (i.e., no cooperation involved) that lasts until the end of the SPS period. The resource selection is random and allows the reduction of the MCS index of subsequent transmissions to increase its robustness. In our example shown in Fig. E.6 UE-A performs a HARQ re-transmission at data period n where it selects an additional slot for its transmission at data period $n+1$. Given that an additional slot was allocated, the MCS index was reduced, making the next transmission successful and hence, avoiding a possible new HARQ re-transmission.

The two previous techniques support mode 2 and cooperative schemes to prevent and recover from data transmission failures by re-transmitting the same information in other NR slot(s) or by allocating additional slot(s) to reduce the previous selected MCS. None of them considers techniques to boost the SINR to avoid re-transmissions or additional slot(s) allocation. In the following, we explore it by recapitulating our design for antenna directivity and beam selection.

4.3 Antenna Directivity and Beam Selection

A UE equipped with an isotropic antenna radiates its signal in the whole 360-degree range, making it possible to reach others that are not within its r_c. Therefore, the cause of interference becomes more critical as the swarm size increases. In [31] we adopted the configuration of a type 2 vehicle specified

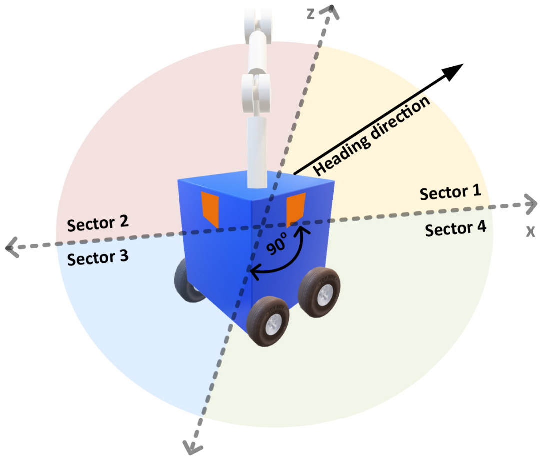

Fig. E.7: Directional antennas placed on each of the robot's chassis faces and the sectors correspondence according to the heading direction.

in [40] to limit UE's signal radiation range to 90 degrees. It equips each robot with four directional antennas, each placed on one face of the robot's chassis. Each antenna creates a beam that should cover a specific 90-degree azimuth sector, denoted as sectors 1, 2, 3, or 4. The robot's face that follows the heading direction corresponds to sector 1 followed by the others in an anti-clockwise ascendant order. Fig. E.7 shows the robot's chassis, the directional antennas (orange squares) placed on them, and the sector that corresponds to each one. Sector 1 is identified with yellow, while sectors 2, 3, and 4 are red, blue, and green, respectively.

As stated before, each directional antenna forms a beam with gain $g(\theta, \phi)$ to cover its respective sector. UEs select one or several beams by considering the position of others located within its critical cooperation range r_c to transmit, receive or transmit and receive data. To do so, UEs leverage the context information [41] (e.g., coordinates, speed and heading direction) instead of relying on a power-based beam selection [42]. The context information is shared by simultaneously broadcasting/listening to DMs in all UE's beams. This allows them to estimate others current and near-future positions to determine those who are entering their respective critical cooperation range r_c, becoming target UEs for data transmissions. It is assumed that UEs have enough time to proceed with beam switching since DM's periodicity provides sufficient discovery probability [18]. The UEs' estimation lets the transmitter UE select the beam presenting the highest gain in the relative horizontal orientation (i.e., angle ϕ_{ID}) towards the target receiver. This process repeats, in the same fashion, for beam selection for data reception. In our example

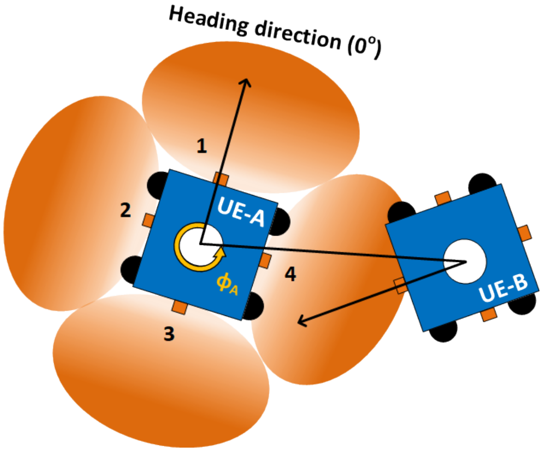

Fig. E.8: Transmitter and/or receiver antenna selection based on DM's reception and angle calculation of neighbors located within r_c. Each patch has its approx. radiation pattern.

in Fig. E.8, transmitter UE-A faces receiver UE-B at an azimuth value of ϕ_A. It corresponds to being in the direction of beam number four, being the one selected for data transmission. The beam color, analogous to the beam's gain, degrades as the angle deviates from the patch's boresight (i.e., the direction in which the patch has its maximum gain), as shown in Fig. E.9.

5 System Level Evaluation

As introduced in Section 2, our use case scenario centers on decentralized communications for a swarm of mobile robots in an industrial factory. We assumed an indoor factory facility of dimensions 120 by 50 meters, the same specified by 3GPP in [43]. Data transmissions occur when robots get into a critical cooperation range r_c of 5 meters to get a collective perception of the environment (i.e., awareness of the presence of other robots and obstacles). The communication requirements for this scenario go beyond the ones currently in V2X as envisioned in [16] contemplating a 10 Mbps throughput, 10 ms of latency, and 99.99% reliability.

5.1 Synchronization

Since our baseline scheme is mode 2, we assume that the robots in the swarm acquire their time and frequency synchronization from the 5G NR SL synchronization procedure [44]. Note that for NR sidelink, the synchronization is not established between two-peer UEs but instead is acquired by these peer

UEs from a common source. NR SL has two primary sources for synchronization: a global navigation satellite system (GNSS) and a gNB or eNB (referred to as gNB/eNB). In addition, a UE can use a SyncRef UE or its own internal clock as its synchronization reference. Finally, note that the synchronization procedure is separate from the communication procedure.

5.2 Channel Model

The wireless channel model follows the 3GPP indoor factory path loss model [43], assuming that all links are non-line-of-sight (NLOS) and single input single output (SISO) as presented in equation (E.1)

$$L_{dB} = \beta + \alpha * 10\log_{10}(d) + \psi * 10\log_{10}(f_c), \tag{E.1}$$

where α is the NLOS path loss exponent, β is the reference offset, d is the distance between transceivers, ψ is the frequency factor, and f_c is the carrier frequency. The estimated channel gain in dB is given by

$$H_{g,dB} = -L_{dB} - X_{dB}, \tag{E.2}$$

where X_{dB} is the correlated shadowing obtained from a Gaussian random field [45]. The covariance function is defined by the shadowing standard deviation (σ) of 5.7 dB and an exponential decaying correlation with a decorrelation distance (δ) of 20 meters. Small-scale fading due to multipath has not been explicitly modelled, but included in the link layer model [18]. The correspondent linear gain is

$$h_g = 10^{\frac{H_{g,dB}}{10}}. \tag{E.3}$$

5.3 Directional antenna model

The function $A_{dB}(\theta, \phi)$ expresses the power distribution of the directional antenna in the horizontal and vertical planes by making use of spherical coordinates (θ,ϕ) [43]. The horizontal and vertical radiation patterns are denoted as $A_{H,dB}(\phi)$ and $A_{V,dB}(\theta)$, respectively. $A_{H,dB}(\phi)$ is given by

$$A_{H,dB}(\phi) = -\min\left\{12\left(\frac{\phi}{\phi_{3dB}}\right)^2, A_{max}\right\}, \tag{E.4}$$

where ϕ_{3dB} is the horizontal HPBW of the directional antenna, A_{max} is the front to back ratio, which is the ratio of magnitude between the main lobe at 0^o and the back lobe at 180^o of a radiation pattern [46] [47], and the value of ϕ can be between $[-180^o, 180^o]$. Similarly, $A_{V,dB}(\theta)$ is defined as

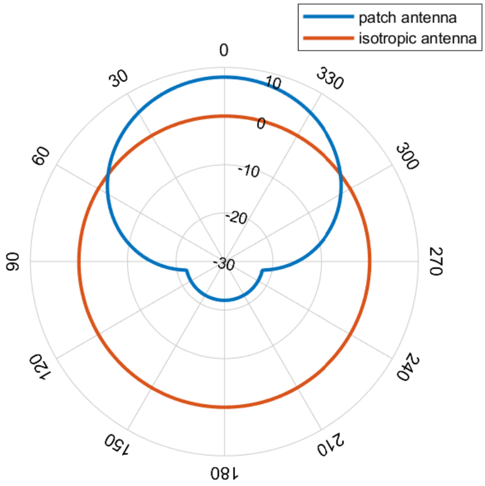

Fig. E.9: 2D radiation pattern of an isotropic antenna and 3GPP directional antenna for 360^o azimuth angles represented over the $\theta = 90^o$ plane.

$$A_{V,dB}(\theta) = -\min\left\{12\left(\frac{\theta - 90^o}{\theta_{3dB}}\right)^2, SLA_V\right\}, \tag{E.5}$$

where θ_{3dB} is the vertical HPBW of the directonal antenna and SLA_V is the vertical direction side-lobe attenuation, and the value of θ can be between $[0^o, 180^o]$.

Finally, the directional antenna's 3D radiation power pattern is computed as

$$A_{dB}(\theta, \phi) = G_{max} - \min\left\{-\left(A_{V,dB}(\theta) + A_{H,dB}(\phi)\right), A_{max}\right\}, \tag{E.6}$$

where G_{max} is the maximum directive gain. The correspondent linear gain is

$$g(\theta, \phi) = 10^{\frac{A_{dB}(\theta,\phi)}{10}}. \tag{E.7}$$

We use a value of 65^o, adopted by 3GPP in [43], for ϕ_{3dB} and θ_{3dB} since it gives the highest possible gain to the directional antenna [31]. Additionally, we assume all robots have the same height, meaning directional antennas placed on their chassis are facing each other at the same level. Therefore, the vertical angle θ has a fixed value of 90 degrees, and $g(\theta, \phi)$ simplifies to $g(\phi)$ where angle ϕ changes based on the transmitter and/or receiver position.

The directional antennas parameter values are presented in Table E.2 while its radiation pattern, juxtaposed with an isotropic one, is shown in Fig. E.9.

5.4 Signal-to-Noise-plus-Interference Ratio

Each robot requires a 100 Kbit data transmission for each 10 ms to achieve the target 10 Mbps. It would require it to allocate more than one NR slot. The number of slots, K, required by each robot is obtained when choosing an appropriate MCS, from [15, Table 5.1.3.1-2], with an expected BLER of 0.01%. Each of these K allocated slots will experience an SINR (γ_k) value depending on the number of robots in the swarm and the chosen resource allocation scheme. Equation (E.8) presents the expression that fits all beam selection configurations where transmitter and receiver beam selection are enabled. We adopted the MRC technique [48] that adds all the S received signals as follows,

$$\gamma_k = \sum_{z=1}^{S} \left(\frac{\frac{p_{tx}}{N} * \left(\sum_{j=1}^{N} \sqrt{g(\phi_{t_j})} \right)^2 * h_g * g(\phi_{r_z})}{\sum_{i=1}^{I} \left(\frac{p_{tx_i}}{N_i} * \left(\sum_{j=1}^{N_i} \sqrt{g(\phi_{t_{i_j}})} \right)^2 * h_{g_i} \right) + n} \right), \tag{E.8}$$

where the transmission power, gain at each active transmitter beam and the channel gain correspond to p_{tx},$g(\phi_{t_j})$ and h_g, respectively. The corresponding values for the i^{th} UE interferer(s) are $(p_{tx_i}, g(\phi_{t_{i_j}}), h_{g_i})$. At each active receiver, the beam gain is denoted as $g(\phi_{r_z})$. Finally, the AWGN is represented by n. All previous introduced values are linear.

In transmitter beam selection, UEs can activate up to four beams ($N \in \{1, 2, 3, 4\}$). Given that, we require UEs to radiate the same transmission power regardless of the number of active beams. To achieve it, we assume a coherent combination of transmissions coming from each beam (voltage summation) and a proportional transmission power reduction each time more than one beam activates (i.e., $\frac{p_{tx}}{N}$, $\frac{p_{tx_i}}{N_i}$ in equation (E.8)). There might be an exceptional case where one receiver UE is located between two beams. Then the two beams will be active, ending up having an effective radiated power equivalent to twice the transmission power of each of the beams at that specific angle (ϕ). The other cases approximate the assumed proportional reduction, corresponding to the desired beam contributing significant power. Similar to transmitter beam selection, receiver beam selection allows UE to activate up to four beams ($N \in \{1, 2, 3, 4\}$). The main difference lies in this configuration is that UEs are more likely to only activate one beam. Activating more beams makes the receiver more sensitive to half-duplex problems (i.e., data transmissions within UE's r_c colliding in reception). The exemption to this case is where a receiver UE needs to receive data from transmitters that do not share the same r_c.

5.5 Effective SINR

We use each of these γ_k values, measured on the most recent transmission, to determine the effective SINR (γ_{MIC}) by adopting the mean instantaneous capacity (MIC) method, explained in [49], as follows,

$$\gamma_{MIC} = 2^{\frac{1}{K}\sum_{k=1}^{K} log_2(1+\gamma_k)} - 1, \tag{E.9}$$

where K is the number of allocated slots, and γ_k is the SINR value at the k^{th} slot. The mapping of effective SINR (γ_{MIC}) to BLER, given the chosen MCS, is done by using a set of BLER curves that were obtained through separate link-level simulations that include all physical layer processing according to 5G NR [50].

In presence of half-duplex (e.g., with DMs, RMs or other data transmissions) in one k^{th} allocated slot, the spectral efficiency $(log_2(1+\gamma_k))$, equation (E.9), in that slot will be zero $[bps/Hz]$. This data loss will impact to a greater or lesser degree the γ_{MIC}, equation (E.9), value depending on the number of slots experimenting half-duplex since it has to be high enough for the selected MCS to have a successful reception. In case all K allocated slots experience half-duplex, for sure, the receiver will not be able to decode the data message.

5.6 HARQ

At the receiver, each re-transmission is combined with previous transmissions by using chase combining to obtain the resulting SINR (γ_{CC}) of the i^{th} re-transmission as follows,

$$\gamma_{CC} = \sum_{i=0}^{RT} \gamma_i \cdot \eta^{RT}, \tag{E.10}$$

where RT is the number of re-transmissions, η is the combining efficiency factor and γ_i is the SINR of the i^{th} (re-) transmission, being the first transmission when $i = 0$. We assume a $\eta = 1$ for our implementation.

5.7 NR parameters

When looking at the 5G NR parameters, we select numerology 2, giving a slot duration of $d_s = 0.25$ ms. For the control channel (where DMs and RMs are transmitted), we choose the value of 7.2 MHz since it is the smallest configurable sidelink sub-channel which consists of twelve sub-carriers. Additionally, we select the lowest MCS having a modulation order of 2 and a code rate of $\frac{120}{1024}$, leaving 196 bits for usage. On the other hand, the data channel bandwidth is set to 100 MHz. In contrast to the control channel, the MCS is dynamically adapted at the time of allocation [18]. The link-level model does not differentiate between data and control signal transmissions making the latter's performance somewhat optimistic given the considerable difference in bandwidth (i.e., 100 MHz vs. 7.2 Mhz) [18]. All simulation parameters are listed in Table E.2.

5.8 Configurations

Our goal is to present the increment of the number of UEs fulfilling the requirements of 10 Mbps throughput, 10 ms latency, and 99.99% reliability by progressively enabling the different enhancing techniques for the three resource allocation schemes (mode 2, device sequential, and group scheduling). Our evaluations consider three configurations applied for the three schemes, which are the following:

1. **Enhanced error-prone signaling** in which non-overlapping and piggybacking techniques (explained in Section 1) are enabled to avoid half-duplex between DMs and data, and RMs and data.
2. **HARQ LAAG** in which in addition to 1) hybrid automatic repeat request (HARQ) and link adaptation by aggregation (LAAG) techniques are enabled to provide time diversity to overcome data failure receptions.
3. **Tx & Rx beam selection** in which in addition to 2) transmitter and receiver beam selection are simultaneously enabled since it provides the best performance to mode 2 in [31]. It increases the effective SINR (γ_{MIC}) and avoids data failure receptions despite the presence of half-duplex in some data segments.

6 Simulation Results

The performance of each of the resource allocation schemes depends on how the resource allocation procedure avoids the presence of half-duplex problems and manages interference. To evaluate it, we selected three KPIs to perform **five studies** presented in Table E.3. Each study adopts one or several of the configurations presented in Section 5.8.

Failure probability (f_p): defined as the probability of not receiving a transmitted 100 kb data message within 10 ms latency. It is directly linked with reliability as presented in equation (E.11)

Table E.2: Simulation parameters

Parameter	Value/range
Carrier frequency, f_c	3.5 GHz
Swarm size (N_r number of UEs)	$[20, 50, 70, 90]$
Critical cooperation range, r_c	5 m
Extended Cooperation range, r_e	25 m
Facility dimensions	120×50 m^2 [43]
Transmission power, P_{tx}	0 dBm
Data channel bandwidth	100 MHz
Control channel bandwidth	7.2 MHz
Resource selection delay	1.25 ms
NR slot duration	250 μs
Thermal noise power spectral density	-174 dBm/Hz
Receiver noise figure	9 dB
Interference	Independent intra-system
UE speed	1 m/s
Mobility model	Random waypoint (RWP)
Pathloss model	InF-SL [43]
Propagation condition	Non line of sight
De-correlation distance δ	20 m [45]
Shadowing standard deviation σ	5.7 dB [45]
Discovery message periodicity	100 ms
Data message periodicity,	10 ms
Data message size,	100 kb
Data message latency requirement,	10 ms
sl-PSFCH-Period-r16	1 ms [38]
Scheduled Tx slots window	3.33 ms [25]
RTx slots window	6.67 ms [25]
Number of antenna elements	4
HPBW (θ_{3dB})	65^o [43]
SLA_V	30 dB
A_{max}	30 dB
G_{max}	8 dBi
Simulation time	1000 s

Table E.3: Performed studies

Study	KPI	Configuration
A.Error-prone signaling	average failure rate	1
B. HARQ & LAAG	average failure rate	2
C. Beam selection	average failure rate	3
D. Reliability	failure probability	1, 2, 3
E. Latency	PIR	1, 2, 3

$$f_p = 1 - r_p \tag{E.11}$$

where r_p is the reliability. A reliability of 99.99% corresponds to 10^{-4} failure probability.

Average failure rate per NR slot (fr_s): defined as the average rate of NR slots experiencing half-duplex or interference that lead up into unsuccessful reception. fr_s is given by

$$fr_s = \frac{\sum N_f}{N_r * T} \tag{E.12}$$

where N_f is the per UE number of slots experiencing failures, N_r is the swarm size, and T is the number of NR slots in the simulation time. We present it in detail by including the portion that corresponds to each kind of failure. For half-duplex, it could appear as data and discovery messages (data-DMs), data and resource selection messages (data-RMs), or between data (data-data). Interference could appear as inner, outer or mixed. Inner interference refers to harmful transmissions originating from UEs located within r_c, while if they originate within r_e, it corresponds to outer interference. Mixed interference indicates the simultaneous presence of the previous two. We link these results to the mean resource occupancy per NR slot (i.e., the average number of UEs occupying the same NR slot for data transmission).

Packet inter-reception (PIR): defined by 3GPP in [40]. It indicates the time between successive packet receptions and is an important metric for applications requiring regular updates.
For studies A, B, and C, we use average failure rate as the KPI to give a fair comparison of the benefits or disadvantages each scheme or technique has in performance; what is of interest here are the lower percentiles. For studies D and E, we use the failure probability and PIR KPIs, respectively, to compare the performance of mode 2 with the cooperative schemes in the three configurations.

We adopted a confidence interval of 95% to our simulations, similar to [51]. In our approach, we have been running simulations progressively, in each step estimating the 95% confidence interval for the obtained results based on the non-parametric bootstrap method [52]. In case the estimated interval exceeded the desired accuracy target, simulations continued to include more (random) samples until enough samples were collected. The simulation time (i.e., the sum of all simulation times in the different simulations) provided 95% of values with a zero standard deviation of the mean PIR distribution at the 99.99 percentile.

6.1 Average failure rate without enhancements

Fig. E.11 shows the average failure rate for the error-prone signaling configuration. The main cause of failure lies in outer interference, which significantly increases with the swarm size. Mode 2 handles it worse due to its random resource selection which also causes the presence of half-duplex data transmissions, as expected. The cooperative schemes avoid half-duplex data and substantially reduce outer interference since the resource selection control signaling makes UEs select as orthogonal slots as possible; otherwise, the ones where interference is the lowest. Since data transmission failures cannot be recovered in this configuration, the three schemes have the same average resource occupancy per NR slot for all swarm sizes as Fig. E.10. Then, the difference lies in how each scheme handles resource allocation.

Additionally, even though a non-overlapping technique (described in Section 1) was applied, there is the presence of some half-duplex of data and discovery messages (DMs), navy blue bar portions. The growth of the swarm size makes UEs increment the SINR threshold within the sensing procedure to increment the set of candidate slots, making the mean resource occupancy reach values above 1. Consequently, the random selection of slots for DM transmissions might overlap a few data transmissions. The group scheduling scheme presents a unique behavior caused by the dependency on a group leader. There are cases where group members do not receive resource selection messages (RMs). The RM re-transmission technique considerably diminishes this issue, but a few RMs are still not received. As a result, a few UEs are deprived of any data transmission, making it impossible to recover that data by using HARQ, LAAG, or beam selection techniques. For that reason, we have added a rebel-sub mode to the UEs, which does not deteriorate the general performance of the group scheduling scheme.

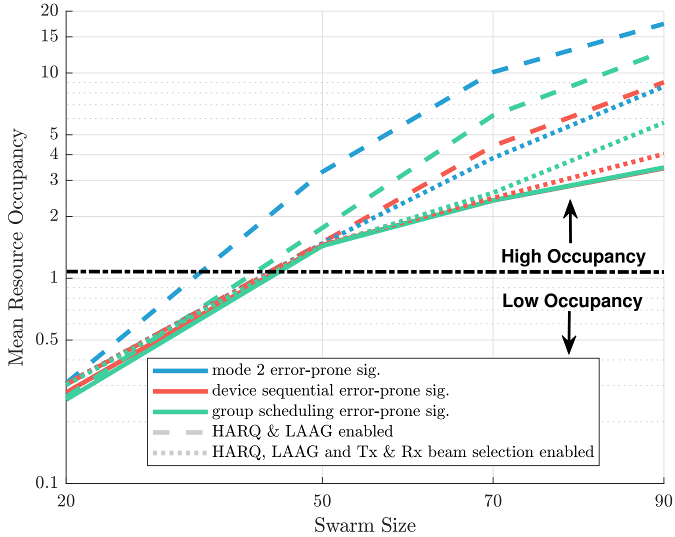

Fig. E.10: Mean resource occupancy for swarm sizes of 20, 50, 70 and 90 UEs. Mean occupancy below one is considered as low

Rebel sub-mode

The group leader UE sends an RM to its group members containing their allocated slots at some point close to the trigger time, depending on if the leader must follow a sequential allocation, edge cases, etc., as explained in Section 3.2. It shortens the time group members have to perform data transmissions within the data period started at the trigger time. If the RM reception fails as the orange slot in Fig. E.12, the group member sends an RM re-transmission request to its leader, which is also prone to a failed reception at the leader side. If it is successfully received, the procedure repeats until the group member successfully receives it. In our example in Fig. E.12, the leader performs two RM re-transmissions to reach the group member. However, unfortunately, it happens after the maximum latency allowed in the data period n. Hence, there is no data transmission, and it is considered a failure due to no RM reception. On the other hand, if the leader doesn't receive the RM re-transmission request, the group member UE will continue sending these requests until it gets one successfully. Again, it can overpass the maximum latency allowed in the data period, and it is considered a failure due to no RM reception.

We enhanced our group scheduling scheme by not relying on the RM re-transmissions as before to solve this issue. Instead, a group member UE, who did not receive their respective RM, rebels against its leader. It proceeds

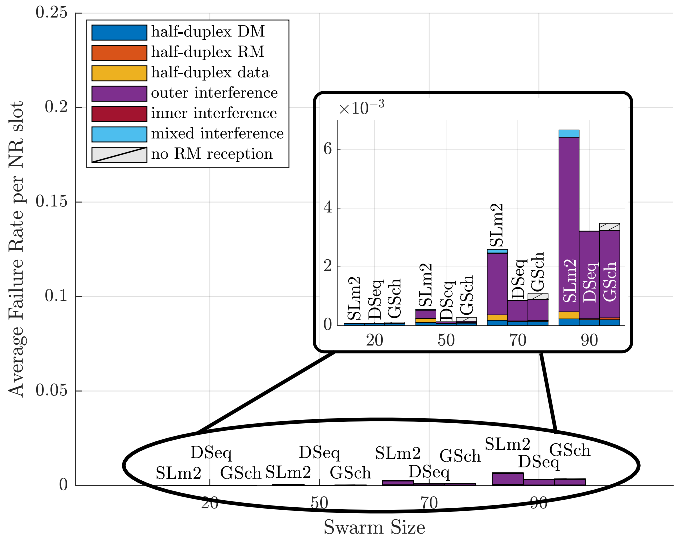

Fig. E.11: Average failure rate per NR slot at configuration 1 for the three resource allocation schemes: mode 2 (baseline), device sequential, and group scheduling, for four swarm sizes.

to follow the group scheduling considering itself as the unique UE for the group. Therefore, it contemplates itself as a leader and group member simultaneously. The benefit is that the UE takes advantage of the information obtained in mode 2's sensing procedure, the one obtained in the DMs and the group scheduling scheme benefits. It is seen in Fig. E.13 that all bar portions corresponding to no RM receptions are eliminated due to rebel sub-mode. Therefore, the certainty of having data failures due to the lack of leader's resource allocation disappears.

6.2 Average failure rate with HARQ & LAAG

When enabling HARQ and LAAG, configuration 2, it is noticeable the increment of mode 2's mean resource occupancy in comparison to device sequential and group scheduling schemes in Fig. E.10 (dashed lines). Device sequential and group scheduling have the same mean resource occupancy until the swarm size reaches a value of 50 UEs. Beyond that swarm size, device sequential is the one experiencing the lowest. Mode 2's random selection of slots makes UEs prone to need more re-transmissions and additional slot(s) allocation. Fig. E.14 shows the average failure rate for this configuration. Mode 2 presents the highest value and the higher presence of data half-duplex (yellow bar portions). Cooperative schemes keep their average failure rate significantly lower than mode 2, even though they present

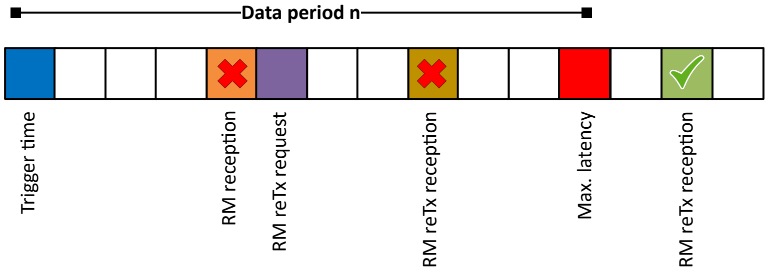

Fig. E.12: RM re-transmissions problem that ends up in having a data transmission failure that neither HARQ nor LAAG can recover.

a lower amount of data half-duplex in larger swarms where UEs tend to be closer. In the case of group scheduling, even though UEs share the same r_c, they could have different group leaders who might not be aware of each other's resource allocation, ending up in half-duplex problems. In device sequential, these tiny cases appear when large sequences of UEs appear, exhausting the resource selection delay and making it feasible for UEs to select the same slot. Interference-wise, it is more likely that data failures are due to mixed interference than outer interference in mode 2. At the same time, device sequential and group scheduling, both kinds of interference, keep the same proportion.

6.3 Average failure rate with beam selection

A vast proportion of all kinds of interference and a considerable one of data half-duplex encountered in configuration 2 are reduced when enabling transmitting and receiving beam selection to all the schemes in Fig. E.15. It is because the gain of a beam decreases as interferers get far from the boresight, making UEs use fewer slots forHARQ and LAAG since UEs boost the SINR at the transmitter and receiver sides. Then, a substantial reduction of the bar portions corresponding to half-duplex and interference is noticeable compared to Fig. E.14. Even though beam selection gives the best performance to all schemes, mode 2 still requires more re-transmissions than cooperative schemes translating it to a higher mean resource occupancy and average failure rate of the three, confirming the benefit of using cooperative schemes.

6.4 Failure probability and swarm's density

The average failure rate per NR slot and mean resource occupancy gave us an impression of how the resource allocation scheme makes usage of NR slots in the three configurations. The failure probability and swarms' density

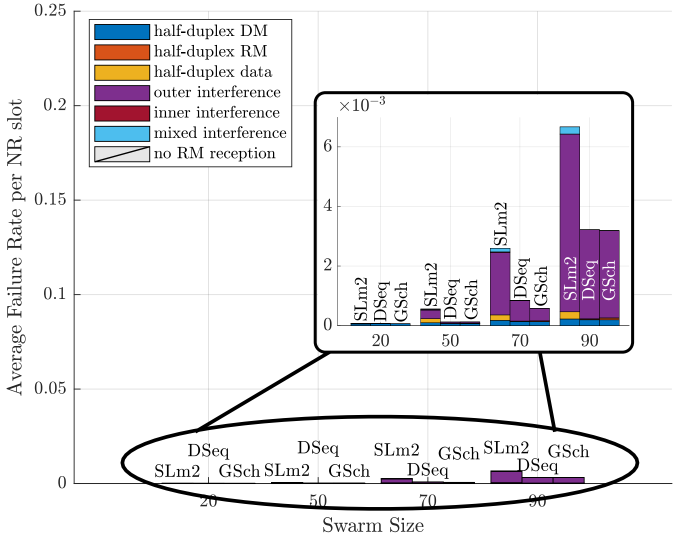

Fig. E.13: Average failure rate per NR slot at configuration 1 after the incorporation of rebel sub-mode for the three resource allocation schemes: mode 2 (baseline), device sequential, and group scheduling, for four swarm sizes.

indicate how many UEs fulfill the stringent communication requirements. Fig. E.16 presents both for all configurations and swarm sizes. Cooperative schemes support a larger swarm size than mode 2 in all configurations. It is clearly seen that group scheduling is not considerably distant from mode 2's performance. The findings of this study suggest the incorporation of the rebel sub-mode in the group scheduling scheme, which makes it less *"cooperative"* when a UE becomes leader and group member itself. Even though these cases might happen, the overall performance of group scheduling allows it to increment a bit the swarm's size. A considerable increase is seen with the device sequential scheme, where it reaches approximately 20% more UEs than mode 2 when both enable all techniques. It confirms that cooperative communication with autonomy represents a better solution for this setup. Forming groups led by some UEs degrades the performance as the swarm's size increases because UEs will belong to different groups and need to transmit data between them, requiring group leaders to exchange RMs. However, it also might happen to device sequential scheme. The difference is that it only happens with the resource selection of one UE, so the impact of an unacknowledged RM will be by far less than a group of RMs in the group scheduling scheme. Therefore, we can conclude that cooperation and UEs' independence are two important factors when designing decentralized cooperative resource allocation schemes that fulfill stringent requirements.

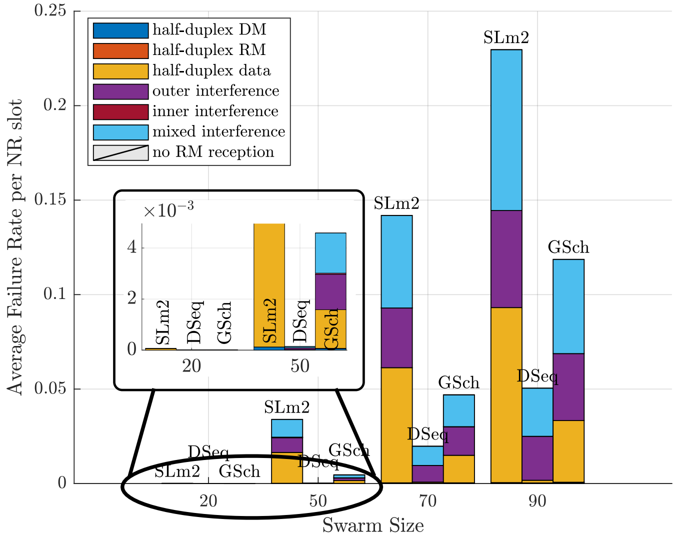

Fig. E.14: Average failure rate per NR slot at configuration 2 for the three resource allocation schemes: mode 2 (baseline), device sequential, and group scheduling, for four swarm sizes.

6.5 Impact of the schemes' number of control signaling messages

Our simulator does not have IUC functionality. However, the analysis of the number of control signaling messages required by mode 2 (unicast and broadcast IUC request) and our proposed cooperative schemes would be beneficial in drawing some conclusions. In Section 3, Table E.1 showed the number of control signal messages mode 2 IUC and our proposed schemes require to perform cooperative resource allocation. Mode 2 IUC requires a more significant amount of control signaling messages than device sequential and group scheduling, even though IUC request was assumed to be broadcast. Therefore, it is prone to experience higher interference since the separate resource pool might be more occupied. Consequently, data transmissions will occur in the same slots where other UEs (our of r_c) transmit IUC requests. Device sequential and group scheduling are promising options for this problem since they achieve the same level of cooperation as mode 2 IUC by using significantly fewer control signaling messages. Additionally, they represent a promising solution when considering other performance aspects, such as UEs' energy consumption.

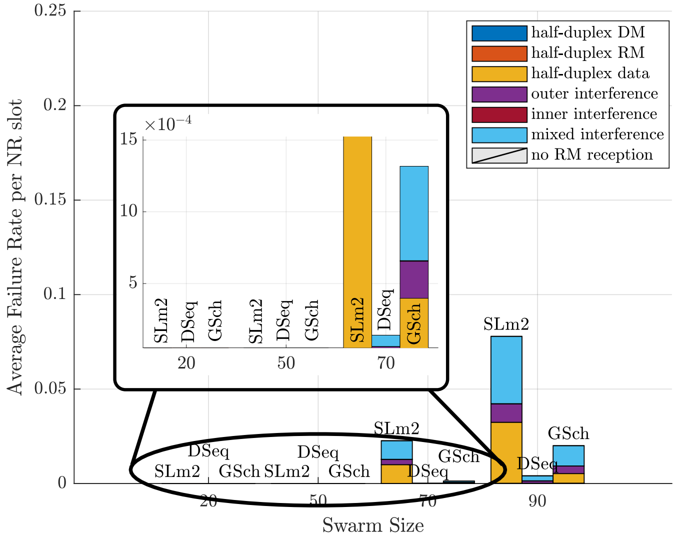

Fig. E.15: Average failure rate per NR slot at configuration 3 for the three resource allocation schemes: mode 2 (baseline), device sequential, and group scheduling, for four swarm sizes.

6.6 Packet inter-reception (PIR)

Fig. E.17 (a) and (b) show the complementary CDF of the PIR for respectively, 20 and 50 UE swarm size simulations. We did not consider other swarm sizes since we wanted to present the PIR's behavior before and after reaching the maximum supported swarm size in all configurations. The fact that semi-persistent transmissions make possible successful receptions of a series of data messages resulting in a 10 ms PIR. PIR values under 10 ms, or between 10 ms and 20 ms, are due to the re-selection of SPS transmission. However, if they go beyond that value, it represents a data failure reception. The resource allocation scheme and configuration with the highest failure probability also experiences the longest PIR. At 20 UE swarm size, the PIRs exceed 10 ms with a probability less than 10^{-2}. All schemes with beam selection enabled keep the lowest PIR with a tiny difference that the cooperative ones maintain below a probability of 10^{-5}, which is impossible with mode 2. At 50 UE swarm size, the cooperative schemes are the ones experiencing PIRs greater than hundreds of milliseconds but for with probability below 10^{-4}. It is eliminated by the incorporation of beam selection for device sequential but remains for group scheduling for probability below 10^{-6}.

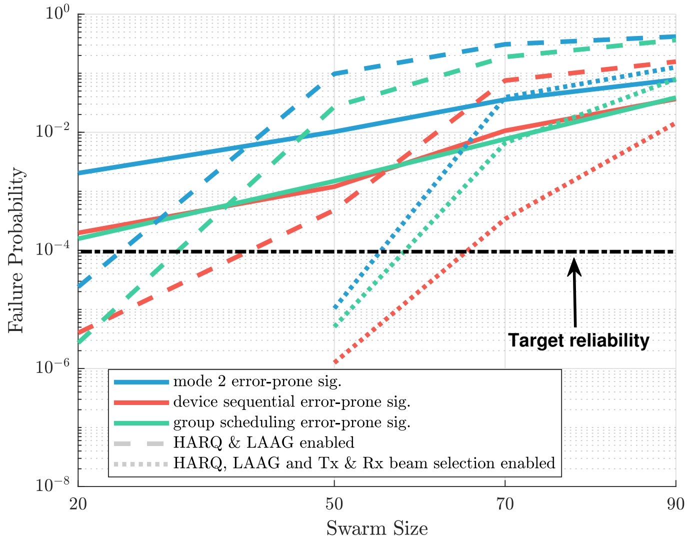

Fig. E.16: Failure probability achieved at three configurations for the four swarm sizes. The 10^{-4} requirement is indicated by the dashed black line.

7 Conclusion

The release 16 of 5G NR sidelink mode 2 decentralized resource allocation scheme didn't provide cooperative capabilities to avoid half-duplex problems. Current release 17 includes coordination capabilities; however, the need for numerous signaling messages to perform inter-UE coordination (IUC) and random resource allocation makes it challenging to fulfill the stringent requirements of 99.99% reliability, 10 Mbps throughput, and 10 ms latency. In comparison, it is clear that *device sequential* and *group scheduling* schemes are beneficial due to the considerable reduction of control signaling, directly outperforming mode 2.

The methodology of identifying the causes of the average failure rate per NR slot allowed us to identify the more representative ones to reduce them with the application of enhancement techniques. Three enhancement techniques, respectively, HARQ, LAAG, and beam selection, were introduced to address these problems and allow the increment of the supported swarm size. Although cooperative resource allocation schemes use signaling overhead, they provide an order of magnitude reduction in failure probability compared to mode 2.

HARQ and LAAG allow UEs to add redundancy and robustness by reducing the MCS of data transmissions. The side effect is the increment of

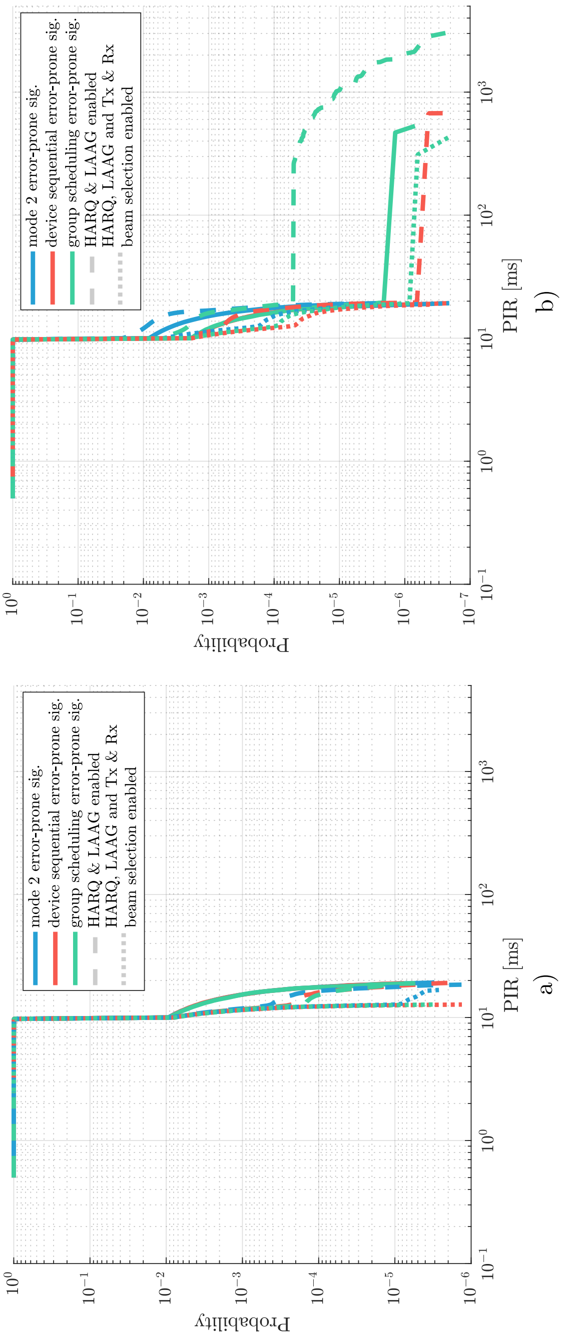

Fig. E.17: Packet inter reception (PIR) complementary CDF at swarm sizes of 20 UEs (a) and 50 UEs (b) for the three simulation configurations the mean resource occupancy as the swarm size increases, producing more half-duplex problems in the case of mode 2 and all kinds of interference for all schemes. Beam selection copes with many of these problems by using directional antennas to reduce the impact of undesired transmissions. Cooperative schemes, specifically device sequential scheme, give an additional 20% of swarm density compared to mode 2; however, interference and a few half-duplex problems become significant when increasing the swarm size.

Interesting topics to be explored in the future include the study of energy consumption together with the adaptive selection of cooperative resource allocation schemes when the swarm size changes dynamically. The study of power allocation would undoubtedly be beneficial to manage the interference when the swarm size overpasses seventy UEs and potentially increases the supported swarm size even further than that value. Finally, a study of the incorporation of network coding principles to our device sequential and group scheduling would allow exploring if additional coordination is required to get its benefits.

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Part V

Conclusions

Conclusions

1 Summary

Proximity communication is vital to enable reliable and robust decentralized communications between moving UEs without network coverage. Such reliability and robustness are challenging to achieve because of the lack of a central entity in charge of resource allocation. Then, cooperative resource allocation represents a promising solution since it focuses on eliminating, or at least considerably reducing, half-duplex problems and interference. It imposes new challenges on the design of out-of-coverage cellular systems. Besides, the predicted trend aims to have a large concentration of UEs, making communication conditions worse. The ongoing fourth industrial revolution (industry 4.0) introduces the use of robotic swarms to provide flexibility and reconfiguration capabilities to goods manufacturing. It requires stringent communication to achieve such tasks, which include minimum throughput of 10 Mbps, minimum reliability of 99.99%, and maximum latency of 10 ms. Factory warehouses are prone to experience zones without network coverage and long handovers that are harmful to the operation of robotic swarms. Then, it is a valuable use case to consider for proximity communications under 3GPP's specifications. The current standard for this kind of communication is 5G NR sidelink, which counts with an out-of-coverage operational mode (mode 2) which performance is limited due to the presence of half-duplex and interference that impacts its reliability. Release 16 of 3GPP's standard does not count with cooperative capabilities to increase its reliability, but they were included in release 17 with inter-UE coordination (IUC).

This thesis focuses on the design and incorporation of cooperative capabilities into mode 2 resource allocation and the application of enhancement techniques to achieve the target stringent communication requirements. The baseline scheme is release 16 sidelink mode 2, where on top of it, two cooperative resource allocation schemes were designed: *device sequential* and *group scheduling*. Based on the 3GPP's specifications, we developed a system-level simulator to evaluate and compare the performance of mode 2 and the designed cooperative schemes.

First, a proof of concept of the cooperative resource allocation schemes is discussed in Part II. Under the assumption of having error-free signaling, we performed a study to evaluate the potential benefit of incorporating cooperative resource allocation capabilities on top of mode 2 to eliminate half-duplex problems and interference. The designed schemes allocate resources following a sequential order or depending on a group leader. The evaluation covered slot occupancy and outage capacity KPIs to perform a fair comparison between mode 2, the proposed cooperative schemes, and a centralized scheme consisting of one UE having all the network's knowledge. The obtained results confirm the great potential of both cooperative schemes over mode 2 since they eliminate half-duplex problems and interference to fulfill the stringent requirements in large swarms. Between the two schemes, there was no noticeable difference in performance. At a swarm size of sixty-five UEs, there was a small gap between the cooperative and the centralized schemes.

In Part III, the control signaling design and its impact on the overall performance were studied. First, the design of the signaling flow was presented for each cooperative scheme. Next, the performance evaluation allowed us to identify undesired behaviors that caused half-duplex problems or deprived transmissions. To overcome them, we proposed three enhancement techniques. The results verified that despite control signaling impact, cooperative resource allocation schemes outperformed mode 2, with the particularity that only a swarm of ten UEs could fulfill the stringent requirements when using the device sequential cooperative scheme. It demands the incorporation of enhancement techniques to increase the swarm size.

Finally, in Part IV, we performed studies to address the problems that caused data failure receptions. NR slots experienced different kinds of half-duplex and interference, requiring the incorporation of enhancement techniques to mitigate their impact. Hybrid automatic repeat request (HARQ), directional antennas and beam selection, and link adaptation with a variation to allocate additional slot(s) (i.e., link adaptation by aggregation (LAAG)) where the proposed solutions. The obtained results indicate that HARQ and beam selection are the techniques that considerably increase the reliability of all schemes. HARQ incorporates time diversity at the cost of increasing the resource grip occupancy. In contrast, beam selection increases the SINR of each data segment, allowing the successful reception despite the presence of half-duplex in some other data segments. Cooperative resource allocation schemes noticeably outperform mode two as the swarm size increases. Regardless of its latest IUC inclusion, it requires a significant number of control signaling messages that directly impact its reliability. Therefore, cooperative schemes represent a promising strategy to increase decentralized proximity communications' reliability further.

2 Research questions revisited

This thesis covers various aspects of using cooperative resource allocation schemes for 6G proximity networks. Based on the obtained results, the initial hypothesis and research questions presented in Part I are worthy of reflection.

H1: A decentralized cooperative resource allocation scheme will be possible with a proper control messaging flow between pairs. The control messaging finishes well before the event trigger period ends.

Q1: What are the considerations and designing process of a decentralized cooperative resource allocation scheme based on NR Sidelink Mode 2?

The baseline of enabling cooperative resource allocation is the availability of all possible information that allows UEs to estimate the proximity of others, obstacles, or humans around the factory facility. Thus, we defined two cooperation ranges, one to obtain all necessary information for resource allocation and the other to perform the resource allocation. The information used for the estimation includes coordinates, heading direction, and speed, and it is broadcast within each UE's extended cooperation range (r_e) in the form of *discovery messages (DMs)*. Our study in Part III determined that UEs count with sufficient discovery probability to estimate others' positions and determine the trigger time to perform cooperative resource allocation. Once the trigger time is set, UEs execute cooperative resource allocation when nearby UEs get into their respective critical cooperation range (r_c). They execute the adopted cooperative scheme (device sequential or group scheduling) to proceed either with the transmission or reception of resource selection messages (RMs). They contain the set of chosen slots by the UE itself (i.e., device sequential scheme) or assigned by its group leader (i.e., group scheduling). It is a fundamental aspect of cooperative resource allocation since, without the successful reception of RMs, it does not exist. Thus, it is of high importance to ensure their reception. However, since it can not always be guaranteed, techniques such as RM re-transmissions or random resource selection (e.g., rebel sub-mode) allow UEs to transmit data and do not be deprived of doing it. Results indicated that the chosen design is sufficient to achieve cooperative resource allocation since, by all means, it outperforms mode 2.

H2: Properly adapted robustness, time, and spatial diversity techniques will provide high reliability to device-to-device (D2D) links.

Q2: How can the adoption of enhancing techniques provide 99.99% reliability to 10 Mbps throughput and 10 ms latency for the decentralized cooperative resource *allocation schemes?*

In Part III of this thesis, we showed the impact of the control signaling on the cooperative schemes' performance, indicating that only ten UEs were supported with the stringent requirements when using the device sequential scheme. Even though it was possible only to support a small swarm, cooperative schemes outperformed mode 2. The main reason for not coping with a larger swarm was the presence of interference in both cooperative schemes and a few half-duplex in the group scheduling scheme. The latter was a product of the non-coordination of leaders when UEs belonging to different groups are within their respective r_c.

Time diversity was included in the HARQ re-transmissions. It allowed cooperative schemes and mode 2 to increase the reliability since the conditions on the re-transmission(s) may differ from the conditions of the first transmission (e.g., absence of half-duplex or interference), but at the cost of increasing the resource grid occupancy. Mode 2 could support twenty UEs while device sequential and group scheduling thirty and close to fifty UEs, respectively. Robustness to the device-to-device (D2D) links was brought by the inclusion of link adaptation with a variant of allocating additional slots for subsequent transmissions, denoted as LAAG. By itself, it did not offer better performance than the other techniques. However, the reliability kept a constant range of values regardless of the increment of the swarm size until fifty UEs, where it noticeable decays. Therefore, combining both HARQ and LAAG represented the best option for group scheduling since the supported UE increased to forty-five UEs. At the same time, the device sequential supports a couple more.

A different way to tackle half-duplex and interference is provided by spatial diversity. The use of directional antennas and beam selection allows UEs to boost the SINR of each data segment transmitted in each slot and reduce the interference from undesired transmissions. The former benefits data reception, even though some data segments might experience either half-duplex or interference. The boost of the SINR at the transmitter and receiver sides may make the effective SINR sufficiently high to allow the receiver to decode it. Then, the results presented indicate the significant reduction of half-duplex and interference in mode 2 and cooperative schemes. The interference reduction is noticeable when using receiver beam selection since UEs are likely to receive one transmission at a time. Therefore, the use of the beam that points to the target transmitter allows the elimination of other transmissions that might take place at the same time instant. Results indicated that combining time and spatial diversity could achieve the best performance. It allows device sequential to be the best option to support a large swarm since it supports a swarm size close to seventy UEs. Mode 2 and group scheduling can reach approximately fifty-five and sixty UEs, respectively.

H3: The impact of the new control signaling flows will not affect either mode 2 or cooperative resource allocation schemes' performance significantly.

Q3: How is the incorporation of the decentralized cooperative resource allocation into the 3GPP release 16 NR SL mode 2 design?

Both mode 2 and our proposed cooperative resource allocation schemes require DMs to estimate others' positions. It represents a method to acquire the required information to estimate proximity and perform cooperative or non-cooperative resource allocation. The necessary adaptation has to be done for the resource selection per se. Currently, 3GPP release 17 includes IUC to provide coordinated resource allocation. It consists of exchanging IUC requests from the transmitter to the target receiver(s). Its performance could not be included in our system-level simulator, but we inferred its potential performance based on its unicast and our assumed broadcast natures. Results indicated that IUC uses significantly more control signaling messages than our proposed schemes. It directly impacts the overall performance since time-frequency resources are limited and insufficient if it is required to support a high number of UEs with such stringent requirements.

Our proposed cooperative schemes follow an evolution approach based on mode 2's functionality since they use mode 2's sensing procedure and another sidelink mode 2's functionalities. The difference is in the resource selection procedure. However, they are fully adaptable. The failure probability results of all performed studies reflected that cooperative schemes consistently outperformed mode 2. Then, device sequential and group scheduling could be adapted to NR sidelink design since they do not interfere with any process. Nevertheless, it requires the inclusion of the RM functionality into the specs and, more critically, their adaptation into the current processes (e.g., exceptional cases such as edge cases and non-aware leaders). It is the primary motivation to envision the inclusion of our proposed cooperative resource allocation schemes into the current studied sixth generation (6G) networks since it can cover all the capabilities we proposed in the different studies. It can also provide adaptive combinations to our proposals, for example, sub-modes (e.g., rebel sub-mode), adaptive first shot transmissions when using HARQ, and dynamic switch among cooperative schemes.

3 Recommendations

Based on the acquired knowledge during the Ph.D studies, the following recommendations are worth consideration:

- When selecting an adequate resource allocation, evaluating the implications it may have on the use case is essential. When adopting a more device-centric resource allocation, better performance is obtained since UEs avoid the leader dependence that may impact the performance due to the leader decisions when swarms tend to be dense. It is complex to address all possible particularities that might happen when forming groups of UEs that, when not solved, directly decrease the reliability. However, when the swarm size is small, the same performance can be achieved by using less control signaling.
- The previous point is linked with the UE's energy consumption. Cooperative resource allocation schemes are attractive to this idea since they significantly reduce the necessary control signaling amount compared to mode 2 IUC. Under the assumption that all schemes perform the same, the fact that cooperative schemes consume less power is an attractive option since current and future technologies look forward to providing improved performance but also less power consumption.

4 Future work

The following research topics are considered as potential directions for future work:

- **Full-duplex receiver:** Specifically, a study of the robotic swarms performance when UEs have full-duplex capabilities. It will provide insights into mode 2 performance when half-duplex problems are not an issue. However, self-interference evaluation is necessary to verify if it harms performance reliability. Then, it would be possible to determine the pros and cons of selecting a receiver with or without complexity (i.e., mode 2 with full-duplex vs. cooperative schemes).
- **Machine learning for adaptive selection of parameters:** Our studies verified the impact of specific parameter selection selected configurations performance (e.g., first shot transmission time and feedback periodicity). Nevertheless, it would be imperative that UEs would know how they can better use the time-frequency resources. It might be possible to use machine learning techniques to estimate the impact of each parameter combination on the given swarm density and conditions. Then, it could be possible that cooperative resource allocation schemes might increase the supported swarm density even further. Moreover, machine learning techniques might be beneficial to enable dynamic cooperative resource allocation based on the swarm size and KPIs performance.

Part VI

Appendix

Appendix

1 Confidence interval

Throughout our studies, one of the main communication requirements has been the maximum latency of 10 ms for 99.99% of all transmissions. We used the latency needed at 99.99% occasions as a key performance indicator (KPI) to compare the performance of the features evaluated with our simulation campaigns. Thus, it is essential to understand the stability of this value and its dependence on the number of simulation samples. Our studies have used a target value for simulation samples, and the confidence interval has been estimated based on the assumption that the value would follow a normal distribution. However, as empirical methods obtain the values and confidence interval via system simulations, this interval cannot be truly known since the underlying distribution is unknown. In this section, a study of the stability of the confidence interval and its dependency on the number of simulation samples is performed to prove that a sufficient number of samples has been used throughout our studies.

We adopted a confidence interval of 95%, same used in [1]. For that purpose, we followed the non-parametric bootstrap method used in [2]. The goal was to obtain the distribution of our main KPI and evaluate the confidence interval as a function of the number of samples used to derive the main KPI. The evaluation consisted of the following steps:

- It was required to obtain sufficient samples for the evaluation, so we decided to run twenty simulations of fifty seconds each, all using different random seeds.
- A prerequisite to combining samples from the 20 simulations is that they are i.i.d. As there is no reliable way to derive this, we decided to do so by a visual inspection reflected in Fig. VI.1. Based on our inspection, we judge that they all followed the same tendency and could be combined to apply the bootstrap method.

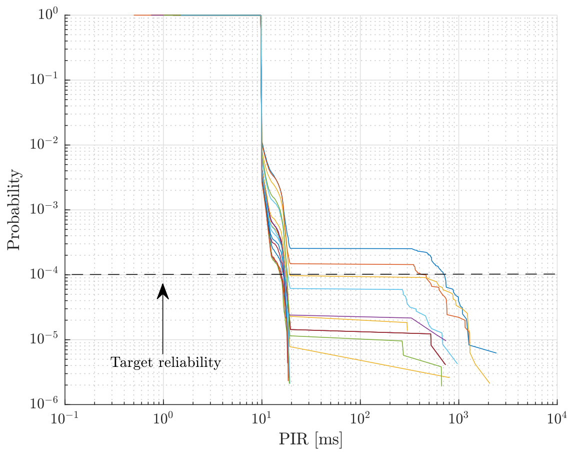

Fig. VI.1: CCDF of the PIR results of the 20 i.i.d. simulations.

- We merged the results of all simulations to obtain a unique set of samples $\mathcal{Z}$ equivalent to the one obtained from a 1000 seconds simulation. Note that this was the simulation time assumed for our studies.

- From $\mathcal{Z}$, we get a subset Z_{nsp_i}, where nsp determines the number of samples from $\mathcal{Z}$, and i is a value from 1 to 2500, meaning the number of realizations of Z_{nsp}. The chosen values for nsp were 50K, 100K, 500K, 1M, 5M, and +9M (equivalent to the size of $\mathcal{Z}$).

- For each Z_{nsp_i}, we determined the KPI value X_{nsp_i}.

- For each X_{nsp_i}, we determined the mean value $\overset{\wedge}{\mu}_{X_{nsp_i}}$ by using equation (VI.1),

$$\overset{\wedge}{\mu}_{X_{nsp_i}} = \frac{\sum_{j=0}^{n_{sp}} X_{nsp_{i_j}}}{n_{sp}}. \tag{VI.1}$$

  Then, we got a mean distribution of each X_{nsp}.

- Finally, the confidence interval of 95% of the mean distribution of X_{nsp} was obtained by using equation (VI.2),

$$P(0.05 \leqslant X_{nsp} \leqslant 0.95) = 1 - \alpha, \tag{VI.2}$$

  where α is 10^{-4} failure probability requirement.

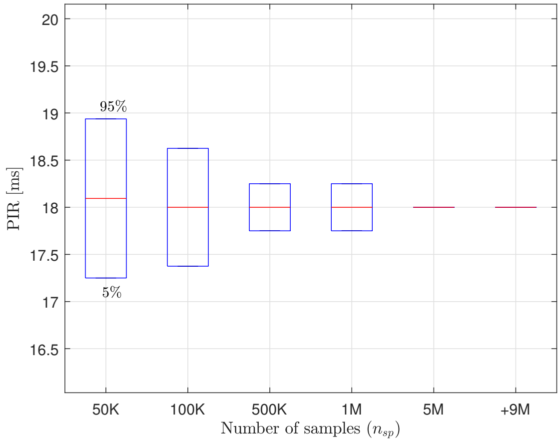

Fig. VI.2: Standard deviation values of the mean distribution for different number of n_{sp} values.

Fig. VI.2 shows the standard deviation values of the mean distributions for the different number of n_{sp} values. The value where the standard deviation is zero represents the minimum number (n_{sp}) of 99.99% of PIR values the simulation should have to provide a confidence interval of 95%. In our case, the chosen simulation time of 1000 seconds goes beyond the minimum required value of 5 million values of the PIR. Therefore, the obtained results can be trusted, and the comparisons made throughout our studies are valid.

It is important to address that, in principle, the PIR distribution is different for each new feature that was evaluated. Hence, it cannot be said for certain without doing a similar exercise to those results. However, the trends have been kept throughout the studies, and no unusual behaviors were detected at the tails to doubt that this exercise, if done for other sets of features evaluated throughout our studies, would not give similar results.

Alternative formulation: that this exercise, if done for other set of features evaluated through out my studies, would not give similar results.

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