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

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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.

***Index Terms*—distributed resource allocation, swarm communication, cooperative communication**

I. 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 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.

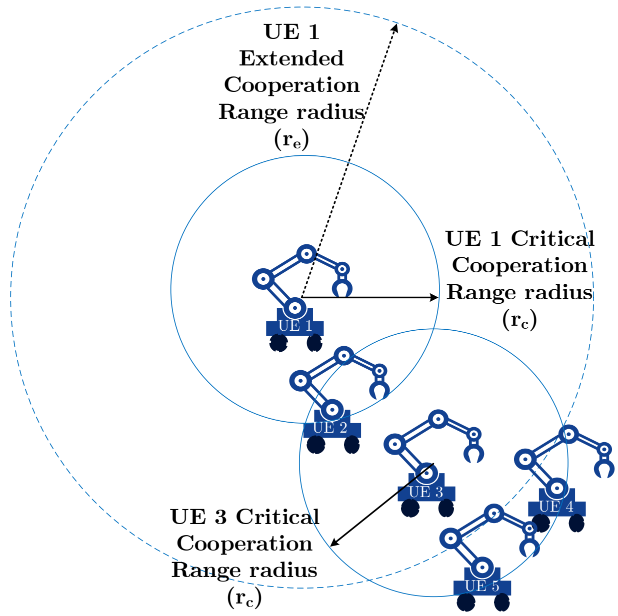

Fig. 1: Device-centric proximity ranges.

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 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.

II. 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 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].

III. Resource Allocation Schemes

We classify the resource allocation schemes relevant to our scenario in Figure 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.

Algorithm RA Resource allocation

Input: $\{(N_\text{s}, R_\text{s})_k\}, k = 1, 2, ..., \text{K}$: 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 $N_{\text{s},k}$ 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 $\bigcup_{n=1}^{K}(R_\text{s})_n \cup R_\text{e}$

3: **end for**

Output: Assigned resource allocation

Algorithm 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)

A. 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 ($S_\text{rx,dB}$),

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

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

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

$H_\text{g,dB}$ 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,

$$C_\text{s} = B \times \log_2(1 + \gamma) \times D_\text{s} \tag{3}$$

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 (4).

$$N_\text{s} = \left\lceil \frac{D_\text{p} \times T}{C_\text{s}} \right\rceil \tag{4}$$

B. 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 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$_i$, $i = 1, 2, ..., N_\text{r}$ 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 1 summarizes the device-sequential allocation procedure.

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 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 3, where UE$_\text{B}$ is within *critical cooperation range* of UE$_\text{A}$ but outside *extended cooperation range* of L$_\text{A}$ (the leader of UE$_\text{A}$). In this case, UE$_\text{B}$ forwards

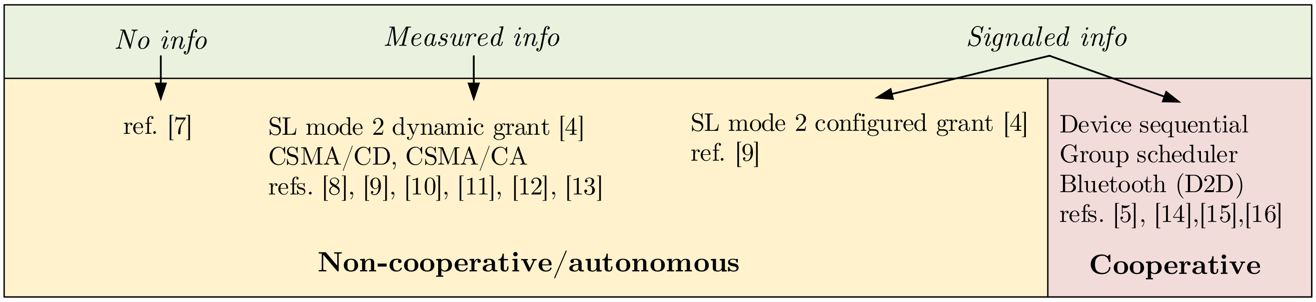

Fig. 2: Characterization of prior art and proposed resource allocation schemes

Algorithm 2 Group scheduling resource allocation

Input: N_s, resource pool

Algorithm (run by UE_i):

1: 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.
2: **if** UE_i is a leader **then**
3: wait for resource allocation from known leaders with lower ID, then execute Algorithm RA for the group and broadcast the resulting resource allocation.
4: **end if**
5: **if** UE_i is an inferior **then**
6: receive resource allocation (RA)
7: **if** RA is from L_i **then**
8: forward RA to leaders in r_e of UE_i and outside r_e of L_i
9: forward RA to UEs in r_c of UE_i and outside r_e of L_i
10: extract allocated slots, A_s, for UE_i
11: **else if** RA is from a UE in r_c of UE_i and outside r_e of L_i **then**
12: forward RA to L_i
13: **end if**
14: **end if**

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

the leader selection of $\mathrm{UE_A}$ to $\mathrm{L_B}$, thereby making $\mathrm{L_B}$ aware of the presence of $\mathrm{UE_A}$. 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 3 $\mathrm{L_A}$ has lower ID than $\mathrm{L_B}$, thus its resource allocation is forwarded to $\mathrm{L_B}$. 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 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 2 summarize the described procedure.

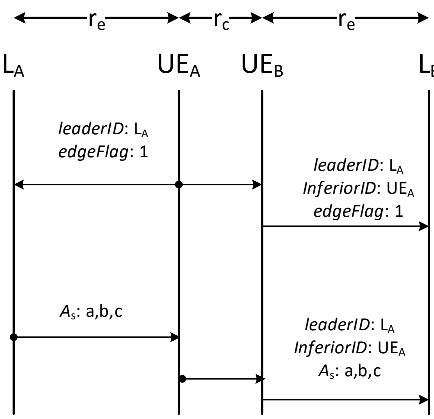

Fig. 3: Edge flag is set when leaders are out of range.

IV. Simulation

We implemented five different resource allocation schemes in our system level simulator: the device **sequential** and **group** scheduling described in Section III 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 II. 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, (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).

$$L_\mathrm{dB} = \beta + \alpha 10 \log_{10}(d) + \psi 10 \log_{10}(f_\mathrm{c}) \tag{5}$$

Additionally, we consider correlated channels in both space and time. That is, we generate the shadowing component,

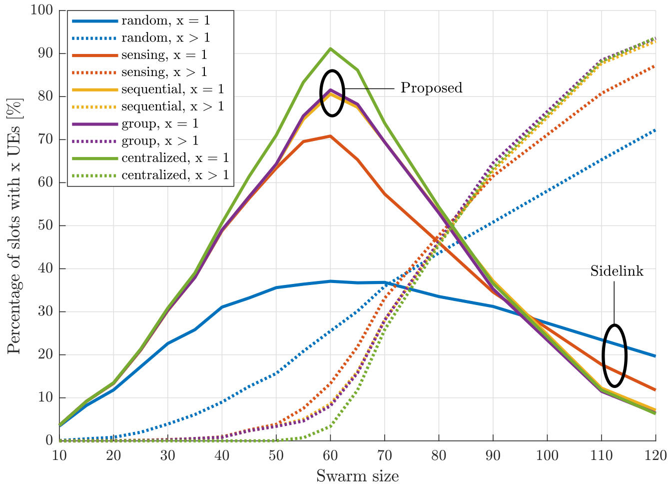

Fig. 4: Slot occupancy (1 or more UEs) for different swarm sizes

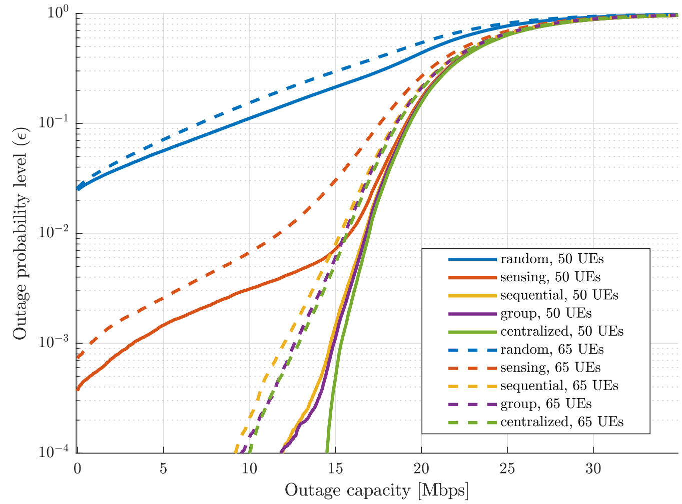

Fig. 5: Outage capacity at swarm size of 50 and 65 UEs.

TABLE I: 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

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

Table I presents the values of the input parameters for the simulation.

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

Figure 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 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 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 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 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.

VI. 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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