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Beyond 5G Wireless IRT for Industry 4.0: Design Principles and Spectrum Aspects

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Abstract—We present our vision for a Beyond 5G Wireless Isochronous Real Time (WIRT) system for industrial control networks, designed for supporting fast closed loop control applications. WIRT aims at ultra-reliable short range wireless links with ~ 0.1 ms latencies and a wired-like 10^{-9} reliability. The usage of a large spectrum and frequency/interference diversity are considered fundamental components for WIRT. Ultra-wideband (UWB) spectrum access and unlicensed transmission at millimeter-waves (60 GHz band) are identified as possible solutions towards ultra-reliable ultra-low latency communication. The suitability and challenges of both approaches are extensively discussed, along with the way forward for WIRT design.

I. INTRODUCTION

Industry 4.0, or the fourth industrial revolution, refers to the evolution of cyber-physical systems towards a holistic value chain supported by decentralized intelligence and connectivity. The target use cases are, among others, manufacturing, production, and intra-vehicle communication. A key objective in Industry 4.0 is to reduce the need for human intervention in industrial processes by using automatic control systems and communication technologies, implemented through an Industrial Control Network (ICN) [1].

Many ICN applications in Industry 4.0 require continuous closed-loop control updates, such as controlling the speed of a machine drive. These loops can have a frequency of hundreds or more cycles per second, and are vulnerable to data loss. In terms of numbers, this translates to very high reliability - up to the order of 10^{-9} - and extremely low latencies in the order of 0.1 – 1 millisecond (ms) round trip time.

Communication in ICN has been typically implemented using fieldbus protocols, which have today evolved to wired Ethernet-based fieldbus systems [1]. Solutions like PROFINET Isochronous Real Time (PROFINET IRT) and IEEE 802.1 Time Sensitive Networking (TSN) are designed to support industrial automation applications requiring very high reliability and low latencies. PROFINET IRT is a proprietary solution that uses transparent clock mechanism and bandwidth reservation [2]. TSN denotes a set of IEEE standards that delivers deterministic communication over standard Ethernet by providing a network wide precision clock, scheduling time-critical traffic and preemptive blocking of non-time-sensitive traffic when needed [3]. However, existing Ethernet based solutions limit flexibility, scalability and deployment options

for services requiring isochronous real time control loops and lead to high operational expenditures (OPEX) for cabling installation and maintenance [4]. Since the last decade, wireless technologies like WLAN, ZigBee and Bluetooth and their proprietary extensions such as Wireless Interface to Sensors and Actuators (WISA) and Wireless Highway Addressable Remote Transducer (HART) [1], [5] have also been used as fieldbus systems. However, these technologies operate in crowded unlicensed spectrum with unpredictable interference levels, and are not capable of supporting very high reliability and low latency applications [5]. Ultra-Reliable and Low Latency Communication (URLLC) requiring ms-level latencies at 10^{-5} reliability is one of the target service classes addressed by the fifth generation new radio (5G NR) wireless cellular system [6]. The recent 5G NR Release 15 includes ICNs in Industry 4.0 as specific URLLC use case. However, it is limited to support at most logic/motion control at ms-range latencies, and cannot serve ICN applications like drive control with closed-loop control at sub-ms update rates. To support many emerging industry 4.0 applications, there is a demand for a wireless counterpart to PROFINET IRT catering to the requirements of high-precision real time communication in ICNs, which 5G NR is unable to fulfill.

In this paper, we present a vision for a novel Beyond 5G Wireless Isochronous Real Time (WIRT) system that aims at filling this vacuum. In particular, we set for our design an ambitious target of a 0.1 ms minimum latency at 10^{-9} reliability. The need for scalability, high reliability and low latency entails operating in a large spectrum and robust measures towards interference. We thus identify potential spectrum bands for WIRT operation and provide a vision for how the desired reliability and latency target can be met in such a system. Also, we discuss how the support of periodic deterministic communication may require the inclusion of a new service class in the current spectrum regulations.

The paper is structured as follows. Section II presents the envisioned requirements of WIRT. The general design principles are described in Section III. A discussion on the WIRT operating spectrum is presented in Section IV. The way forward and open challenges for the design of WIRT are described in Section V. Finally, Section VI concludes the paper.

II. GENERAL REQUIREMENTS

The general requirements for the envisioned Beyond 5G WIRT system are presented in Table I. As mentioned in the introduction, WIRT is expected to serve applications requiring fast control cycles between nodes located at a close distance. Examples of use cases are drive control in industrial automation, or intra-vehicle communication for engine and suspension control.

TABLE I
KEY REQUIREMENTS FOR WIRT

Parameter	Requirement/Description
Application domain	Manufacturing, embedded systems, in-vehicle/aircraft control, etc.
Reliability	10^{-9}
Minimum Latency	0.1 ms
Data payload	32 bytes
Traffic type	Periodic
Spectrum access	Unlicensed
Network topology	Star / Meshed
Nodes per cell	20 – 200
MIMO capability	Limited at the devices, multiple antennas at the GW
Form factor/power	Small size/low power
Range	in the order of 10m
Mobility	No
Interference management.	Possibly coordinated within cells in the same network, implicit across different networks

A WIRT cell is composed of an access point (connected to a controller) and a number of end devices, representatives of sensors and actuators. We refer to the access point as a gateway (GW), since it can interface with existing wired or wireless networks for higher hierarchy control operations besides serving the end devices. We set a reliability target of 10^{-9} as assumed for critical wired ICN applications, and a 0.1 ms minimum latency. We also consider the same payload as defined by the 3GPP for URLLC studies [6]. Periodic traffic with deterministic cycles is to be supported.

The usage of unlicensed bands allows WIRT to operate as a stand-alone radio, with obvious benefits in term of deployment flexibility and rapid installation. Further, intra-vehicle use cases are clearly facilitated by their usability across regions. The candidate unlicensed bands for WIRT will be presented in Section IV. Multiple Input Multiple Output (MIMO) antenna technology is to be considered as a fundamental technology component for achieving high reliability [7]. However, the small form factor of the end device may prevent the usage of a large number of antennas, at least for transmission in the below 10 GHz spectrum region. The GW can in principle accommodate more antennas. Since WIRT devices can be battery-driven, we strive for a low-power design which extends the battery life, reducing the maintenance effort.

We expect a WIRT cell to support a number of nodes (sensors/actuators) ranging from 20 to 200. The latter number represents a reasonable estimate for the number of sensors in a "smart" vehicle in the near future [8]. Obviously, not all the

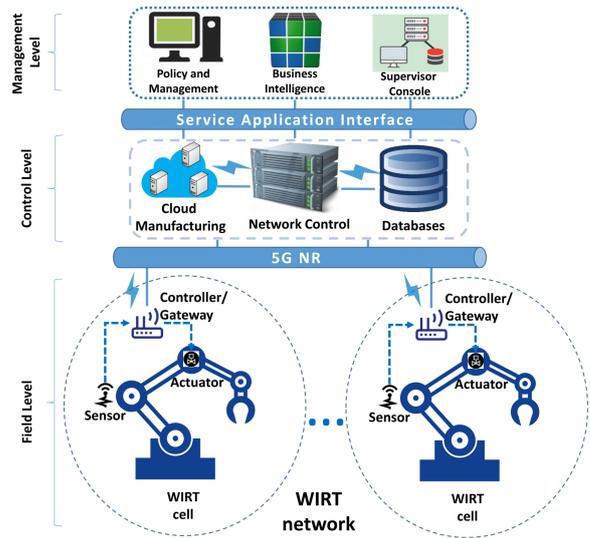


Fig. 1. WIRT network in an industrial environment.

links necessitate to cope with the minimum latency. We rather aim at a scalable latency as a function of the cycle timing and supported number of nodes. Such aspects will be further discussed in Section III.

The range of a WIRT cell is in the order of 10 m, and no mobility is supported. This differs from 5G URLLC, which supports mobility across cells and a communication range in the order of ~ 100 m or more. In that respect, WIRT is expected to complement existing wired or wireless infrastructure for ICNs. Communication at field level can run over a wireless 5G URLLC radio, while WIRT supports short range closed loop control. As an example, WIRT cells can be deployed at each station of an assembly line for enabling control of robot arms and manipulators, while the general operations of the stations in the assembly line can be controlled via 5G. Co-existing wireless infrastructure can then act as a backhaul and as a control network at a higher hierarchy. The concept is pictorially depicted in Figure 1. Note that the processing of 5G NR may run over an edge cloud, while WIRT may require embedded software in the plant to achieve ultra-low latency. In the following, we refer to a WIRT network as a set of WIRT cells whose GWs are connected via the same infrastructure.

Operations of WIRT cells belonging to the same network can in principle be coordinated such that mutual interference can be minimized. Implicit interference coordination mechanisms are required for reducing the mutual harm in the case of cells connected to different networks, e.g. different assembly lines or vehicles in close proximity.

III. DESIGN PRINCIPLES

A. Support of isochronous real time transmission

As a general setup for a WIRT cell, let us consider a star topology where a controller is associated to a GW and

connects to a number of sensors and actuators. In this scenario, uplink (UL) communication consists of transmission of measurements from sensors to the GW, and the downlink (DL) by the transmissions from the GW to the actuators. We target isochronous real time (IRT) transmission, which subsumes a synchronized system where each sensor/actuator is allocated an amount of dedicated periodic radio resources. The system is persistently scheduled, subsuming a preliminary connection establishment procedure for assigning the dedicated resources. The data information flow is unidirectional, while the control plane for resource assignment is bidirectional. The persistence of IRT transmissions eases the tight timing control which is needed for synchronization and jitter reduction.

UL and DL transmissions are arranged in a Time Division Duplex (TDD) fashion. Every frame is composed of an UL and a DL subframe, and its duration is dictated by the control loop cycle. The UL/DL ratio is to be set according to the number of active sensors and actuators to be served. In case of symmetric traffic (i.e., the measurement reported by a sensor are meant to issue a control command for a single actuator), such ratio is equal to 1. Asymmetric scenarios reflect, for instance, the case in which the measurements reported by multiple sensors are meant to issue a command for a single or a lower number of actuators; in this case, the traffic is heavier on the UL direction.

An example of transmission frame with associated processing times is displayed in Figure 2, considering the case of a 0.2 ms loop with symmetric UL/DL traffic. Only the data plane is highlighted for the sake of simplicity. We divide the 100 microseconds (μs) subframes in 5 slots of 20 μs duration. Assuming the 0.1 ms minimum latency target, a transmission from a sensor (or to an actuator) has to be terminated within a slot, leaving a time margin of $\sim 80 \mu\text{s}$ for receiver processing. In the shown setup, up to 5 sensors/actuators loops can be time-multiplexed. A higher number of devices can be supported by introducing frequency multiplexing. For example, using 4 frequency channels allows to support the 20 devices that we have set as a minimum target for WIRT. Supporting a significantly larger number of devices (up to 200) may only be possible with more relaxed cycle timings.

The presented transmission procedure holds at regime and subsumes a preliminary phase where the periodic radio resources are requested and then allocated to a certain transmitter. The control plane may run at a slower pace than the data plane, but it should be able to dynamically handle procedures such as link adaptation and power control.

B. Enabling ultra-reliable ultra-low latency communication

In traditional wireless networks, reliability can be improved by using techniques such as packet retransmissions and diversity over multiple domains.

The usage of Hybrid Automatic Repeat reQuest (HARQ) retransmissions is to be disregarded given the tight latency target. Blind packet repetitions, i.e. consecutive transmissions of the same packet, are included in 5G NR Release 15 [9] and have a clear potential in WIRT since they avoid delays

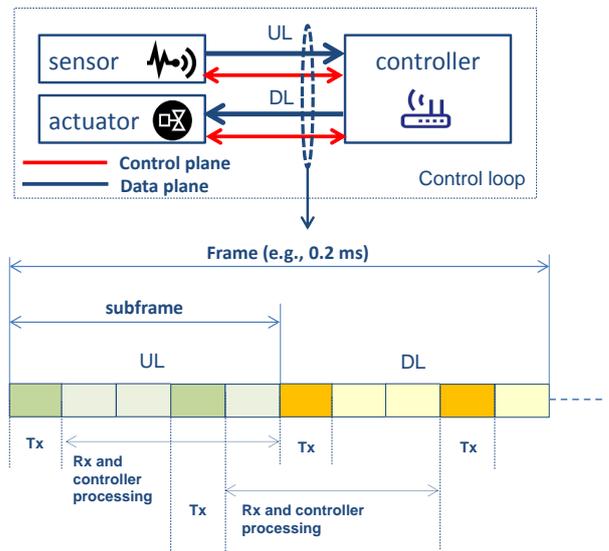


Fig. 2. Example of frame structure, with symmetric UL/DL traffic.

associated to the HARQ round-trip-time at the expense of a higher resource utilization.

Diversity is also recognized as a fundamental ingredient towards ultra-reliable communication. High spatial diversity gain can be achieved by using a large number of uncorrelated transmit and receive antennas. However, as mentioned above the limited form factor of the WIRT end devices may prevent the usage of a large number of antennas when operating in spectra below 10 GHz. This may limit the potential of receive diversity in the downlink, and suggests the usage of transmit diversity solutions. Frequency diversity can be achieved by hopping the transmission over multiple frequency channels, similarly to, e.g. Bluetooth. The benefits of frequency diversity in WIRT are twofold: it allows circumventing the negative impact of frequency selective fading which can affect portions of the bandwidth, and allows to avoid the interference that can selectively affect some of the used channels. Achieving such interference robustness is particularly relevant in case of uncoordinated WIRT networks located in close proximity.

In conclusion, we believe WIRT should exploit to a large degree frequency diversity, e.g. via channel hopping and packet repetitions, for achieving reliability up to the ambitious 10^{-9} target. Accommodating a number of channel hops and the tight latency target call for extremely short transmission intervals. For example, the $\sim 20 \mu\text{s}$ time slots in the example in Figure 2 should accommodate multiple repetitions of the same packet over different frequency chunks! A very large bandwidth is therefore needed to support ultra-reliable communication with ultra-low latency. This opens up a discussion on the spectrum region where WIRT is to be deployed.

IV. SPECTRUM ASPECTS

As mention in Section II, we target unlicensed spectrum access for WIRT. The scarcity of unlicensed spectrum in the

below 2 GHz region, as well as the limited device form factor, prevent the usage of such frequencies. When looking at the centimeter-wave spectrum region above 2 GHz, the obvious candidate unlicensed spectra are the 2.4 and 5 GHz bands. The 2.4 GHz band is still rather narrow (~ 83 MHz) and extremely crowded, leading to potentially cumbersome interference levels besides having limited room for channel hopping and interference diversity. The 5 GHz band is fragmented in several chunks with different regional regulations in terms of channel access [10]. Both Federal Communications Commission (FCC) and the European Electronic Communications Committee (ECC) require a Dynamic Frequency Selection (DFS) mechanism to run at each device in the ranges 5.250-5.350 GHz and 5.470-5.725 GHz for avoiding interference with radar systems operating in the same bands. Further, though the current occupancy of the IEEE 802.11 channels at 5 GHz is significantly lower than at 2.4 GHz, the proliferation of IEEE 802.11 devices operating in the 5 GHz band is expected to grow in the coming years [11]; as an example, intra-vehicle use cases might be severely affected by the presence of infotainment services operating in the same band.

Ad hoc licenced-exempt bands in the centimeter-wave spectrum region seem then to be unsuited for WIRT. Ultra-wideband (UWB) transmission represents a potential alternative since it allows for unlicensed access to a very large spectrum (up to ~ 7 GHz) with strict regulations in terms of power spectral density in order not to harm legacy systems operating in the same bands [12]. The usage of unlicensed spectrum in the millimeter-wave region, i.e. the 60 GHz spectrum, can also circumvent the limitations of 2.4 and 5 GHz spectra given the large available bandwidth. While propagation at such frequencies is known to suffer from severe losses, the short wavelength allows for large antenna on chip arrays and easy beamforming. The general characteristics of both solutions and their suitability for WIRT will be further discussed in the following subsections.

A. UWB

FCC and the ITU define UWB as an antenna transmission for which the emitted signal bandwidth exceeds the lesser of 500 MHz or 20% of the arithmetic center frequency. In Europe, UWB signals must have instead a minimum bandwidth of 50 MHz. FCC and ECC have set emission limits in terms of max mean and peak effective radiated power (EIRP) for different applications and frequency bands in the range 3.1-10.6 GHz. For instance, for indoor applications the FCC imposes a maximum mean EIRP of -41.3 dBm/MHz and a peak EIRP of 0 dBm/50 MHz over the entire 3.1-10.6 GHz range [13]. ECC adopts the same limitations for generic applications but over a reduced range (6-8.5 GHz) [14], while operating over different frequency chunks leads to the necessity of applying further mitigation techniques such as Detect and Avoidance (DAA) mechanisms. Ground-based vehicular applications have also more strict requirements in terms of emission power. The low transmit power makes

UWB an attractive technology for short range transmission. An attempt to standardize UWB appeared in the IEEE 802.15.3a Personal Area Networks (PAN) standard. However, the task group was dissolved in 2006 due to disagreements between the involved parties. The work was then completed by the WiMedia alliance in 2009 [15]. UWB is also an optional physical layer in the IEEE 802.15.4 standard for Low-Rate Wireless PANs (LR-WPANs) [16].

The low power spectral density of UWB prevents harming coexisting narrowband systems operating over the same bands. From the perspective of an UWB user, the large band of the transmission translates then to robustness to narrowband interferers. Two multiple access options are typically considered for UWB: Direct sequence spread spectrum (DS-SS) and multiband OFDM. In DS-SS each information bit is mapped over a pseudorandom code which is transmitted as a train of extremely short pulses. The advantage of DS-SS is the simple transceiver architecture due to carrier-less transmission, as well as robustness to multipath. However, channel estimation and synchronization can be rather challenging. The multiband OFDM option divides the spectrum in a number of chunks and applies the traditional multicarrier approach at each chunk. Multiband OFDM allows benefiting from low complexity frequency-domain processing, higher spectral efficiency, and improved scalability of the spectrum.

Advantages for WIRT: Though very popular in the radio community in the first years of last decade, UWB technology has then faced a declining interest due to its uncertain market position. Originally conceived for broadband applications, UWB has indeed experienced the strong competition of IEEE 802.11 and its evolutions, providing similar data rate performance at a lower chip cost. However, we identify the strongest potential of UWB for ultra-low latency applications as targeted by WIRT, rather than for broadband applications. In particular, we foresee the multiband OFDM approach as the most promising given its superior spectral efficiency and the known multicarrier benefits.

The possibility of transmitting over a large band allows for very short transmission times. For instance, the numerology of WiMedia alliance for multiband OFDM sets a $0.3125 \mu\text{s}$ symbol duration, and assume hops over a different 528 MHz wide channel on a symbol basis [15]. By assuming a slot time of $20 \mu\text{s}$, up to 64 symbols can be transmitted. This enables the possibility of harvesting large frequency and interference diversity, also compared to the current 5G NR numerology, where the minimum symbol duration is $\sim 4.5 \mu\text{s}$ [17]. The maximum mean EIRP requirement of -41.3 dBm/MHz leads to a limit on the instantaneous power according to the cycle time and transmission interval; for instance, in case of 0.2 ms cycles and $20 \mu\text{s}$ slots, the resultant 10% duty cycle leads to a maximum power of ~ -4 dBm in case of transmission over a 528 MHz channel. The low transmit power of UWB transmissions inevitably translates to the support of a limited range, but it is also expected to be beneficial in terms of reduced interference footprint. Cycle time, operational bandwidth and transmission range are therefore interdependent and their mutual interaction

is to be analyzed. In order to extend the number of supported devices, regulatory bodies should also consider the possibility of enabling unlicensed UWB access for above 10 GHz bands.

It is worth mentioning that the usage of UWB in industrial environments has also been recently suggested in [18] using the physical layer of IEEE 802.15.4-2011, showing significantly lower packet loss rate than ZigBee devices operating in chirp spread spectrum (CSS) mode.

B. 60 GHz band

In the last decade, the evolution of CMOS technology combined with high-gain, steerable antennas has strengthened the promise of using millimeter-wave transmission for broadband applications [19]. FCC has allocated 7 GHz spectrum in the range 57-64 GHz for unlicensed operations in 2001, and the range has been then extended up to 71 GHz in 2015 [20]. ECC has instead limited the unlicensed band to the range 57-66 GHz [21]. The maximum EIRP is set to 40 dBm. IEEE 802.11ad is the main standard operating in the 60 GHz spectrum, and offers data rates up to 11 times faster than what is provided by 802.11n in unlicensed centimeter-wave bands [22]. Other relevant standards are ECMA-387 for wireless personal area networks [23], and the proprietary WirelessHD for high definition video streaming [24].

Radio propagation at 60 GHz is characterized by a quasi-optical behavior and suffers from high free space path loss (+21 dB with respect to 5 GHz), besides the large diffraction losses around obstacles and huge absorption losses by common materials. On the other hand, the short wavelength (~ 5 mm) allows for building compact antenna arrays on chip; this enables directional beamforming, which coherently adds up the signals sent and received from the multiple antenna elements. The 40 dBm EIRP limit is significantly more relaxed than in the case of unlicensed spectrum in the below 10 GHz region. High directional transmission combined with a sufficiently high transmit power can compensate the propagation losses over a limited distance and offers a sufficient link budget for detection, at least in the presence of a Line-of-Sight (LOS) component. Metallic obstructions may act as strong reflectors allowing for Non-LOS (NLOS) communication. Directional transmissions suffer from deafness arising in the case of misaligned transmit and receiver beams, which can affect the effectiveness of contention based techniques for medium access [22]. On the other hand, directional transmissions lead to a large spatial reuse, i.e. the possibility of a large number of simultaneous transmissions coexisting in the same neighborhood without mutual interference. Directional interference can however appear in case of receive beam alignment with unintended transmitters, with potential disruptive effects. Interference management techniques are therefore expected to be significantly different than in centimeter-wave systems characterized by omni-directional propagation.

Advantages for WIRT: Similarly to UWB, radio standards operating in the 60 GHz spectrum are also mainly conceived for broadband services. However, the large spectrum available has obvious convenience for WIRT since it enables ultra-short

transmissions and possibility of harvesting large frequency diversity. The limited coverage is also not a concern given the short operational range of the WIRT cells.

However, current European regulations for broadband operations at the 60 GHz band, mandate the usage of a Listen Before Talk (LBT) mechanism at each device for broadband services [25], similarly to the case of unlicensed spectrum at the centimeter-wave region. By following LBT, a device can access the spectrum upon assessing the absence of concurrent transmissions for a certain time interval. In case the radio channel is occupied by another transmitter, transmission must be deferred. The usage of LBT is meant to improve throughput fairness for best-effort communication, but obviously clashes with our need of a deterministic periodic access.

We recommend regulatory bodies to introduce periodic deterministic communication for control systems as a new class of applications, and enable the possibility of using interference mitigation mechanisms other than LBT for its support over unlicensed bands. For example, the recommendation of a maximum duty cycle has a better match with WIRT since it does not inhibit periodic deterministic transmissions, at the expense of a penalty in terms of supported cycle time. Duty cycle restrictions is already a well known spectrum access mitigation technique at below 2 GHz unlicensed bands, e.g. the 868 MHz band, for low power wide area network (LPWAN) technologies such as LoRa and Sigfox.

V. WAY FORWARD FOR WIRT DESIGN

Both options of UWB unlicensed access in the centimeter-wave spectrum region, and operations in the 60 GHz band seem to cope with the necessity of WIRT of harvesting a large interference and frequency diversity gain, while allowing for extremely short transmission times. The specific scenario where the WIRT cells are to be deployed will dictate the most suited physical layer to be used.

Transceiver design including selection of the coding scheme has a major relevance due to the need of ultra-short processing times. In that respect, coding schemes which exploit a high degree of parallelism, e.g. Low Density Parity Check (LDPC) codes or Polar codes, have a clear potential for WIRT. Engineering the physical layer of WIRT also includes a careful design of frame and superframe structure for supporting the initial random access procedure, broadcast signaling and overall system information mapping. Our effort will be towards a lean design meant at minimizing signaling overhead and battery drain. An energy consumption analysis is to be carried out, with particular focus on the Analog-to-Digital (A/D) converters which are known to be critical components when operating at a large bandwidth due to their high sampling rate [26].

Addressing the potential of WIRT in achieving ultra-reliable communication necessarily require a deep understanding of the radio propagation characteristics in the targeted scenarios. Channel models for both UWB and 60 GHz cases have been presented in the literature (e.g., [27], [28]), but further measurement campaigns may be needed for characterizing the

new industrial scenarios in terms of coherence bandwidth, shadowing and angular spread. The derived channel model can then be used for both link and system level analysis. Link analysis will include transmit/receive diversity MIMO, beamforming and hardware impairments such as power envelope distortion of power amplifier and limited A/D resolution. The system analysis aims at verifying the performance of networks of WIRT cells, suffering from mutual interference as well as from interference by coexisting radio systems. Though the interference can be explicitly coordinated within a WIRT network, implicit interference coordination techniques may still be considered for neighbor networks or coexisting radio systems. For instance, interference prediction techniques may allow to avoid channels which are likely to be occupied in the near future [29]. Further significant aspects for the design will include link adaptation, power control, connection establishment procedures. In general, we aim at addressing the trade-off between cycle time, number of supported users, transmission range and energy consumption in dense networks of WIRT cells, when coping with a 10^{-9} reliability target.

Finally, a proof-of-concept based for instance on software defined radio will provide an evidence of the effectiveness of the proposed design.

VI. CONCLUSIONS

Replacing wired closed loop industrial control networks with wireless has huge potential in terms of flexibility and CAPEX/OPEX reduction. We have presented our preliminary vision for a Beyond 5G Wireless Isochronous Real Time (WIRT) system design targeting a factor of $\sim \times 10$ latency reduction with respect to the 1 ms target of 5G URLLC, at a wired-like 10^{-9} reliability level. WIRT is meant for short range independent cells composed of a number of sensors/actuators communicating wirelessly with a controller. We have presented the general design principles for supporting isochronous deterministic communication cycles, and identified large spectrum access and frequency/interference diversity as fundamental components for the design. Ultra-wideband (UWB) access and operations in the 60 GHz band are promising options for WIRT given the large available spectrum. However, regulatory bodies should allow for mitigation techniques other than LBT for supporting isochronous transmission in the 60 GHz band.

We have also identified the future steps for the WIRT system design. They include characterization and modeling of the radio channel in industrial scenarios to be used for detailed link/system level verification, energy consumption analysis, design of implicit interference coordination techniques, and finally an on-field proof-of-concept.

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