# Extreme communications in 6G: Vision and challenges for ‘in-X’ subnetworks

White paper

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# Abstract

Sixth generation (6G) radio access technology is expected to support extreme communications requirements in terms of throughput, latency and reliability, which can only be achieved by providing capillary wireless coverage. In this paper, we present our vision for short-range, low power 6G 'in-X' subnetworks, with the 'X' standing for the entity in which the cell is deployed, e.g., a production module, a robot, a vehicle, a house or even a human body. Such cells can support services that can be life-critical and that traditionally relied on wired systems. We discuss potential deployment options, as well as candidate air interface components and spectrum bands. Interference management is identified as a major challenge in dense deployments, which needs to handle also non-cellular types of interference like jamming attacks and impulsive noise. A qualitative example of interference-robust system design is also presented.

# Introduction

While the mass market is currently witnessing the first large scale 5G deployments, research on 6G radio technology has already started, and attractive visions have been brought forward in industrial and academic fora [1]. 6G is expected to bridge the gap between digital, physical and biological worlds by supporting services such as holographic telepresence, extreme virtual reality with tactile feedback, remote surgery and high accuracy sensing [2].

The internet of things will take a further leap towards the internet of everything, with seamless interconnection of objects, processes and people rather than objects only [3]. The connectivity landscape will then increasingly be extended to wearables, bio-implants, intelligent machines and vehicle components. The massive computational needs are to be ubiquitously distributed among devices, access points, edge and central clouds, with the use of synchronous digital twins that can accurately represent the real world for augmenting intelligence and making smart decisions [4]. Also, 6G may unleash the Industry 4.0 vision of a wire-free factory, where wireless replaces cables for the most demanding services in terms of latency and reliability [5].

This ambitious 6G vision translates into more demanding radio performance requirements. Services such as telepresence and mixed reality may require data rates above 100 Gbps, while industrial services such as fast motion control in printing machines could require fraction of millisecond (ms) latencies and seven to nine nines reliability. These requirements are beyond what is currently supported by 5G and can only be achieved by moving the network infrastructure to the very edge, together with the intelligence and decision-making capabilities.

Recent 6G overview articles (e.g., [2], [5–7]), have identified a plethora of novel technologies for the support of the challenging services mentioned above. Relevant examples are reconfigurable intelligent surfaces [8], holographic beamforming [9], sub-terahertz communication [10], orbital angular momentum multiplexing [11], multi-mode ultra-massive antenna systems [12], AI-enabled networks [13] and joint communication and sensing schemes [14]. Also, other-than-radio communication paradigms such as molecular communication are being explored [15].

In this article, we present our vision for 6G 'in-X' subnetworks, aiming at supporting extreme communication requirements. In-X subnetworks were first introduced in [16] and [17] as autonomous, highly specialized cells with limited coverage. They would be deployed in locations where high-performance requirements are demanded, such as production modules, vehicles or human bodies for critical functions like heartbeat control. These scenarios may be characterized by uncoordinated deployments and high device density, for instance, vehicles in a congested road or humans attending crowded events. Using wireless for such applications avoids the drawbacks related to a wired setup, including higher cost, limited deployment flexibility and maintenance of cables.

For in-X subnetworks, there is a diverse set of requirements covering throughput, latency and reliability depending on the specific use case. The term extreme communication has been introduced specifically for subnetworks because the communication requirements can reach the ultimate values envisioned for 6G in all these key performance indicators (KPIs): fraction of ms for latency, nine nines for reliability and tens of Gbps for link throughput.

The term subnetworks refers to the fact that such cells can be part of larger 6G networks, while being able to continue their operations when out of coverage of the wide area network. This is because subnetworks are in some cases supporting life-critical services that would not allow for any interruption. In that respect, 6G in-X subnetworks can be seen as a further leap to the concept of heterogeneous networks, aiming at improving data rates and the reliability of wide area connectivity by offering capillary coverage [18].

In this paper, we present our 6G in-X subnetworks concept by using a top-down approach. We start by introducing motivation, opportunities and possible use cases and deployments for these short-range low power cells. We then narrow our focus to the lower layer aspects of the design. We first discuss the possible operational spectra and the potential air interface technology components, along with major challenges and threats. Emphasis is then given to the problem of inter-cell interference and jamming as potential showstoppers for life-critical operations. Finally, we present a qualitative example of a system design able to deal with their effects.

Note that, while the existing 6G literature referred to above is mainly focused on introducing novel technologies and discussing possible applications in a plethora of use cases, in this article we take the opposite approach. We present specific scenarios and use cases characterized by hyper-dense short-range cells supporting extreme requirements and elaborate on the technologies for achieving such requirements. To the best of our knowledge, no article presented in the recent literature has discussed in detail the challenges and opportunities offered by short-range communications supporting extreme requirements.

The main contributions of this article can be summarized as follows:

- Consider the specific set of scenarios and use cases characterized by short-range links and extreme requirements,
- Identify the specific challenges hindering the achievement of these extreme requirements in such dense scenarios,
- Provide a holistic view of the technology components that could overcome these challenges, also proposing new research directions.

# Why in-X subnetworks?

As suggested by the acronym, 6G in-X subnetworks are to be installed in specific entities such as in-vehicle, in-body, in-house, etc., as depicted in Figure 1. In our vision, an in-X subnetwork should have the following characteristics:

- Support of extreme communication requirements, either in terms of data rate, latency and/or reliability, even when out of wide area coverage. Applications with moderate requirements should eventually be supported together with the most demanding ones.
- Low transmit power in both uplink (UL) and downlink (DL), translating to limited coverage range. Eventual range extension can be obtained via multi-hop transmission.
- Star or tree topology. An in-X subnetwork should have a hierarchical structure where an access point (AP) controls the operations of the connected devices. For applications with non-extreme latency requirements, some of the connected devices can eventually act as relays and forward traffic to other devices.
- Lack of mobility across subnetworks. Due to the nature of the deployments, each device can only be connected to a single AP for the entire operation time. Subnetworks can, however, be mobile, such as the ones installed in vehicles or in humans.

Note that in our vision, all four characteristics must be present to define a 6G in-X subnetwork, because the lack of just one would end up in a use case already tackled by other technologies. For example, if we do not target extreme communication requirements, then all the remaining aspects define a typical wireless personal area network use case, with Wi-Fi, Bluetooth or ZigBee as good candidates [19].

Short-range communication with a range of up to 10 m can ensure the required service level for local connectivity in the specific location where needed, reducing the risk of potential coverage holes that may appear in case a broader cellular infrastructure is to provide the same service. Short-range communication is obtained by using very low transmit power, in the order of 0 dBm or below.

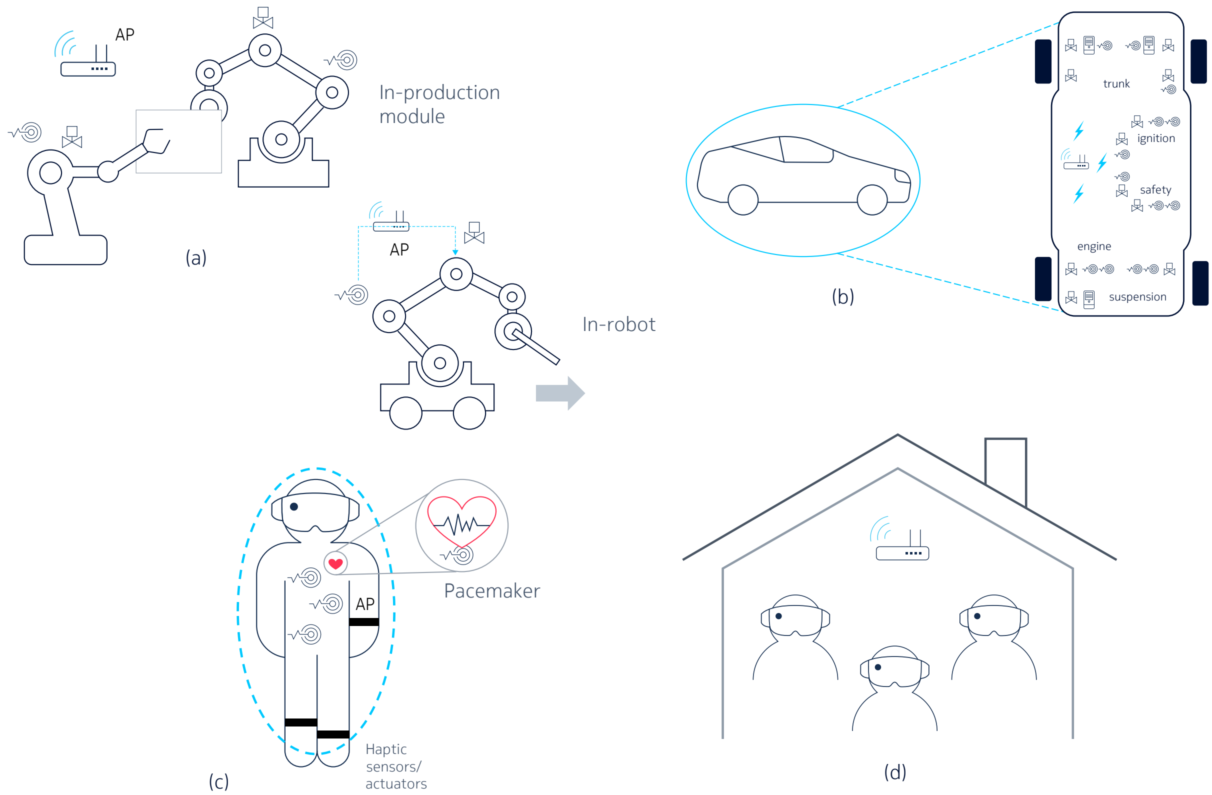
Low transmit power short-range communications also have spectral efficiency benefits. Modern radio interfaces introduce guard periods, e.g., the cyclic prefix (CP) in case of orthogonal frequency division multiplexing (OFDM), to accommodate delay spread. Short-range cells will lead to a low delay spread, and therefore enable an air interface with a guard period having minimum duration. For example, our early short-range measurements in industrial scenarios have revealed that the 90th percentile maximum excess delay is about 150 ns in the 3–8 GHz frequency range [20]. This reduces system overhead and therefore improves the spectral efficiency. On the other hand, it also imposes a requirement for time synchronization among the devices on the same in-X subnetwork that is at least one order of magnitude below the 1 μs targeted by 5G [21].

In contrast to wide area networks, in which there is a large difference between UL and DL power [22], the use of comparable low transmit power for both UL and DL prevents major interference imbalances and their disruptive effects due to lack of synchronization among the subnetworks.

## In-X subnetworks as parts of a larger network

In-X subnetworks should be able to handle traffic flows with different characteristics. High critical data flows require latencies << 1 ms and reliability beyond five nines. Medium critical flows have latencies > 1 ms and a maximum of five nines reliability. Non-critical flows have non-strictly limited latencies. For in-X subnetworks, the high critical traffic is locally generated. Many in-X subnetworks support control operations in production modules, vehicles, human bodies, etc., and feature a star topology where the AP communicates with devices as wireless sensors or actuators. The AP should have integrated controller capabilities, or eventually be connected to a co-located embedded edge server [23].

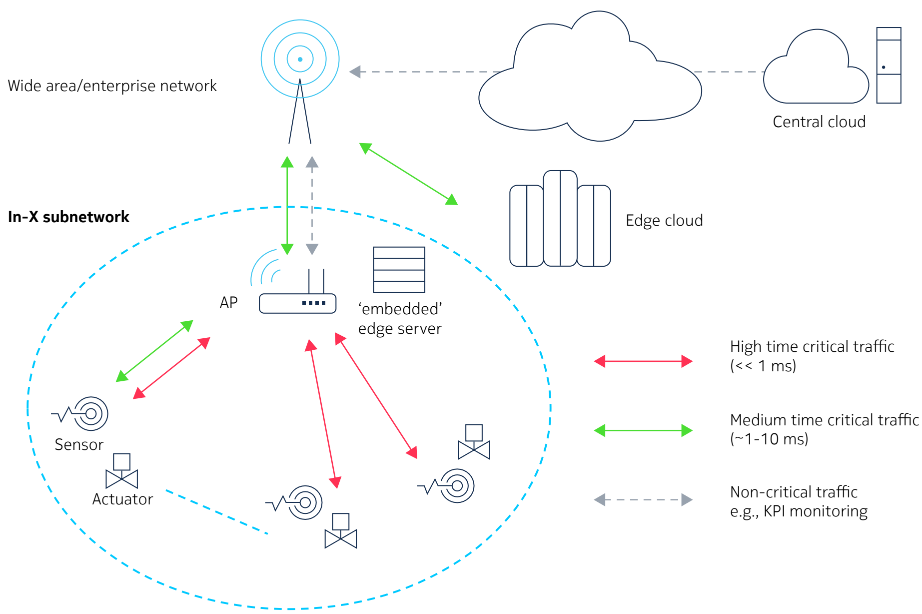
Figure 1. Examples of installations for (a) industrial, (b) in-vehicle, (c) in-body and (d) in-house subnetworks




The AP receives measurements from the sensors, which are processed by the controller that then issues commands to the actuators. The high critical data flows are thus kept within the in-X subnetwork, as the tight latency requirement does not allow for external processing. Medium critical data flows can eventually be processed in an edge cloud or cloudlet [24]; subnetworks can then be connected to an external network hosting these edge processing capabilities. Also, the AP can collect data and statistics on KPIs to be shared to the outside world and processed in the central cloud. The principle is illustrated in Figure 2 and will be further outlined in the next section.

As mentioned in the introduction, subnetworks are expected to be part of a larger 6G system. We foresee significant benefits in being connected to the external world via the same 6G radio system rather than using a different technology such as 4G/5G for vehicles, or Wi-Fi for indoor factories. In this respect, the AP behaves as a user equipment (UE) from the perspective of the 6G system and can access the wide area network for traffic/control transmissions with medium or non-critical flows. In particular, the AP can realize functions such as device-to-network relaying between the in-X devices and the 6G wide area network. Within the in-X subnetwork, depending on the application scenarios, the AP may behave as a UE-like node or a base-station-like node from the perspective of the in-X devices. In the current 5G architecture, this corresponds to the realization of the PC5 and Uu interfaces, respectively [25]. On the other hand, for instance in the former case, the requirements for the AP in the in-X subnetwork are beyond what is currently supported by 5G PC5 and could be achieved only by adding additional control and/or management functions over the other in-X subnetwork devices.

Figure 2. Data traffic flows in and out an in-X subnetwork




Future 6G networks are also expected to feature advanced authorization, resilience and security features, as well as evolved traffic policies that can be pushed to the devices in the in-X subnetworks [2] [26]. Also, the multiplexing of services partly handled within the in-X subnetworks and partly in an edge cloud can be more efficiently supported in terms of radio resource management by a same air interface. A 6G macro network can, moreover, take care of coordinating the interference among in-X subnetworks in its coverage area (discussed further below).

# Use cases and requirements

In the following, we present different examples of use cases for in-X subnetworks whose requirements in terms of latency, reliability, throughput and density are presented in Table 1. Requirements can be quite heterogeneous and depend on the specific use case. However, they represent a clear breakthrough when compared to 5G and reach the ultimate values envisioned for 6G. We claim that extreme communication in subnetworks should entail the support of at least one of the following sets of requirements:

- Minimum latencies below 100 μs with service availability above five nines,
- Link data rates above 5 Gbps with service availability above five nines and latencies below 20 ms,
- Service availability of nine nines with latencies below 20 ms.

These are tentative requirements, as more detailed values will be defined at the beginning of the 6G standardization phase.

Note that in 5G there was no specific enhancement for very short-range communications as targeted by our in-X subnetworks concept. For instance, while the 5G vision contemplated the usage of wireless for control of mobile robots or production modules with latencies of 0.5 ms or more [27, Table 5.21] and ranges up to hundreds of meters, our 6G in-X wireless system is expected, as we will detail in the remainder of the section, to replace the wired connectivity within a robot or a production module, with latencies down to 100 µs. Not all services and applications require such performance, and one of the challenges is integrating or accommodating services with extreme and relaxed requirements in the same air interface.

Requirements are based on the current wired standards and protocols that support these use cases. For characterizing reliability in cyber-physical control applications, 3GPP has introduced new quality of service (QoS) requirements like communication service availability, communication service reliability, mean time between failures and survival time [27].

In contrast to use cases characterized by mobile broadband, where packet error rate is a good metric to quantify reliability, these control applications are often characterized by small packets with semi-periodic traffic. Thus, while losing a single packet does not cause much harm to the system, extreme requirements are set on a sequence/burst of errors [28], with the length of the burst potentially going up to a relatively high number like six in certain scenarios [29]. For in-X subnetworks, therefore, we also consider similar metrics. In Table 1, we indicate the communication service availability. This is the percentage of time the service is delivered according to agreed QoS requirements. The system is considered unavailable when an expected packet is not received within the sum of maximum allowed latency and survival time [27, Section 3].

Besides the metrics introduced in Table 1, other KPIs can be considered depending on the specific use case. Strictly connected to the survival time and communication service availability is the age of information. This metric is introduced to quantify the freshness of information of a remote system and defined as the time elapsed since the generation of the last successfully received packet [30]. Specifically for control loops, another useful metric is the probability of loop failure (PLF). This measures the service spatial availability and is defined as the probability that a control loop experiences an outage below a predefined target value [17]. For malicious attacks like jammers, important metrics to evaluate the detection capabilities of the system are the false alarm and missed detection rates [31]. A false alarm declares a jamming attack that did not take place. Missed detection occurs when a jammer goes undetected. Finally, new metrics could be developed that relate to the extreme reliability requirements envisioned for subnetworks supporting life-critical services. If developed in the context of extreme value theory [32], these metrics could be useful for characterizing extremely rare events that, despite their rarity, can still hinder communication.

The communication requirements presented in Table 1 are intended as the most extreme ones to be satisfied in the best operational conditions. Nonetheless, for some of the use cases these requirements can eventually be relaxed if the corresponding application requirements can also be relaxed. This will be further discussed in the section on interference management, below.

## Industrial in-X subnetworks

We consider a possible Industry 4.0 scenario where mobile robots are transporting materials over a set of manufacturing stations distributed in an industrial area. In current wireless manufacturing setups, the general operations of the mobile robots and manufacturing station are instructed by a central fleet manager using a 5G or Wi-Fi network [33]. In the future, we assume that each robot and production module is also equipped with a 6G in-X subnetwork. Such subnetworks are expected to cope with the critical applications running nowadays over wired links with protocols like EtherCAT that guarantee latency within 100 µs [34]. For example, subnetworks installed in a manufacturing station can control the force applied to torque, grippers and robotic manipulators and their precision. Similarly, the subnetwork installed in a mobile robot controls the precision of the robot movements as well as proximity of other robots or obstacles in their path.

Services originating in the in-X subnetworks but having more relaxed requirements, e.g., control of slowly moving parts, can eventually be processed in an edge server installed in the factory facilities using a 6G local area connection. This way, the processing capabilities of the in-X controller or embedded edge server can be limited to the most demanding services only. The AP in each subnetwork can collect statistics and KPIs from the supported control loops. For example, it can transfer jitter patterns statistics from the sensors, which can then be processed by the local or edge cloud server [35]. This server can make use of machine learning techniques to identify potential anomalies in the behavior of the robots and eventually take actions such as stopping the robot if it identifies a possibility that it will reduce production efficiency or create a hazard.

## In-vehicle subnetworks

In-vehicle subnetworks are meant to replace the controller area network (CAN) bus [36] and automotive Ethernet [37] operations with wireless, translating to a lower vehicle weight and therefore lower fuel/power consumption. In that respect, in-vehicle subnetworks can take care of motor control, power steering, anti-lock braking system (ABS), etc. Data traffic can be highly critical with latencies in the order of 100 μs and down to 54 μs for high priority trigger messages [38, Section 3]. Also, critical traffic may coexist with high data rate applications for advanced driver-assistance systems (ADAS) such as video feeds from cameras for reversing aid, adaptive cruise control and traffic sign recognition [39].

Data gathered by an in-X AP installed in a vehicle can be transferred via cellular connection to roadside units, which can identify possible anomalies in the braking system, or in the engine, and issue a warning message to the vehicle. This can improve road safety by preventing possible accidents. Note that the applications for in-X subnetworks are complementary to other radio technologies involved in vehicular communication, such as vehicular-to-vehicular services for platooning, lane changes, forward collision warnings and intersection movement assist [40].

Besides cars and trucks, we envision another important application of the in-vehicle subnetworks in avionics, where wireless communications can be used to get rid of the large weight of cables to connect all sensors, controllers and actuators in an aircraft [41]. Multiple in-X subnetworks may need to be installed across the multiple segments of the aircraft, including wings, and a centralized controller can take care of coordinating their operations for ensuring flight stability control using, for instance, flaps, spoilers and slats actuation.

Table 1. Use cases and requirements for in-X subnetworks

| Use case | In-robot, in production module | In-vehicle | In-body | In-house |
|---|---|---|---|---|
| Example of applications | Motion control, force/ torque control, position/ proximity control | Engine control, electric power steering, ABS, electric park brakes, suspensions, ADAS sensors | Heartbeat control, vital signs monitoring, insulin pumping, muscle haptic control | Entertainment, gaming, training, education, healthcare (robotic-aided surgery) |
| Number of devices | ~20 (motion/force control)<br>~20-40 (mobile robots) | ~50-100 | <20 | ~10 |
| Max range | ~5 m | ~10 m | ~2 m | ~10 m |
| Data rate per link | <10 Mbps | <10 Mbps (control)<br><10 Gbps (ADAS sensors) | <20 Mbps | ~7 Gbps (ultimate VR) |
| Traffic type | Periodic, event-based | Periodic, event-based, uncompressed video streaming | Periodic, event-based | Event-based, compressed video streaming |
| Min latency | ~100 μs | ~54 μs | ~20 ms | ~5 ms (VR)<br>~2 ms (healthcare) |
| Communication service availability | 99.9999% to 99.999999% | 99.9999% to 99.999999% | 99.9999999% | 99.9999% (VR)<br>99.999999% (healthcare) |
| Max subnetwork density | ~40,000 / km$^2$ | ~150 / lane-km (car)<br>~15 / aircraft (~ 80 m long) | ~2 / m$^2$ | ~1 / room |
| Life-critical | No | Yes | Yes | No (entertainment, gaming, training, education)<br>Yes (healthcare) |
| Criticality of power consumption | Low | Low | High | Low/medium |

## In-body subnetworks

This use case describes subnetworks made by devices installed in a human body, either on the surface (e.g., wearables, skin patches, sensors for temperature and blood pressure) or in implants (e.g., pacemaker, insulin pump and muscle controllers). The AP can be a wristband or even a brain implant [42] that controls the operations of the connected devices. A wireless pacemaker controls heartbeat; it can be installed with a catheter and does not require a traumatic chest incision [43]. Implants such as wireless insulin pumps [44] ensure the right glucose level is maintained in diabetic patients. Muscle controllers can enable movements in patients with motor disabilities [45].

In-body subnetworks can also enable exoskeletons as structural mechanisms whose joints are connected to human joints for empowering their actuating capabilities [46]. The wristbands or brain implants can be connected to an external network for real-time monitoring of health parameters, and eventually require prompt actions. For example, the wristband can identify residual anomalies in heartbeat patterns that cannot be handled by the pacemaker and connect to the hospital for early intervention.

The performance requirements of in-body subnetworks may not be extreme either in terms of data rate or latency. However, applications are life-critical, and it is of fundamental importance that the required service level is delivered to the patients without interruption. Moreover, operations are necessarily battery-driven, with expected battery life in the order of years. This leads to major energy consumption constraints, which should be handled by the radio design.

## In-house subnetworks

In this category, we target applications with traffic flow between devices and units that stay in the same house or, in some cases, the same room. This is typically associated to high throughput, not latency limited applications. As an example, in-house subnetworks support gaming with extended virtual reality (VR) [47], where several people, each with multiple smart wearables (e.g., glasses, armbands) play with the support of a console connected to all the devices [48]. For other applications, the content can be received from the external network and stored in a local device acting as an AP, which delivers content to the connected users such as interactive movies with 8K definition. Besides high data rates, certain applications can require haptic feedback, which demands latency of less than a few ms. An example of this use case is full body haptic suits worn in VR applications, or cutting-edge haptic feedback for surgeons during robotic-aided surgery [27].

# Spectrum aspects

Support for the extreme communication requirements of in-X subnetworks calls for the use of a large spectrum band. Our initial performance analysis [17] suggests that the requirements of in-X subnetworks in industrial scenarios, as depicted in Table 1, will be several hundreds of MHz. This means the licensed spectrum below 6 GHz, commonly used for mobile communications, is not a viable solution as it is already overcrowded. While lower frequencies benefit from favorable propagation conditions and better diffraction across objects, translating to a better robustness to non-line-of-sight shadowing, the bands available above 20 GHz are significantly larger.

Due to the heterogeneous requirements and characteristics of the considered in-X subnetworks, we believe both licensed and unlicensed spectrum options are to be used, depending on the specific use case. The licensed option calls either for a contract between a mobile operator and a vertical or for bands directly issued by governments to the verticals. This has the obvious benefit of exclusive access to the spectrum and therefore controllable interference. It can be applied to static deployments with fixed or nomadic cells, such as cells installed in production modules or mobile robots in a factory. The mmWave 26-28 GHz band represents a possible solution given the amount of available spectrum (around 3 GHz) [49]. In the case of mobile cells, such as in-body and in-vehicle, the use of licensed spectrum can be problematic as it requires a roaming agreement among countries to ensure service continuity across borders.

The unlicensed spectrum in the 5, 6, and 60 GHz bands has the advantage of not being subject to any license costs. It also unleashes opportunities for flexible installations across regions and would fit well, for instance, for in-vehicle and in-body subnetworks. On the other hand, unlicensed spectrum raises major challenges in terms of coexistence and interference that can severely hinder the possibility of achieving the extreme requirements. Also, current regulations of many countries/regions in such bands require the usage of a listen before talk (LBT) procedure for channel access; each device needs to sense the channel and eventually defer its transmission if the channel is occupied [50]. While LBT can be used for applications which are not delay-tolerant, it is clearly a showstopper for time-critical traffic.

LBT has been a very good technique for efficiently sharing unlicensed spectrum and guaranteeing fairness among different devices and different technologies. However, its fundamental principle of just “waiting if the channel is occupied” collides with time critical requirements. In-X subnetworks target a latency on the order of 100 μs. We believe the use of such bands for this type of traffic would be possible only if potentially new disruptive regulations are introduced that better match with periodic and latency-critical traffic. The regulations could grant spectrum access, for example, using criteria based on adaptive frequency or channel hopping, duty cycle, or a very low level of maximum transmit power, as is done, in part, for 2.4 GHz [51]. These kinds of criteria are under discussion in Europe and the United States (US) for the opening of the 6 GHz band [52].

We also foresee the opportunity of opening new unlicensed bands dedicated to specific in-X subnetwork use cases such as in-body and in-vehicle. The process can be analogous to the one for dedicated short-range communications (DSRC), where 75 MHz of dedicated spectrum in the 5.9 GHz band has been allocated by the Federal Communications Commission (FCC) in the US [53], although a significantly larger bandwidth will be needed for in-X subnetworks. Such bands represent a greenfield where new regulations tailored to the specific needs of in-X subnetwork can be established.

Sub-terahertz bands (from 90 to 300 GHz) are considered as the new frontier of wireless communications. 6G research is considering their usage for mobile use cases and extreme throughput services [2], with short-range communications as a potential use case because of the limited path loss. Even if sub-terahertz bands have already been in use for imaging [54] and body scanning [55], their use for life-critical services is disputable due to poor performance in non-line-of-sight conditions, which are the most common for in-X subnetworks. Nonetheless, we foresee the possibility of using sub-terahertz bands for scenarios where the AP antennas can be distributed across the subnetwork area, in order to counteract possible blockage effects.

Another interesting possibility is to operate 6G in-X subnetworks as an underlay system over spectra allocated to licensed systems. Ultra-wideband (UWB) regulations allow for spectrum access in the 3.1–10.6 GHz region, with a maximum spectral density of -41.3 dBm/MHz and a constraint on minimum instantaneous bandwidth (e.g., 500 MHz according to the FCC) [56]. The use of low-power spectral density combined with wideband transmission leads to negligible interference to incumbent systems operating over the same spectra. Incumbent systems are seen as narrowband interferers by the UWB links, which can easily recover the lost bits of information via channel coding. The UWB approach is, therefore, a good match with in-X subnetworks as they operate with low transmit power and need to access a large spectrum.

In our view, current UWB regulations can still be over-restrictive for dense deployments, where the cumulative power can be several orders of magnitude larger than the limits allowed by regulations. Nonetheless, regulations disregard the effective activity of the incumbents at a given time and location. As we expect new spectrum sharing arrangements in the 6G time frame, we foresee the possibility of disruptive spectrum regulations also for UWB. Intelligent in-X subnetworks might be allowed more relaxed limits in terms of power spectral density in case they are able to dynamically select spectra where incumbents are not active on a temporal and/or geographical basis. Subnetworks are therefore expected to be cognitive, and feature modern AI techniques that learn and predict the incumbent activity in order to select the proper spectrum resources and not affect incumbent operations. We believe such AI-based spectrum access is a major topic of future research and can truly unleash the potential of in-X subnetworks.

As a concluding remark, while the main new spectrum-related aspect of 5G was the use of mmWave bands mainly for supporting higher throughput, we envision at least three disruptive directions regarding spectrum for 6G in-X subnetworks. First is new regulations that allow more flexible use of unlicensed spectrum to support truly high-critical traffic. Second, more dynamic sharing arrangements among incumbents and subnetworks when the latter are operating as an underlay system. Third, the potential use of sub-terahertz bands needs to be studied to understand whether they can really be leveraged to support extreme requirements.

# Air interface components

The main challenges in the design of the air interface for in-X subnetworks stem from the need for supporting extreme requirements in terms of data rate, latency and reliability, as well as from the heterogeneity of the targeted use cases. As shown in Table 1, some are characterized by periodic traffic with extremely low latency in the order of 100 μs, and others have a low but more relaxed latency constraint of a few ms, but require very high throughput in the order of several Gbps.

A recent branch of wireless communications research investigates disruptive air interface designs based on AI [57] [58]. The vision is to replace traditional heuristic approaches for data transmission and reception with machine learning blocks that can autonomously learn the proper transmission modes based on a training phase over the actual operational channel. This approach has the advantage of tailoring the transmission and reception processing to the specific radio characteristics where the system is operating, including hardware impairments, rather than exploiting generic algorithms and protocols. On the other hand, the design of an air interface able to support extreme heterogeneous requirements can benefit from a decade of domain knowledge, and 5G has already been developed to support unprecedented flexibility in radio design [59]. We therefore recommend in a first phase to use established technology components for air interface design for in-X subnetworks. Later, the design may include some of the disruptive machine learning elements that are proved to be successful.

In this section, we introduce possible basic air interface components for in-X subnetworks, capitalizing on the knowledge of previous radio technologies. The main envisioned air interface features for in-X subnetworks are summarized in Table 2, along with other characteristics that will be presented in the next sections. Note that subnetworks are by design non-cooperative, and operate independently. As mentioned above, they can eventually communicate with a wide area network, but direct communication among subnetworks is not considered. In the air interface description, we will focus only on communication within a subnetwork.

## Physical layer (PHY)

OFDM has been selected as the radio waveform in 4G and 5G for its cost-effective implementation and ability to efficiently cope with multipath fading [60]. Also, single carrier frequency division multiplexing (SC-FDM) waveform, a.k.a. discrete Fourier transform (DFT) spread OFDM (DFTs-OFDM), can be obtained as a straightforward add-on to OFDM [61] and has the benefit of a low peak-to-average power ratio (PAPR). Given the need for flexibility, the OFDM subcarrier spacing (SCS) in 5G, reflecting the symbol duration, is not fixed as in previous radio generations. It can take a set of different values depending on the service to be supported as well as on the operational spectra. Low latency services and high carrier frequencies are benefiting from large SCS (e.g., 60 kHz and above), while small SCS (down to 15 kHz) offers better tolerance to multipath fading and improved frequency granularity.

We believe a multi-carrier modulation will also be the fundamental waveform for 6G in-X subnetworks, with OFDM being the strongest candidate. Services demanding sub-ms latencies can be associated to very large SCS and short OFDM symbol duration. According to our initial studies, SCS of at least 120 kHz is needed to support 100 μs control loops while leaving a margin for processing at the controller [17]. Applications demanding higher throughput can eventually use smaller SCS down to 60 kHz. It might be challenging, however, to use even smaller SCS, as that would require a very large DFT size given the expected bandwidth of several hundreds of MHz. In contrast to 5G, where the CP is in the order of a few μs for smaller SCS, the low delay spread with in-X subnetworks enables the use of a significantly lower CP, in the order of few hundreds of ns, thus improving spectral efficiency. For use cases with strict energy consumption constraints such as in-body subnetworks, it can be advantageous to have single carrier options such as SC-FDM.

For services demanding sub-ms latencies and high reliability with limited spectral efficiency demands, quadrature amplitude modulation (QAM) with lower order constellations like QPSK and 16-QAM will be sufficient. For high throughput delay-tolerant applications, higher order constellations up to 4096-QAM will be needed to properly exploit the large signal-to-interference plus noise ratio (SINR) that could be experienced in such short-range communications [62]. Adaptive modulation and coding (AMC) can eventually be used to take advantage of the different experienced SINR conditions [63]. As mentioned earlier, for time-critical traffic the set of possible modulation and coding schemes (MCSs) can be limited; AMC can be conservative and based on the tail of SINR or interference distributions [64]. Nonetheless, AMC can help reduce the time-on-air for each transmission in the case of advantageous channel conditions, with benefits in terms of lower power consumption and interference footprint.

Multi-antenna techniques are a must for either counteracting small scale fading (enhancing reliability) or achieving high throughput via spatial multiplexing and should be part of 6G in-X design. Nonetheless, in most cases, the nature of in-X subnetworks calls for small form factor devices and APs, which prevent the use of large multiple-input multiple-output (MIMO) antenna arrays, especially in the case of low carrier frequencies. The use of multi-antenna techniques with a small number of antennas is not, however, sufficient to harvest the necessary diversity or multiplexing gain for achieving extreme requirements, and should be accompanied by large spectrum.

For certain types of deployments where a number of wired connectors can be installed, the multiple antennas of the AP can be placed in different positions in the in-X subnetwork area. This way, the AP acts as a distributed antenna system with benefits in terms of large-scale fading mitigation [65]. An example can be in-vehicle subnetworks where antennas can be in different positions in the chassis to avoid signal blocking between sensors and actuators. The robust avoidance of blockage can make sub-terahertz bands a possible solution for scenarios where a distributed antenna system can be installed. For in-X subnetworks supporting applications with non-extreme latency requirements, cooperative relaying techniques can also be used to increase spatial diversity [66].

## Medium access control (MAC)

In the last years, there has been much attention within MAC research on non-orthogonal multiple access (NOMA) [67] [68] and random-access schemes [69]. They promise improved spectral efficiencies and support for large numbers of devices, especially for massive access scenarios. This comes at the expense of extra complexity, however, as receivers need to be equipped with interference cancellation capabilities. As well, though the subnetwork density can be very high, the number of devices that need to be supported in a subnetwork is relatively limited, as shown in Table 1. That reduces the potential advantage of NOMA or recent random-access schemes for subnetworks. The limited number of antennas expected in a subnetwork AP, moreover, may prevent the use of efficient multi-antenna NOMA schemes [70].

We believe, therefore, that transmissions in a subnetwork should be made orthogonal, whenever possible, with the AP scheduling resources for each device. In particular, the use of orthogonal transmissions improves reliability, preventing subnetworks from suffering intra-cell interference. Contention-based schemes are known to be efficient for supporting best effort data rates but are unsuited for periodic traffic or for traffic with guaranteed delays [71]. As subnetworks are expected to support diverse types of traffic, however, contention-based schemes can eventually be used for such best effort services, while orthogonal resources can be allocated to the services with guaranteed requirements.

It is worth mentioning that another exception to the use of orthogonal transmissions is represented by the overlay transmission of sporadic low latency packets, which will be described later in this section. NOMA schemes can eventually also be used for high data rate applications in those subnetworks equipped with interference cancellation receivers. Identifying specific applications in subnetworks that can benefit from NOMA is left for future work.

Fast control loops with isochronous deterministic traffic can, for example, be supported by semi-persistent scheduling, with orthogonal radio resources pre-allocated to each device. Semi-persistent scheduling has the clear advantage of preventing signaling exchange between the devices and the AP for each packet transmission. Also, the scheduler is, in this case, significantly simplified as packet arrivals are known in advance.

Traditional cellular networks rely on retransmission schemes such as hybrid automatic repeat request (HARQ) to deal with transmission failures [72]. This is known to improve reliability without significantly impacting spectral efficiency. However, HARQ requires a transmitter to wait for reception of a feedback message with a negative acknowledgement upon a transmission failure before a retransmission can be initiated. Moreover, the feedback message is error prone, leading to occurrence of possible false positives. This prevents the use of HARQ for services with tight latency requirements (e.g., ~100 μs).

Promising technology components for applications with tight latency requirements are instead blind packet repetitions, eventually combined with channel hopping for the sake of harvesting frequency and interference diversity. As the term suggests, in blind repetition schemes a packet transmission is repeated multiple times to proactively counteract potential failures. The obvious price to pay is in spectral efficiency as resources are pre-allocated to the multiple transmissions regardless of the effective channel quality. We refer to [73] [74] for a detailed comparison between blind packet repetitions and HARQ-based retransmissions in an ultra-reliable low latency communication context.

Event-based, low latency traffic such as stop alarms can, instead, exploit pre-emptive scheduling techniques. Resources allocated to best-effort traffic can be rapidly emptied for supporting sudden critical packets [75]. This allows resources to be instantly allocated for transmissions that may only happen sporadically, with a small or negligible penalty for best-effort traffic. While pre-emptive schemes are a suitable solution for the DL, overlay transmission of event-based packets with best-effort traffic can be considered in the UL to avoid delays associated with scheduling request and grant [76]. As shown in [77], this may require specific power control settings for the sporadic traffic and the use of a successive interference cancellation receiver [78].

High throughput applications can inherit aspects of 5G design for broadband traffic. Traditional grant-based procedures can be used, and AMC can operate here at a fast pace to exploit the instantaneous channel conditions and enhance spectral efficiency. HARQ can be used for retrieving errors due to imperfect channel quality reports or sudden variations in channel quality. In general, the use of HARQ is also beneficial for reducing the interference footprint and is, therefore, recommended for applications that are not strictly latency-limited and tolerate the delays associated with transmission and reception of acknowledgement messages. Rank adaptation can also be used to adapt the number of spatial streams to the channel and interference condition [79]. Power control that leverages unused resources in non-congested cells can, furthermore, be used to reduce the generated interference [80], which is beneficial both for increasing throughput and serving traffic with moderate latency requirements, that is, in the order of tens of ms [81].

Special care should be spent in the design of medium access control components for battery-driven subnetworks, such as in the in-body case. These subnetworks do not feature extreme requirements in terms of latency and throughput. Traditional grant-based approaches with HARQ can also be preferable for the control traffic as they avoid the energy waste of blind repetitions.

### Duplexing

Regarding the duplexing mode, when compared to time division duplex (TDD), frequency division duplex (FDD) has a clear advantage for low latency applications as it allows direct access to the channel for the devices that have a packet to be transmitted. On the other hand, FDD requires paired bands, which are scarce, thus 5G deployments are mainly considering TDD. In fact, TDD benefits from better spectrum utilization, as it does not require a bandwidth separation of DL and UL, and lower device costs [82]. Moreover, as the strictest latency requirements are often associated with isochronous traffic — packets whose arrival time is easily predictable and regular — our initial analysis shows that a TDD system with a properly designed frame structure [17] can support a loop cycle of 100 μs.

For event-based traffic with low latency, a further option is to consider full duplex (FD) radios [83] that allow transmission and reception on the same band. Self-interference (SI) cancellation is needed, making the devices more complex, but the low transmit power of in-X subnetworks make the SI cancellation with FD more efficient. There is also a low complexity FD option known as flexible FDD [84] that allows use of unpaired bands in a semi-FDD mode, with a limited number of blanked subcarriers used as a sort of guard band between UL and DL allocation. Simpler SI cancellation is sufficient with flexible FDD because of the baseband frequency separation of DL and UL signals.

For in-X subnetworks supporting heterogeneous services such as in-vehicle with sub-ms control loops and high data rate flows for ADAS sensors, further flexible duplexing options can be envisioned. For example, the allocated band can be organized in sub-bands that are scheduled to the different services, each one operating in TDD but with its own specific UL/DL switching point. This scheme still requires SI cancellation at the AP. This is less complex when compared to FD, however, because of the baseband separation of the different service data flows, similarly to flexible FDD.

## Interference management as a major challenge

The installation of in-X subnetworks can easily lead to dense scenarios, thus, to potentially high interference levels. Typical examples include vehicles on a congested road and humans attending sport or music events. In some cases, subnetworks can even share the same physical location, for example, an in-body subnetwork installed in a person sitting in a car with its own in-vehicle subnetwork. The short-range transmission, the use of large spectrum and the spatial and frequency diversity are expected to make the desired receive signal sufficiently strong, but it also potentially makes external interference a limiting factor, especially for life-critical services. The air interface components mentioned in the previous section, such as blind repetitions combined with channel hopping, offer a tier of protection to the interference but might not be sufficient for ensuring high reliability. This calls for additional mechanisms for managing spectrum resources.

Note that, interference management is more challenging for 6G in-X subnetworks than 5G, given the potentially higher cell density, as well as the cell mobility that leads to different interference behavior than what is experienced in typical cellular setups with static base stations. The performance requirements in terms of latency and/or reliability can also be significantly stricter than in 5G. Typical reactive approaches used in 5G interference management, where resource allocation decisions are usually operating on a relaxed time scale and sporadic errors may be tolerated, should be discouraged for 6G in-X subnetworks, at least for those services demanding fractions of ms latency. We believe, rather, that interference management for in-X subnetworks should be proactive and prevent packet losses that might hinder the support of life-critical services.

Interference management can operate on the frequency, time and spatial domains [85]. Interference coordination schemes based on the time domain, however, are to be disregarded for in-X subnetworks supporting low latency services. Similarly, spatial coordination solutions based on beamforming may be ineffective given the limited AP and device form factors, which only allow a low number of antennas, especially for low carrier frequencies. Interference management for in-X subnetworks should then operate on the frequency domain, by dividing the available spectrum in several frequency chunks to be selected or assigned to the subnetworks so that mutual interference is minimized.

Table 2. In-X subnetworks relevant features

<table>
<tr><td>PHY and MAC</td><td>Isochronous traffic with <100 μs cycles<br>• OFDM waveform<br>• Short CP (up to 400 ns)<br>• Large SCS (≥120 kHz)<br>• QPSK, 16-QAM<br>• Single stream MIMO<br>• Semi-persistent scheduling<br>• Blind packet repetitions<br>• Channel hopping<br>• TDD</td><td>Event-based traffic with low latency<br>• OFDM waveform<br>• Short CP (up to 400 ns)<br>• Large SCS (≥120 kHz)<br>• QPSK, 16-QAM<br>• Single stream MIMO<br>• Pre-emptive scheduling<br>• Blind packet repetitions<br>• Channel hopping<br>• TDD, FD, flexible FDD</td><td>High data rate traffic<br>• OFDM waveform<br>• Short CP (up to 400 ns)<br>• SCS ≥60 kHz<br>• Up to 4096-QAM<br>• Multi-stream MIMO (up to 4 streams)<br>• Grant-based scheduling<br>• Fast link adaptation<br>• Rank adaptation<br>• TDD</td></tr>
<tr><td>Spectrum</td><td colspan="3">Licensed<br>• Suited especially for static or nomadic subnetworks, either contract between vertical and operator or government issued bands needed<br>• Possible bands: 26-28 GHz<br><br>Unlicensed, shared with other technologies<br>• Suited for mobile subnetworks, flexible installation<br>• Possible bands: 5 GHz, 6 GHz, 60 GHz, sub-terahertz (new regulations other than LBT needed to support isochronous traffic)<br>Unlicensed, dedicated spectra to in-X subnetworks<br>• Greenfield bands where new regulations tailored to the needs of in-X subnetworks can be established<br>Underlay, e.g., UWB<br>• Possible bands: 3.1-10.6 GHz (new regulations needed with more dynamic limits on the power spectral density)</td></tr>
<tr><td>Interference management</td><td colspan="3">Centralized<br>• Reliable connection with a central controller needed<br>• Efficient in terms of spectrum utilization<br>• Insufficient for life-critical subnetworks, as dependent on the quality of connection with the external central controller<br>Distributed and implicit<br>• Needed to complement or substitute centralized techniques for autonomous or out-of-coverage life-critical subnetworks<br>• Solution space includes heuristic approaches, Bayesian optimization, reinforcement learning solutions<br>Hybrid<br>• Relying on centralized coordination when in coverage area of a mobile operator, while using distributed implicit coordination when out of coverage<br>• Suited for battery-driven subnetworks, e.g., in-body<br>Dealing with additional sources of interference<br>• Jamming detection based on pilot/data transmission and time, frequency, and spatial resource blanking<br>• Jamming mitigation applying conservative link adaptation, frequency hopping, transmit pattern scrambling, and advanced MIMO<br>• Exploit spatial, frequency and time diversity to increase robustness against impulsive noise</td></tr>
</table>

It is known from the literature that centralized interference coordination typically outperforms distributed schemes [86]. This leads to more efficient use of spectrum, thus the ability to support a larger number of links with predefined performance requirements per subnetwork. However, centralized coordination requires a communication link between a central control element and each of the subnetworks that periodically reports signal quality metrics to be used for taking decisions on the portion of spectrum to be used at a given time. Also, centralized schemes are applicable to licensed spectrum only or to controlled deployments where all the subnetworks operating in that band can be managed by the same control element.

Spectrum management solutions to be used thus depend on the deployment and the type of in-X subnetwork. In-factory deployments with a unique wireless service provider can benefit from such centralized interference management. In the case of subnetworks associated to fixed production modules, the spectrum can be assigned in a static or semi-static manner. For robots navigating across the factory, spectrum allocation can instead be dynamic. The central controller can track the position of all the robots and allocate resources to them so that interference is minimized depending on mutual distance or reported signal quality levels.

Use cases characterized by mobile subnetworks (e.g., in-body, in-vehicle) cannot rely, however, only on centralized interference coordination solutions. Such use cases include life-critical services, which cannot entirely depend on an external network, where intermittent communication links can be experienced due to coverage holes (e.g., vehicles driving in a tunnel or humans entering radio-isolated buildings). Interference coordination for life-critical subnetworks must be based, at least partially, on distributed techniques. The use of distributed explicit coordination — where subnetworks exchange information on the portion of the band where they are active in order to trigger eventual decisions on spectrum utilization — may be prone to coordination signal loss in case of poor propagation conditions. Moreover, such signals may be transmitted by potentially malicious neighbors and cannot be trusted.

We therefore believe that implicit coordination mechanisms must be used for mobile in-X subnetworks. These subnetworks must be able to make decisions on the portion of spectrum to be used only based on local sensing, i.e., without explicit signaling. They should then be able to sense the aggregate interference levels or, better, the interference level generated by individual neighbors in the different subbands and perform proactive decisions on the resource to be used. Channel selection policies, as well as the selection of transmission parameters, can be based on smart heuristics [87] or conventional optimization methods.

On the other side, the use of AI data-driven methods recently sparked new research avenues in the context of radio resource management [88]. For example, techniques such as reinforcement learning based on live interaction with the environment can learn the actions to be taken for maximizing a long-term reward for that specific environment [89]. This may translate to improved spectral efficiency with respect to conventional methods that may be highly ineffective when considering the environment variability and the limited information available at each subnetwork. Moreover, Bayesian reinforcement learning allows the introduction of a priori knowledge of the environment in the learning process, for the sake of speeding up convergence [90]. For example, for in-X subnetworks, preliminary knowledge on interference behavior and cell mobility patterns can be incorporated to accelerate the learning phase. Exploring new data-driven methods for distributed interference management is a promising research direction.

Hybrid approaches may also be envisioned. Subnetworks operating in licensed spectrum can rely on centralized interference coordination when in the coverage area of a macro network, while switching to implicit coordination in the case of poor coverage. This can be beneficial for battery-driven subnetworks such as in-body subnetworks, given the more efficient spectrum usage enabled by centralized coordination. The principle is depicted in Figure 3. The subnetworks operating with the hybrid coordination approach may therefore be subscribers of a mobile operator, and should be able to implicitly manage its spectrum when out of coverage, or eventually fall back to unlicensed spectrum in such conditions.

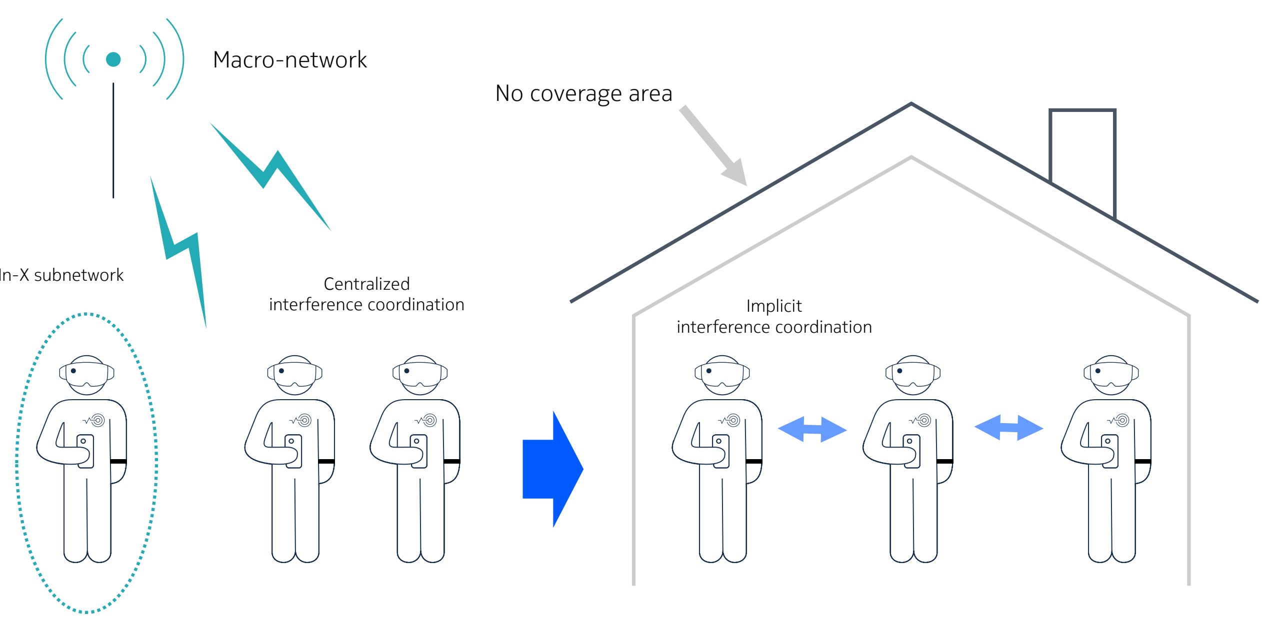
A major challenge of the hybrid approach design is to seamlessly perform the switch between centralized and distributed coordination, i.e., without affecting the performance of the underlying application, especially for the case of life-critical services. The inclusion of a hybrid interference management mode is another major difference with respect to 5G, where only centralized schemes or distributed schemes based on explicit signaling among cells are considered. In summary, in contrast to 5G, interference management in in-X subnetworks must be proactive and hybrid, i.e., able to seamlessly switch between centralized and distributed modes without any service interruption.

A qualitative example of how these approaches to interference management — centralized, distributed, and hybrid — can be implemented in conjunction with the air interface components will be further discussed in the following section, where a system design to support high critical in-X traffic is presented.

## Dealing with additional sources of interference

The extreme reliability requirements of life-critical applications supported by the in-X subnetworks require a detailed characterization of the tail of the interference distribution [91]. Besides intra- and inter-cell interference, the system needs to be robust in managing different types of radio interference that could be caused by rare events while still being very troublesome. Regarding the in-X subnetworks, we envision two important sources of interference that need to be considered and represent an important area for future research: jamming attacks and impulsive noise.

Figure 3. Hybrid interference management for life-critical in-body subnetworks




Intentional malicious smart jammers can disrupt the communication link quality and pose a major threat to meeting extreme performance requirements [92]. A smart jammer can indeed learn the timing, frame and traffic pattern of an in-X subnetwork, in particular with periodic traffic that characterizes most of the control loops, and emulate its transmissions with potentially disruptive effects.

A jamming-resilient system typically needs to perform two tasks: detection and mitigation. Jamming detection aims at distinguishing malicious interferers from legitimate ones, which is a very challenging task. The system observing a performance degradation needs to understand whether it is happening because of a malicious device or legitimate radio conditions like fading or close interfering in-X subnetworks.

Several techniques can be used for jamming detection, mostly at the physical layer, based on pilot/data transmission and pseudo-random blanking of frequency, time or spatial resources [93]. Moreover, AI with both unsupervised [94] and supervised learning, for example, in the form of support vector machine, random forest and neural network [95], can be used to improve the detection capabilities of classical statistical signal processing algorithms and heuristics. It can also help to better characterize the jammer strategies, thus allowing for specific mitigation countermeasures.

As jammers do not respect the rules established for communicating in the band where they are active, tailored mitigation solutions must be set in place. For in-X subnetworks such as industrial use cases, operations can always be stopped to protect harm to humans even though that may result in economic losses. In life-critical applications such as in-body subnetworks, however, operations cannot be stopped. In this last case, anti-jamming measures based on conservative link adaptation, frequency hopping, transmit pattern scrambling and advanced MIMO schemes must be activated. These techniques are the same as those described in the section on air interface components, but they need to be tailored to the case of a jammer as interferer, for instance, potentially estimating the jammer channel or power level during the detection phase. For use cases with extremely low latency and limited computation capabilities at the device, moreover, there might not be enough time to promptly react after detecting a jammer, so an air interface with jamming mitigation schemes should always be active in this scenario. Particularly critical is the situation where a malicious attacker can jam the control channels and undermine the possibility of establishing communication between the AP and the devices. Therefore resilience to jamming should be considered as a design criterion for control channels and their multiplexing with data. For example, a periodic occurrence of control information such as broadcast messages should be avoided as potentially easy to be tracked and jammed. The mapping of control channels over physical resources should rather follow a pseudo-random pattern and be wideband.

Another type of interference that needs to be taken into account when considering in-X system design is the impulsive noise caused by the presence of certain types of electro-mechanical devices, like microwave ovens or printers in offices and production modules in industrial areas. Several studies have tried to characterize this type of impairment in the past decades. Measurement results have shown impulsive noise power several tens of dB above the thermal noise power for frequencies below 6 GHz using a receiver located a few meters from the source of the impulsive noise [96]. Historically, the impact of this type of impairment has been disregarded in cellular communications as very spatially and temporally localized, despite its potentially significant power.

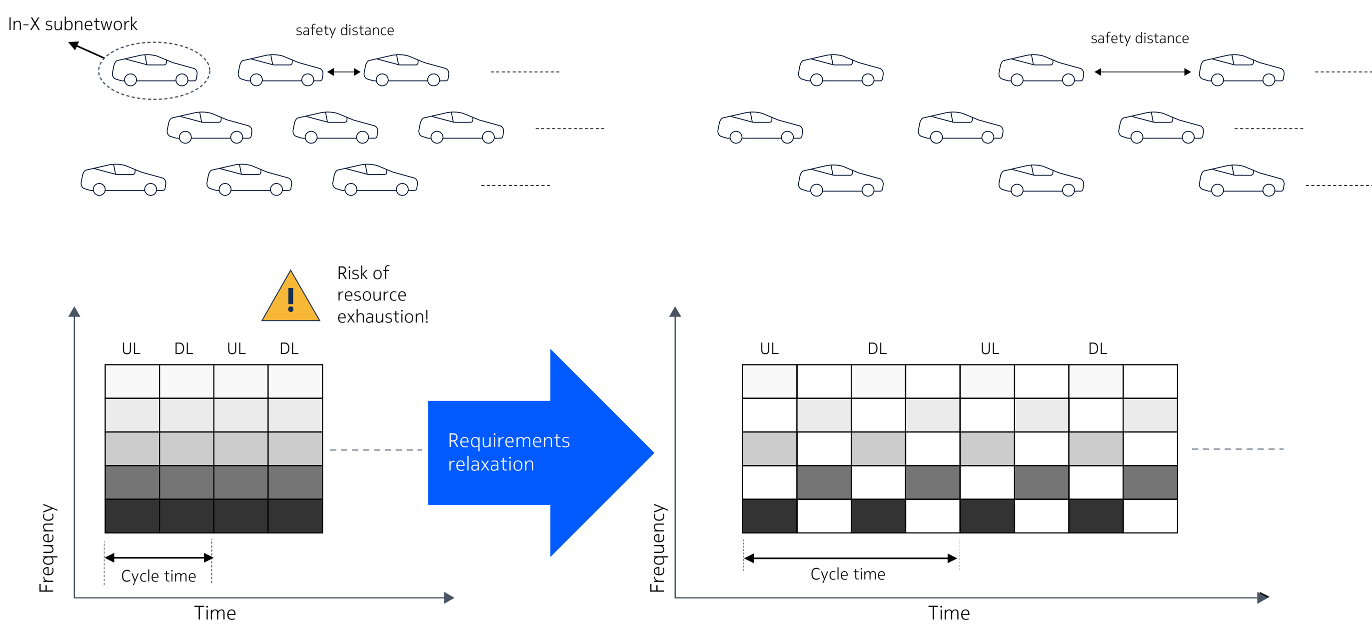
The situation changes with in-X subnetworks that support life-critical applications and face extreme requirements. Even if jamming seems more dangerous because it is caused by a malicious attacker, the impulsive noise, even if unintentional, can be equally dangerous. Thus, the system needs to be robust in defending against it, too. In practice, interference mitigation techniques exploiting spatial, frequency and time diversity introduced in the previous section need to be designed considering not only Gaussian thermal noise and inter-cell interference, but also impulsive noise, whose distribution needs to be characterized depending on the scenario. Although the power of the impulsive noise decreases with the carrier frequency at which it is measured, its impact on higher carrier frequencies such as mmWave bands is still not clear, and more measurement studies are needed.

## Communication requirement relaxation

An underlying assumption for the interference management mechanisms is that there are sufficient available resources for supporting the service requirements of all devices on a subnetwork. This may not be the case for scenarios characterized by very high subnetwork and device density, where it might not be possible to allocate the resources for satisfying the requirements of all devices. And yet, service interruptions cannot be tolerated, especially for life-critical operations.

We believe, therefore, that in-X subnetworks should feature the possibility of relaxing the communication requirements in case of high load and risk of resource exhaustion, without compromising the reliability.

Figure 4. Effects of communication requirement relaxation




In the case of a factory hall with many in-X subnetworks (each with several sensor/actuator pairs) installed in robots or production modules, for example, the communication cycle can be relaxed (e.g., from 100 μs to 1 ms or larger) whenever the mutual interference levels are deemed too high to support the tightest timing at the expected reliability level. This kind of latency requirement relaxation is possible only if accompanied by a corresponding relaxation of the actions supported by those control loops. In the factory hall case, a reduction of the cycle time can translate to slower timing for the robot/production module actions. Similarly, in the in-vehicle use case a relaxed engine control timing must translate to a lower vehicle speed and/or a larger safety distance, as depicted in Figure 4. The principle of communication requirement relaxation is conceptually similar to the video quality degradation for multimedia broadcast [97].

With more relaxed service requirements, transmissions become more sporadic at the point of eliminating the risk of resource exhaustion. For example, with reference to the air interface components, by relaxing the latency from a fraction of ms to 1-5 ms, one can use HARQ rather than blind repetitions, resulting in lower resource utilization. Centralized interference management further helps to reduce the need for requirement relaxation given the more efficient use of resources. One can foresee scenarios where vehicles on a very congested road still run at high speed with small safety distance when in wide area coverage thanks to the centralized interference management; while they reduce speed and/or increase safety distance in out-of-coverage conditions, as they rely on less efficient distributed interference management.

Note, however, that for some of the use cases (e.g., in-body heart-beat control), requirement relaxation cannot be tolerated. Fortunately, such use cases are typically linked to non-extreme latencies (for instance, in the order of 20 ms for the in-body case as shown in Table 1). In general, significant effort is required during the in-X subnetwork concept design phase to ensure accurate requirement definition and classification of use cases and their suitability for communication requirement relaxation. It will also be a major engineering task to design dynamic mechanisms for performing relaxation wherever there is risk of resource exhaustion in the wireless channel.

The concept of adapting control systems to the underlying communication cycle is related to the emerging field of communication and control co-design [98]. Considering wireless channel dynamics in the design of control systems helps to relax the communication requirements without compromising control performance [99]. This may also help reduce the need to relax the control actions when the interference level in the radio channel increases. AI techniques may also be used in this context, for the sake of improving the link spectral efficiency. For example, an AI receiver can be trained to optimize loss function control metrics rather than radio metrics, possibly translating to improved resource utilization.

# Example of interference-robust system design

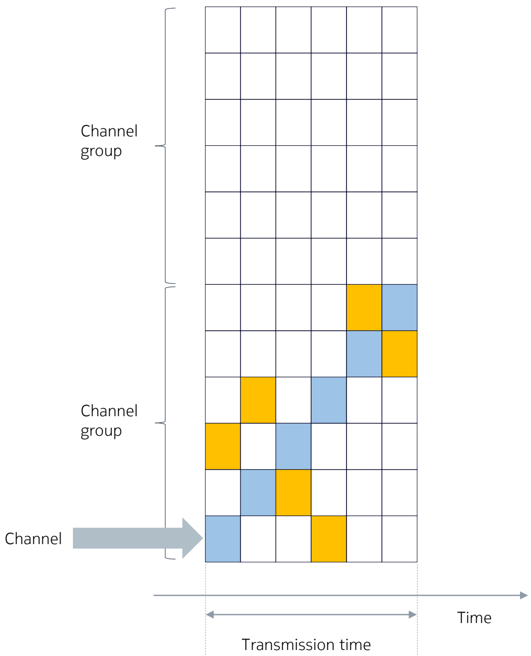
In this final section, we present an example of how air interface design and interference management introduced in the previous sections can guarantee the support of high critical in-X traffic. The presented example is still qualitative, and our hope is that it can inspire new research and engineering solutions in the context of radio resource management for life-critical services.

We consider in-X subnetworks supporting life-critical services where ultra-low latency (e.g., down to 100 μs) must be guaranteed with high reliability. This can be the case for isochronous or event-based traffic and represents the most challenging operational conditions for in-X subnetworks. Such traffic can be eventually multiplexed with high throughput traffic, but this is left for further analysis.

We assume the available bandwidth is divided into several channel groups, where each group consists of a set of channels. Each in-X subnetwork operates at a given time over a single channel group. The division in channel groups is meant to ease interference management as channel group association can be signaled with a minimum number of bits. For example, in the case of four channel groups only two signaling bits are needed.

The air interface components needed to support time-critical traffic are, among others, short OFDM symbols and packet repetitions combined with channel hopping. Devices within an in-X subnetwork can be time synchronized, and the AP assigns orthogonal hopping patterns so that intra-cell interference is avoided. Figure 5 shows the resource grid for a transmission instance composed of a number of units in the time domain and a number of channels in the frequency domain. The channels are organized in channel groups. A device transmits by hopping over multiple channels within a group according to a predefined pattern, with the number of repetitions of the same packet equal to the number of hops. Note that the two devices in the figure are allocated orthogonal patterns, such that they do not generate mutual interference. Each device terminates its transmission after six time units and six channel hops.

Figure 5. Example of transmission grid and channel hopping patterns for two devices (one color is used for each device)




Note that the hopping patterns can eventually be defined across multiple transmissions, e.g., according to pseudo-random sequences, so that more robust resistance to jamming attacks can be obtained. Table 3 reports an example of numerologies for the support of ultra-short transmissions with channel hopping. Such transmissions can be event-based, or arranged in a periodic manner.

Table 3. Possible numerologies for in-X radio design for time-critical traffic

| | | | | |
|---|---|---|---|---|
| SCS (kHz) | 120 | 240 | 480 | 960 |
| CP duration (ns) | 333 | 166 | 83 | 41 |
| OFDM symbol duration (μs) | 8.66 | 4.33 | 2.16 | 1.08 |
| CP overhead (%) | 3.84 | | | |
| Channel bandwidth (MHz) | 100 | | | |
| Channel group bandwidth (MHz) | 600 | | | |
| Max hopping factor | 6 | | | |
| Max OFDM symbols per channel hop | 1 | 2 | 4 | 8 |
| Max transmission duration (μs) | 52 | | | |
| Min time to hop over all channels (μs) | 52 | 26 | 13 | 6.5 |
| Number of subcarriers | 832 | 416 | 208 | 104 |
| Reference sequence overhead (%) | 20 | | | |
| Payload (bytes) | 20 | | | |
| Min per link spectral efficiency (bit/s/Hz) | 0.005 | | | |

We consider a channel group bandwidth of 600 MHz, divided in six channels of 100 MHz. According to its hopping pattern, the device should repeat its packet transmission a number of times over a different channel within ~52 μs, so that a sufficient margin is left at the receiver to process the packet within 100 μs. We refer to the number of channel hops as the hopping factor. In the case of a 120 kHz SCS, the packet should be mapped over a single OFDM symbol per channel hop, while a larger number of symbols per packet can be used for higher SCS. The minimum per link spectral efficiency of 0.005 bit/s/Hz is calculated assuming a 20-byte packet and a maximum hopping factor of six with packet repetitions across multiple channels.

With 20% of the subcarriers dedicated to control signalling and reference sequences, that corresponds to an MCS spectral efficiency of 0.24 bit/s/Hz, which 5G codes already support at -3 dB SINR with a packet error rate of $10^{-5}$ in a single-input single-output setup without any retransmission or repetition [65, Figure 1]. By using a similar approach as in [17], we estimate that exploiting energy combining over six packet repetitions and, when available, four receive antennas, introduces a large margin (more than 10 dB) for fading and further interference.

The CP duration also decreases proportionally to the increase of SCS, with a relative overhead of 3.84% (lower than the ~6.6% in 5G). Higher SCS configurations are used with cells where a very low delay spread is expected. They eventually allow for faster channel hops and a minimum time for hopping over all the channels. This happens when the packet is mapped over a single OFDM symbol and the transmission rate is increased accordingly. Note that in the presented numerology configurations, the switching time between channels is neglected, which may further reduce the number of possible hops.

It is worth mentioning that a similar numerology can also be used for high throughput services. In this case, multiple channels can be aggregated for boosting the data rate, and a very high modulation order can be used. For example, in case of a 4096-QAM modulation, six channels and four spatial streams, a theoretical data rate above 20 Gbps can be achieved.

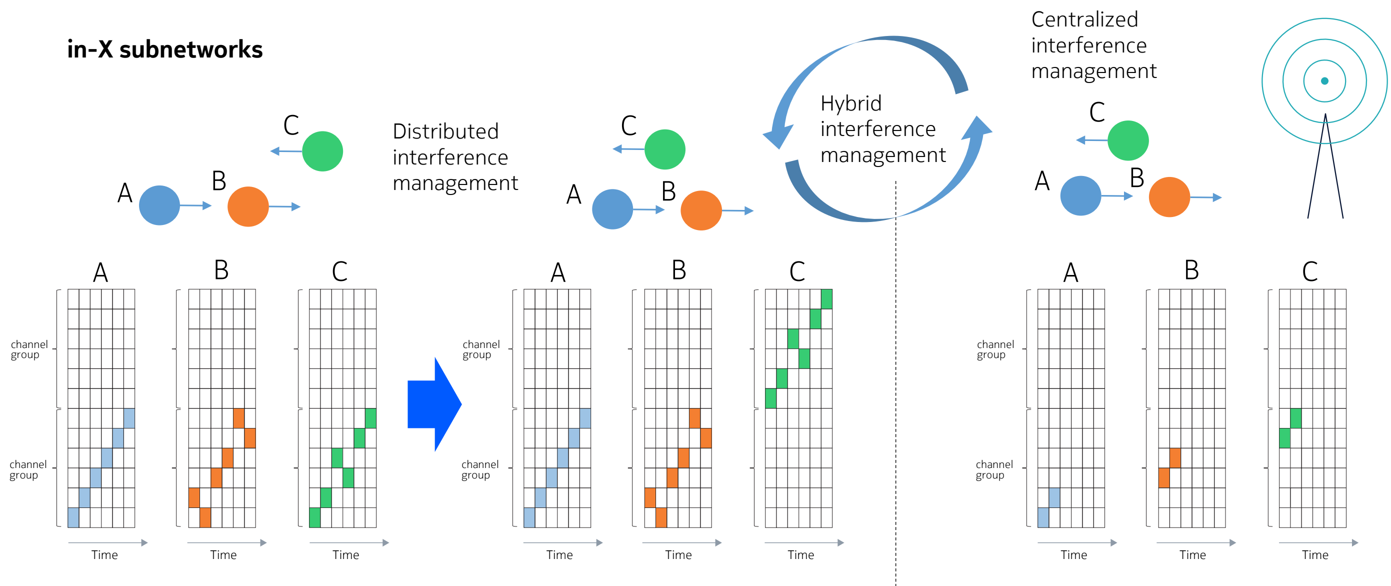
As mentioned in the section on air interface components, channel hopping can provide interference diversity because it diminishes the risk of persistent interference with devices in neighbor cells operating within the same channel group. Also, it offers a tier of robust resistance to potential jammers. The number of hops can be set by the AP according to the reliability requirement and the estimated risk of external interference. Such resilience might not suffice, however, in cases where interference from neighboring cells becomes significantly stronger, in which case further actions need to be taken. Operations depend on the specific interference management scheme and are detailed below. We assume that the network load is not at risk of resource exhaustion, thus there is no need for communication requirement relaxation.

## Distributed implicit interference management

We first consider the case where the in-X subnetworks are completely autonomous or out of wide area coverage. By default, transmissions should happen with a high hopping factor (e.g., 4–6 with reference to the example above) in order to ensure robustness to unexpectedly rising interference levels. The AP should be able to perform wideband sensing in the operational channel group, as well as in the other channel groups. It should persistently monitor the available spectrum and capture the transitional interference behavior. In other words, it must be able to identify potentially growing interference levels in the operational channel group before their effect becomes disruptive.

Where a high hopping factor is deemed insufficient to guarantee transmission success, the AP should switch to a channel group where interference levels are lower. While a high hopping factor provides robust resistance to unexpected interference, including jamming, channel group switching can resolve predictable interference, such as that generated by an approaching in-X subnetwork operating over the same resources. This should be performed seamlessly for the connected devices — without interrupting the underlying operations. Pseudo-random delays between the decision to switch a channel group and its actuation can be introduced to avoid possible ping-pong effects when subnetworks decide to switch simultaneously over the same channel group. Delays must be set lower than the predicted time at which the interference on the operational channel group is expected to become disruptive.

Figure 6. Resource allocation for different interference management modes




The effects of distributed interference management are highlighted in the illustrative example in Figure 6. We consider three mobile in-X subnetworks, denoted as A, B and C and, for simplicity, a single served device whose resource allocation for a certain transmission is also shown. Subnetworks A and B move in the same direction, while subnetwork C moves in the opposite direction. Only two channel groups are available, and each group consists of six channels. All subnetworks operate with a hopping factor equal to six, thus over all the available channels in the group.

In the first moment, the three subnetworks operate over the same channel group. Although they are not synchronized and operate with different hopping patterns — based on different pseudo-random sequences — there is a risk of significant overlap for some of the transmission instances. We assume that A and B generate mutual interference within a tolerable level; as they move in the same direction, no major increase in mutual interference is estimated. On the other hand, the interference generated by subnetwork C grows as it gets closer. Similarly, subnetwork C measures growing interference from the approaching cells so that, when the interference level reaches a certain cautionary threshold, it can switch channel group. A simple conflict resolution protocol, like the one mentioned above, can be used to reduce the risk that A and B also switch their channel group. After C switches the channel group, all subnetworks can continue operations without suffering from disruptive interference.

## Centralized interference management

In this case, the wide area network takes care of coordinating the operations of the in-X subnetworks over different channel groups to minimize the risk of significant interference. The network receives location information from its connected in-X APs, and through a DL control channel communicates their channel allocation information, including both the channel group and, eventually, the subset of channels. The channel selection is aided by local interference measurements performed by each in-X subnetwork and reported to the wide area network.

While the operational channel group and subset of channels is instructed by the wide area network, the in-X AP can adjust the hopping pattern per device and the number of repetitions according to the estimated signal quality per link. Since centralized management significantly reduces interference risk, the hopping factor can be significantly lower than in the implicit coordination case (e.g., 1–2). As mentioned in the previous section, this also translates to lower energy consumption. Nonetheless, for certain applications (e.g., industrial) a small hopping factor (e.g., 2–3) should still be set to robustly resist potential jammers. A further advantage of operating with a small hopping factor is the possibility of opportunistically reusing part of the bandwidth for other traffic types, e.g., best-effort high throughput. This can be the case where a cell supports video feeds beside high-critical traffic.

The right side of Figure 6 shows the resource allocation enabled by the centralized interference management. All the subnetworks are in this case instructed by the wide area network to operate over the same channel group, with a minimum hopping factor of two. Note, orthogonal channels are assigned to each subnetwork so that there is no risk of interference, although they operate on the same channel group.

## Hybrid interference management

There can be scenarios where interference management is centralized by default, but connectivity to the wide area network temporarily drops and services must continue their operations reliably. The in-X AP, in this hybrid scenario, should seamlessly switch between centralized and implicit coordination mode. When the periodic channel allocation message is received from the wide area network, the in-X AP can rely on such information and operate with a small hopping factor. As the in-X subnetwork moves out of wide area coverage, the channel allocation messages will start to be lost, at which point the in-X AP will have to activate the implicit allocation mode. When operating in distributed implicit mode, the hopping factor must be increased and the AP should monitor growing interference levels, which may force a channel group switch. In Figure 6, the hybrid interference management mode is indicated by the double-arrow, which represents the mobility direction of subnetworks in and out of the coverage of the wide area network, where centralized and distributed techniques are to be applied, respectively.

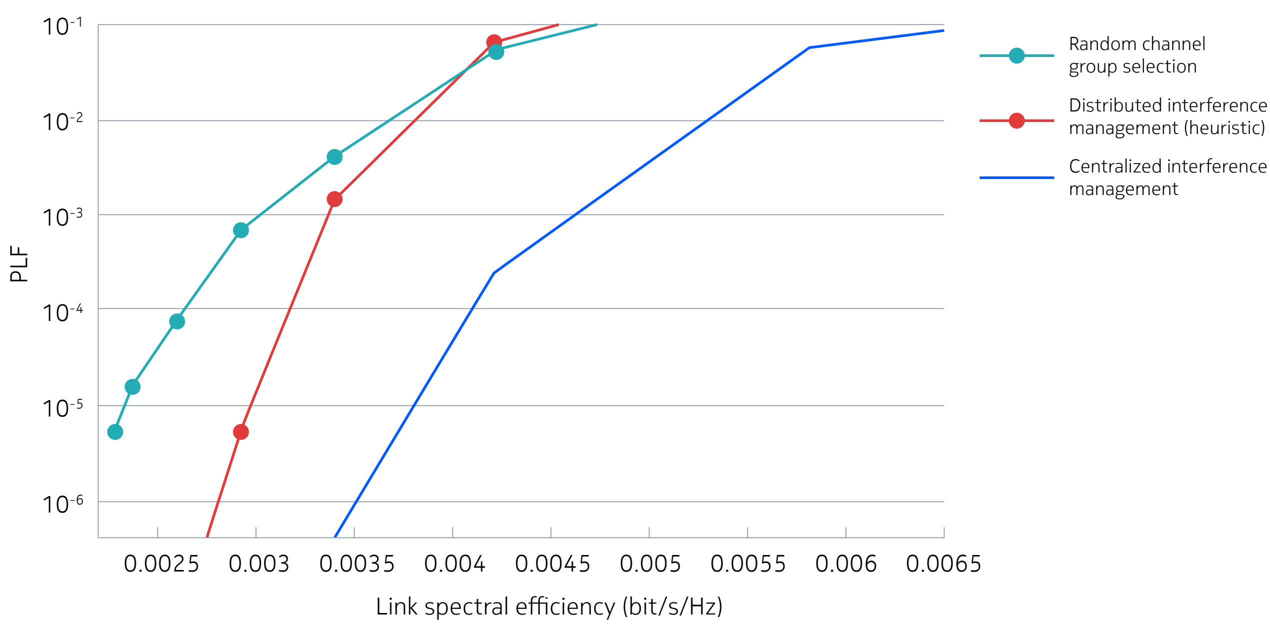
## Benefits of interference management

Preliminary simulation results highlight the performance benefits of interference management in a scenario with high density in-X subnetworks. In the simulation, we considered 16 mobile subnetworks with cell radii of 2.5 m moving in random directions at 2 m/s in a 30 m × 30 m area (900 $m^2$). This represents, for instance, the use case of mobile robots in a factory. Subnetworks randomly change the direction of motion in case they “bounce” off each other and when they reach the boundary of the deployment area. In each subnetwork, the AP serves six devices. Subnetworks operate in TDD mode, where devices and AP transmit a 20-byte payload in very short time, using the numerology from Table 3, and assuming a hopping factor equal to 4.

We assumed a channel bandwidth size in the range 50-300 MHz to capture performance sensitivity to spectral efficiency. A total of four channel groups is assumed. The large-scale radio propagation parameters are set according to the 3GPP indoor factory model for sparse clutter [100] assuming a carrier frequency of 6 GHz. Shadowing is spatially correlated based on a Gaussian random fields model [101] with a decorrelation distance of 4 m, and assuming Rayleigh small-scale block fading with coherence bandwidth of 20 MHz. Both devices and APs are equipped with two receive antennas and apply maximum ratio combining [102], and the receiver combines the energy from multiple repetitions before attempting decoding. We refer to [17, Section V-A] for a detailed mathematical description of the receive SINR and detection model.

We analyzed the performance gain of distributed and centralized interference management when compared to a baseline where each subnetwork selects randomly the operational channel group. The adopted distributed scheme is a simple greedy heuristic where each subnetwork selects the channel group where the lowest interference level is measured. The centralized scheme is instead based on graph coloring [103]: the interference relationships among the subnetworks are mapped to a conflict graph, which is then colored so that different channel groups are allocated to the subnetworks experiencing significant mutual interference. In this initial analysis, given the limited deployment area, we do not consider hybrid schemes, as we assume all the subnetworks to either be within the coverage area of an enterprise network, which can act as interference manager, or to operate fully autonomously in case the network is absent. Also, for simplicity, we keep the hopping factor fixed for all schemes, even in the centralized one.

Figure 7. Probability of loop failure for distributed and centralized interference management




Results are generated for different bandwidth sizes and using a large number of re-deployments in order to obtain above 100 million samples. We refer to our previous work [87] for a detailed description of the interference management schemes employed, as well as for the results generation procedure. Figure 7 shows the PLF as a function of the spectral efficiency. As mentioned in the section "Why in-X subnetworks?", PLF is a measure of spatial availability of the service and reflects the risk of obtaining, at a given time and location, an outage probability lower than a predefined value ($10^{-6}$ in this example).

Both interference management schemes lead to significantly higher link spectral efficiency than the baseline random channel group selection. For example, the distributed scheme leads to a spectral efficiency gain of ~30% at a $10^{-5}$ PLF and gain increases up to and above ~70% for the centralized scheme. Note that the distributed scheme used here is based on a simple heuristic: performance is expected to further improve when using more evolved solutions based, for instance, on Bayesian reinforcement learning. Similarly, the centralized schemes can also benefit from advanced approaches that optimize the hopping factor. We believe our initial results can inspire further relevant research in the context of interference management for in-X subnetworks.

# Conclusions

In this article, we have introduced short-range, low-power 6G in-X subnetworks as a solution to provide capillary wireless coverage for the support of extreme communication requirements in terms of throughput, latency and reliability. Such subnetworks are to be installed in entities like robots, production modules, vehicles or human bodies. They can be part of a larger network infrastructure but should also be able to operate autonomously in case of life-critical services.

Licensed spectra can be used in case of static or nomadic subnetworks, while mobile subnetworks can rely on unlicensed options, including the possibility of running in-X subnetworks as an underlay system in bands allocated to other systems. New regulations might, however, be needed to support time-critical traffic.

As in-X subnetworks can likely lead to very dense deployments, interference coordination is a must for ensuring the fulfillment of extreme requirements. Implicit coordination schemes must complement centralized ones for situations when in-X subnetworks are out of wide area coverage. The extreme reliability requirements of the life-critical applications supported by the in-X subnetworks also require a system design capable of dealing with non-cellular sources of interference such as jamming attacks and impulsive noise. Also, communication requirements may eventually need to be relaxed in case of paramount interference levels, provided that the actions supported by the underlying control system can be relaxed accordingly.

We believe the challenges identified in this article can spark new research avenues in the context of dynamic radio resource management for 6G.

# Recognition

Gilberto Berardinelli, Ramoni O. Adeogun and Preben Mogensen are with Aalborg University, Aalborg, Denmark. Preben Mogensen is also with Nokia Standards, Aalborg, Denmark. Paolo Baracca and Frank Schaich are with Nokia Bell Labs, Stuttgart, Germany. Saeed R. Khosravirad and Harish Viswanathan are with Nokia Bell Labs, Murray Hill, United States. Karthik Upadhya is with Nokia Bell Labs, Espoo, Finland. Dong Li and Tao Tao are with Nokia Shanghai Bell, Shanghai, China.

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