# TERAHERTZ NETWORKS FOR FUTURE INDUSTRIAL INTERNET OF THINGS

Sara Cavallero[1], Nicolò Decarli[2], Giampaolo Cuozzo[1], Chiara Buratti[1], Davide Dardari[1], Roberto Verdone[1]
[1]DEI - University of Bologna and WiLab/CNIT, e-mail: {s.cavallero, giampaolo.cuozzo, c.buratti, davide.dardari, roberto.verdone}@unibo.it, [2]CNR - IEIIT and WiLab/CNIT, e-mail: nicolo.decarli@ieiit.cnr.it

***Abstract*** – *Wireless technology is expected to become a fundamental enabler to improve the efficiency, safety, and revenues of advanced manufacturing processes, as well as to realize new paradigms such as digital twins. The extremely challenging industrial scenario requires some technological shifts such as the adoption of the so far unexplored THz band. The purpose of this paper is to provide an overview of THz networks applied to the Industrial Internet of Things (IIoT). First, the main requirements of future industrial THz-based networks, challenges, and state-of-the-art are described. Subsequently, the key enabling technologies are introduced and discussed. Finally, we present some research directions for THz-based industrial networks.*

**Keywords** – Communications, IIoT requirements, Industrial IoT, multi-goal network optimization, sensing, smart radio environments, THz networks

## 1. INTRODUCTION

In the last few decades, a fourth industrial revolution has emerged. This trend towards an automated and interconnected industry supported by Information and Communication Technologies (ICTs) is often represented by the expression “Industry 4.0” (I4.0). This revolution heavily relies on the Internet of Things (IoT) paradigm: networks of physical objects embedded with sensors and actuators aim to connect and exchange data with other systems over the Internet. When an IoT system is used to realize an Industry 4.0 project, it is then called the Industrial Internet of Things (IIoT). The IIoT paradigm also includes Cyber-Physical Systems (CPSs), where the emphasis is on the digital representation of the physical world: machines are represented by digital “twins” thanks to the information sent in real time by the sensors mounted on them.

An industrial scenario, where advanced manufacturing functions are integrated with IIoT applications to improve the efficiency, safety, and revenues of industrial processes, is extremely challenging from the point of view of deploying wireless networks. In this context, a heterogeneous set of entities, such as sensors, actuators, Automated Guided Vehicles (AGVs), Unmanned Aerial Vehicles (UAVs), and Programmable Logic Controllers (PLCs), are wirelessly interconnected inside the factory for the development of specific use cases, which may need intra-machine or inter-machine communications [1]. The wireless network that has to serve the machines is subject to processes that evolve continuously in time and space within the plant; moreover, multiple IIoT applications, with different requirements, might exist at the same time. Some of these IIoT applications have very stringent requirements in terms of reliability, i.e. up to 99.99999%, and a latency even below 1 ms [2, 3]; these requirements cannot be reached by current wireless technologies, including 5G. In this vision paper, we consider a complex industrial scenario with inter-machine and intra-machine Terahertz (THz) communications assisted by Intelligent Reflecting Surfaces (IRSs) and with Integrated Sensing And Communication (ISAC) capabilities, as depicted in Fig. 1. All these components and peculiarities of THz communications will be discussed in the following sections, with the objective of identifying possible solutions for the realization of a multi-goal mesh network that optimises the performance of such scenarios and guarantees the stringent space-time evolving requirements.

The paper is organized as follows: Section 2 reports the main requirements for future industrial networks; then, Section 3 discusses the state-of-the-art and the major challenges concerning Physical (PHY) and Medium Access Control (MAC) layer protocols, as well as, ISAC at THz frequencies. Section 4 describes possible research directions for THz-based IIoT networks justified by results that have already been obtained and explains which is our vision about the optimization of multi-goal networks; finally, conclusions are drawn in Section 5.

## 2. REQUIREMENTS OF FUTURE INDUSTRIAL NETWORKS

Consider a generic wireless link between an IIoT device that sends in uplink the measured data to a destination PLC for elaboration purposes (see Fig. 2). Typical IIoT requirements in terms of data acquisition periodicity, latency and spatial resolution for the localization of objects are reported in Table 1 [4, 5, 6].

### 2.1 Data acquisition periodicity

The data acquisition periodicity (i.e., the interval of time between two subsequent measurements) implies the use of a data rate compatible with the inverse of the typical requirement, which means some Msample/s. The typical

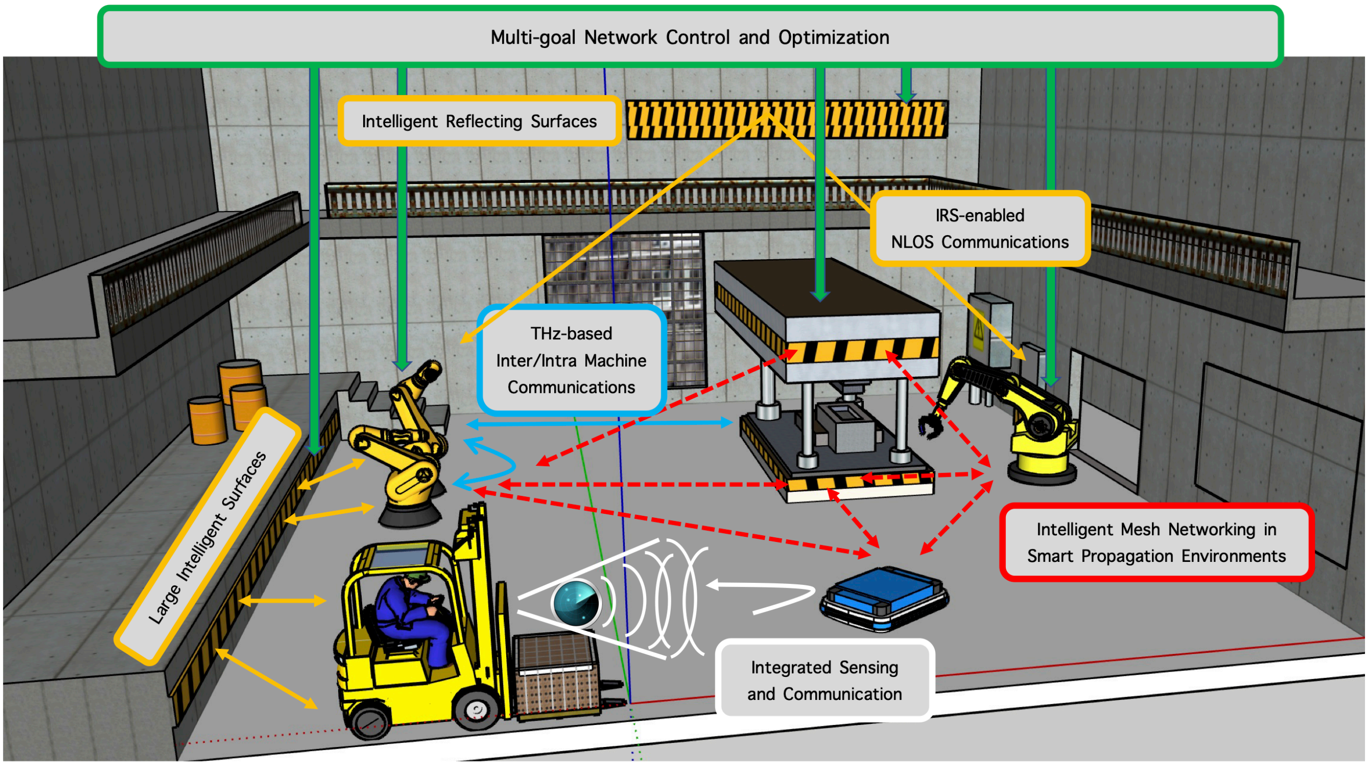


**Fig. 1** – Reference IIoT scenario envisioned, with inter-machine and intra-machine communications assisted by IRSs and ISAC

**Table 1** – IIoT requirements

| IIoT Requirements | Typical values |
|---|---|
| Data acquisition periodicity | $1\ \mu s$ |
| Latency | $< 100\ \mu s$ |
| Spatial Resolution | $\sim cm$ |

size of a data packet for IIoT applications spans from a few to tens of bytes. Therefore, for each individual link from an IIoT device the throughput should be in the order of hundreds of Mbit/s. As a result, in an IIoT factory scenario with thousands of devices, the throughput managed by a single access point should be in the order of $100$ Gbit/s; taking into account protocol redundancy and overheads, the bit rate, $R_{\mathrm{b}}$, has to be larger than $1$ Tbit/s. This requirement pushes the development of future industrial wireless networks in the direction of higher frequencies than the ones used in 5G, where bandwidths of several tens (or hundreds) of GHz will be available. In particular, the THz band, that is, the interval of frequencies from 0.1 to 10 THz, offers bandwidths of several GHz which provide ultra-high data rates, while device miniaturization will beneit at the same time from the smaller wavelengths [7, 8, 9, 10, 11]. THz bands offer a number of challenges, including very high channel losses that limit the transmission range, even in Line-Of-Sight (LOS) conditions. This problem can be tackled by means of high rank LOS Multiple Input Multiple Output (MIMO) techniques discussed in Section 4.1.1. However, the use of THz frequencies has implications not only at the channel and

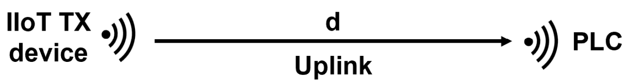


**Fig. 2** – Direct uplink communication between an IIoT device and a PLC

physical layer. Indeed, at these frequencies, the ultra-high bit rates, combined with the short packet lengths typical of IIoT applications, make packet transmission times shorter than the propagation delays. This fact sets un precedented issues that, at the MAC layer of the protocol stack, need speciic considerations. Section 4.2 will discuss the possible solutions.

## 2.2 Latency

The latency (i.e., interval of time measured at application layer between the instant when a data packet is originated at the source and the instant when it is successfully received by the destination) should be close to $100\ \mu s$ to guarantee the reaction time typical of control loops [12]. In general terms, for a one-hop communication link like in Fig. 2, latency can be assessed as:

$$L = (T_{\mathrm{p_{TX}}} + T_{\mathrm{acc}} + T_{\mathrm{TX}} + \tau_{\mathrm{prop}} + T_{\mathrm{p_{RX}}}) \times \left(1 + \sum_{i=1}^{N_{\mathrm{r}}} \mathrm{BLER}^{i}\right) \quad (1)$$

where:

- $T_{\mathrm{p_{TX}}}$ is the processing time at the transmitter needed to add the protocol headers and build the data block sent at the PHY layer;
- $T_{\mathrm{p_{RX}}}$ is the processing time at the receiver to extract the information bits from the data block at the application layer;
- $T_{\mathrm{acc}}$ is the average time needed for accessing the channel. Considering for example a simple Time Division Multiple Access (TDMA) MAC protocol with 20 mini-slots and a data block of $L_{\mathrm{data}} = 50$ bytes, then $T_{\mathrm{acc}}$ depends on the average number of mini-slots a data packet has to wait before being assigned a radio resource, $\overline{N_{\mathrm{slot}}}$, which in our example will be 10. Assuming a bit rate of 100 Gbit/s, we can compute $T_{\mathrm{acc}} = \frac{\overline{N_{\mathrm{slot}}} * L_{\mathrm{data}}}{R_{\mathrm{b}}} = \frac{10*50*8}{100*10^9} = 40\,\mathrm{ns}$;
- $T_{\mathrm{TX}}$ is the time needed to transmit the data block, $T_{\mathrm{TX}} = \frac{L_{\mathrm{data}}}{R_{\mathrm{b}}} = \frac{50*8}{100*10^9} = 4\,\mathrm{ns}$;
- the propagation delay $\tau_{\mathrm{prop}}$, given a distance $d = 5\,\mathrm{m}$, is $\tau_{\mathrm{prop}} = \frac{d}{c} = \frac{5}{3\cdot 10^8} = 16.7\,\mathrm{ns} > T_{\mathrm{TX}}$ and it cannot be considered negligible anymore with respect to the data transmission time.
- BLER is the Block Error Rate;
- $N_{\mathrm{r}}$ is the maximum number of retransmissions.

Given the overall bit rate considered, and the expected advancements of computing technologies in the years to come, processing times can be assumed ten times faster than the ones defined by 5G, which is, for example, $T_{\mathrm{p5G}} = 0.32\,\mathrm{ms}$ [13]; so we can suppose them as $T_{\mathrm{p_{TX}}} = T_{\mathrm{p_{RX}}} = \frac{T_{\mathrm{p5G}}}{10} = \frac{0.32\cdot 10^{-3}}{10} = 32\,\mu\mathrm{s}$. Under the assumption of no errors and losses during the communication $(\mathrm{BLER} = 0)$, the overall latency is $L \sim 64\,\mu\mathrm{s} < 100\,\mu\mathrm{s}$ and, as can be seen, processing times are the most relevant contribution to its final value. In an industrial scenario, the communication between a transmitter and a receiver can be characterized by the presence of obstacles. The need to have ultra-reliable links, and the use of THz frequencies, impose LOS conditions. This means that in the presence of obstacles, two-hop links might be considered. However, data forwarding through a router will introduce further delays related to the processing and transmission times at the router, which will make the latency requirement possibly unsatisfied. In this case, a possible solution is to place IRSs in between, as shown in Fig. 3. IRSs are metasurfaces which are able to smartly reflect the signal towards the final destination and improve the performance of wireless data transmission systems; they will be discussed as one of the key technological enablers at the PHY layer in this paper. From a latency point of view, the advantage of using IRS compared to routers or relays, is that they do not perform any processing and therefore do not introduce any additional delay. What changes in the latency formula *(1)* is that instead of having $\tau_{\mathrm{prop}}$ we have two propagation delays $\tau_{\mathrm{prop}_1} = \tau_{\mathrm{prop}_2}$ that depend on the two distances $d_1$ and $d_2$ as:

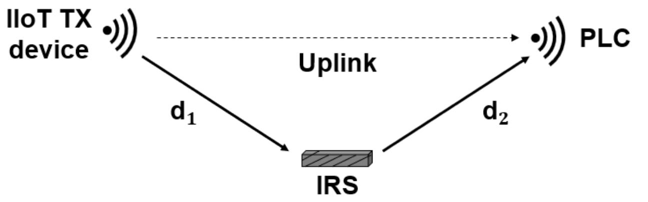


**Fig. 3** – Uplink communication between an IIoT device and a PLC by means of an IRS

$$L = (T_{\mathrm{p_{TX}}} + T_{\mathrm{acc}} + T_{\mathrm{TX}} + \tau_{\mathrm{prop}_1} + \tau_{\mathrm{prop}_2} + T_{\mathrm{p_{RX}}}) \times \left(1 + \sum_{i=1}^{N_{\mathrm{r}}} \mathrm{BLER}^i\right) \quad (2)$$

For the sake of simplicity, since propagation delays are in the order of a few tens of ns, we can assume $\tau_{\mathrm{prop}_1} + \tau_{\mathrm{prop}_2} \sim \tau_{\mathrm{prop}}$. Considering BLER $= 0$, then the final latency is $L \sim 64\,\mu\mathrm{s} < 100\,\mu\mathrm{s}$, as in the previous case of a direct link. Thus, IRSs represent a very interesting solution to tackle the issues of the presence of obstacles in industrial scenarios, while satisfying latency requirements. In Section 4.1 the concept of smart radio environments using IRS will be discussed further.

## 2.3 Spatial resolution

Finally, the spatial resolution (i.e., precision in determining the position of the measurements taken by a mobile sensor) of 1 cm is crucial for IIoT scenarios where the environment is characterized by robotic arms, mechanical pieces and unmanned vehicles that move in the close vicinity to human operators. Such level of resolution can be only achieved through ultra-wideband communications; having signal bandwidths in the order of $10\,\mathrm{GHz}$ allows us to have pulses with $1\,\mathrm{ns}$ duration. The shorter the pulses, the easier the recognition of their reception instant and so the ranging measurement [14]. This also pushes the technology trend towards THz frequencies, where large bandwidth is available. One of the emerging technologies, that will significantly impact the ability of future wireless networks to perform localization of objects in a industrial scenario, is ISAC. The base station, through a unique waveform, will both communicate with devices and localize them. Section 4.3 will discuss further the role of ISAC.

# 3. CHALLENGES, STATE-OF-THE-ART, AND KEY ENABLING TECHNOLOGIES

## 3.1 PHY layer solutions

Typically, the PHY layer of a wireless communication network is designed to counteract/exploit propagation characteristics accounting for technological constrains, as well as support the needs from higher layers, as discussed in the next section.

One of the major challenges for transmissions with carrier frequencies above 100 GHz is the increased path loss, whose main contributions come from the free space path loss and the loss due to molecular absorption. The latter leads to very high attenuation in certain frequency bands whose utilization must be generally avoided [15, 16]. It is worth highlighting that, at THz frequencies, the interaction of the electromagnetic waves with the molecules of the medium produces also a new type of noise, the so-called *molecular noise*. More precisely, part of the absorbed energy is re-emitted into the channel by the molecules of the medium, and this event causes a disturbance to the useful wave. This phenomenon results in a frequency selective channel (even in free space) with peaks at specific frequencies (resonance frequencies), whose bandwidth depends on the distance. As a consequence, ad-hoc modulation formats have been proposed [17, 18, 19].

Since the path loss increases with the frequency, to establish links of several meters with limited transmitted power, THz communications must rely on highly directional antennas, e.g., large antenna arrays, working in LOS condition [20]. This implies high array gain but, in principle, no multiplexing gain if conventional MIMO approaches are adopted, as discussed in Section 4.1.1. At the same time, pencil-like beams, which are obtained at THz frequencies with electrically large arrays, make device discovery and beam alignment much more challenging compared to traditional systems, with the risk of extremely experiencing high latency.

Technological constraints might emerge due to the extremely small size of antenna elements (in the order of 1 mm) and the difficulty in realizing phase shifters and other RF components at THz. For instance, the phase noise calls for ad-hoc modulation schemes that are more insensitive to it, such as those based on the transmission of chirps, i.e., frequency-sweep pulses.

Another challenging issue at THz is blockage. Any object whose size is larger than a few cm might completely block the signal and the multipath components may be too weak to be exploited in Non-Line-Of-Sight (NLOS) conditions. Therefore, hybrid and mesh network solutions exploiting multiple devices such as collaborative nodes, active and passive relays, the latter based on IRSs, have to be investigated, as it will be discussed in the next sections. Such solutions have to be designed without forgetting the low-latency requirement and the complexity aspects.

## 3.2 MAC protocols

In the current literature, only a few pieces of work have addressed protocol aspects when considering high frequencies, such as millimiter wave (mmWave) or THz. [7] is a survey on MAC protocols for THz communications which classifies and discusses the design issues of the existing THz-MAC protocols. Going into more details, several Carrier Sense Multiple Access (CSMA)-based solutions are studied taking into account the issues that characterize high-frequency propagation and exploiting the advantages of sensing the channel. As explained previously in Section 3.1, one of the solutions to overcome the high propagation losses is the adoption of directional antennas. However, directional transmissions require beams to be aligned and steered to avoid the deafness problem, that is a situation where the main beams of transmitter and receiver do not exactly point to each other, making impossible to establish high-quality links. In [21], authors propose a receiver-initiated handshake to allow the transmitter to understand the receiver antenna direction, as well as to guarantee the transmitter-receiver synchronization. Other work (e.g., [22, 23]) uses two antenna settings: one radio operates in omnidirectional mode for sensing, while directional antennas are used in the transmission phase. However, the use of two antenna settings causes the asymmetry-in-gain problem, resulting in deafness and collisions. Moreover, by using low frequencies during the discovery phase, the devices lose the advantage of working at high frequencies, finding only other devices close to them and making it difficult to meet stringent latency requirements.

Another problem that characterizes wireless networks is the hidden terminal problem, where one device is hidden from the others if it is out of their reception range. This results in the possibility of simultaneous transmissions to the receiver because the channel is sensed free even if it is not. In the modelling of CSMA protocols at lower frequencies, a hidden terminal problem is considered assuming ideal channel conditions, thanks to the use of Request To Send (RTS)/Clear To Send (CTS) control packets (see, e.g., [24, 25]) or deriving performance metrics in function of the probabilities that devices can hear each other ([26, 27, 28]]). However, this problem becomes more pronounced when considering THz frequencies, as the higher frequency leads to increased propagation losses and, on the other hand, the solution of adopting directional antennas restricts the range in which one can hear other devices to a specific direction. Other works in the literature propose solutions to cope with the frequency selective nature of the THz channel. Orthogonal Chirp Division Multiplexing (OCDM), where chirps of common duration sweep over a shared band, keeping constant values of frequency distance that ensure orthogonality [29], is a physical layer solution that provides benefits exploited for different application domains: underwater [30], radar [31], video-broadcasting [32], power lines [33]. Other contributions have addressed the complexity of the receiver [34] or applied MIMO to OCDM [35]. Moreover, as shown in [36], the OCDM principle can also be exploited at MAC layer to multiplex multiple users in the same time-frequency slot. This technique is called Orthogonal Chirp Division Multiple Access (OCDMA) and it will be detailed in Section 4.2. Finally, Non-Orthogonal Multiple Access (NOMA) is an item considered in 3GPP for 5G new radio, with the capability of maximizing the spectrum efficiency, improve user fairness and throughput while reducing the latency. References [37, 38, 39] are surveys describing the pros and cons of using non-orthogonal resources and underlying all the potential of this channel access method, by distinguishing between power-domain and code-domain multiplexing.

### 3.3 Integrated sensing and communication

Environment sensing in terms of Channel State Information (CSI) and location awareness is an essential requirement both for enabling location-based services and for unleashing smart management of communication network resources. While for the time being CSI estimation, communication and localization have been considered separately, especially at THz they must be considered jointly [40]. In fact, the LOS characteristic of THz communications makes CSI and position estimation geometrically related. The main issue here is how to design the signal waveforms in such a way that they can be efficiently exploited both for communications, sensing, and localization [41, 42], toward the so-called ISAC.

Moreover, the extremely short wavelength of THz signals gives the unique opportunity to obtain very accurate radio images of the surrounding environment that can be exploited both to optimize the performance of the network and provide new services such as Simultaneous Localization and Mapping (SLAM)[43].

Unfortunately, the high blockage probability of THz signals in harsh propagation environments might seriously compromise the localization process whose coverage is much more demanding than communications because each location must be covered by at least 3-4 access points to allow multi-lateration instead of just one needed for communications. In this respect, the main goal is to achieve soft coverage within the considered environment, i.e., extremely low spatial and temporal outage for the positioning information, even in the presence of only a few access points. In fact, traditional localization systems, such as those based on ultra-wideband technology, are able to provide high accuracy in cases of LOS, but have considerably lower reliability when NLOS conditions are present. Moreover, the deployment of a large number of access points can be too demanding for practical applications. In Section 4 possible solutions will be discussed.

## 4. RESEARCH DIRECTIONS FOR THZ-BASED IIOT NETWORKS

### 4.1 PHY layer solutions

The use of THz technologies poses new challenges and opens up new opportunities at the same time since traditional models based on the assumption of far-field Electromagnetic (EM) propagation fails. As an example, in classical operating conditions, i.e., in the Fraunhofer region of the antenna, the radio link is much longer than the antenna dimension, so that plane wave propagation is assumed. Conversely, when the antenna size (here intended as size of the whole array, not of the single array element) grows, operating conditions fall within the Fresnel region in which (radiating) near-field propagation takes place. For example, Fig. 4 reports the Fraunhofer region boundary (i.e., the conventional limit among far field and near field) when antennas of different size are considered. It can be noticed that, in the THz region, even with antennas of a practical size, e.g. 10 cm, the near field (i.e., the spherical wavefront propagation) must be considered for almost any practical operating distance in IIoT applications. Moreover, when big antennas are employed, for example large IRSs, practical operating distances will fall completely within the near-field. In this case, new opportunities are offered, as will be detailed in the next section.

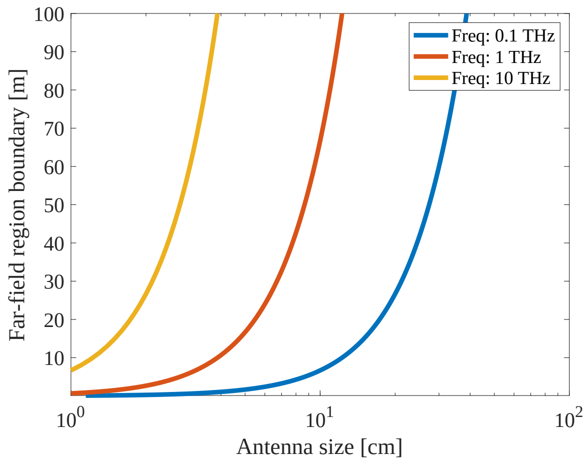


**Fig. 4** – Far-field region (Fraunhofer) boundary [m] as a function of the antenna size [cm], for different frequencies in the THz band

#### *4.1.1 High-rank LOS-MIMO*

A first interesting opportunity offered by propagation within the near-field region, is that of overcoming one of the main limitations coming from the use of THz frequency, resulting in quasi-LOS propagation with limited multipath, thus preventing the exploitation of spatial multiplexing for improving the link capacity. In fact, within the near-field region, the channel rank becomes larger than one even in strong LOS conditions [44], thus capable of boosting significantly the channel capacity through high-rank LOS MIMO, with a capacity gain much higher than that obtained with simple beamforming gain.

The study of capacity gain achievable with high-rank LOS MIMO solutions is at its infancy, and new methods for exploiting this capability, starting from the theoretical modeling of communications in the near field, needs to be investigated. An interesting possibility is that of modeling dense antenna arrays or even metasurface-based antennas (also known as Large Intelligent Surfaces (LISs)) as a continuous array of an infinite number of infinitesimal antennas, where proper distribution of currents must be considered for exploiting the different communication modes, as discussed in [45]. Wireless communications exploiting an uncountable infinite number of antennas in a finite space has been recently defined as holographic MIMO [44, 46]. Optimal communications between LISs, considering a continuum of infinitesimal antennas and the continuous wireless channel, can be modeled as the problem of communicating between a couple of spatial regions (or volumes in the case the antenna thickness is not considered negligible). This enables moving away from the classical MIMO model of point-defined antennas, which can be considered as a particular case of this general formulation, where the continuous space EM channel and continuous signals (propagating waves) are sampled according to a specific placement of the array elements. Then, communications are viewed as a functional analysis problem depending only on geometric relationships, whose goal is to determine the optimal set of EM functions at transmitter and receiver sides to transfer information between the spatial regions. In this manner, the ultimate limits for communication, namely the intrinsic capacity of the continuous-space wireless channel, can be investigated independently of the specific technology and number of antenna elements. Unfortunately, optimal LOS MIMO schemes require an extremely accurate knowledge of system geometry (i.e., devices' position), which might involve long and somewhat complex CSI/beamforming processes. Therefore, an open issue is the study of simplified CSI estimation schemes and/or ad hoc EM functions that are less sensitive to position estimation mismatches. Moreover, in the specific context of THz-based IIoT applications, practical schemes capable of approximating the realization of complex distributions of current in terms of amplitude/phase over metasurface-based antennas need to be identified, thus reducing drastically the overall complexity [47].

#### *4.1.2 Smart radio environments*

IRSs have emerged as promising devices for manipulating the THz waves. As metasurfaces, they show powerful capabilities in controlling the amplitude, phase, polarization and wave front of EM waves with unprecedented freedom. As example, IRSs allow real-time reconfiguration of the phase distribution allowing to control the beam direction [48, 49].

In order to cope with NLOS channel conditions without additional latency and significant increase of complexity, IRSs will be a candidate for creating multi-link diversity providing the necessary soft coverage and seamless communications, also in mobility conditions [50]. In this direction, the greatest challenges come from the need for defining optimization algorithms for IRSs under the constraint of low complexity, in order to keep as low as possible the additional signaling required for their control. As an example, when instantaneous CSI is not available or too complex to obtain, optimization based on statistical CSI accounting for users' movement prediction obtained from the sensing capability of the network could be considered [51]. This opportunity would allow for the reduction of signaling with the IRS as well as relaxing the configuration rate requirements, thus pushing for the use of simpler metasurfaces instead of more performing but more complex relays, requiring full CSI availability.

The exploitation of smart radio environments in THz-based intelligent mesh networks, should also account for the simultaneous presence of nodes with different complexity (radio transceivers, sensors, backscatter-based radios...). As for standard point-to-point links, also IRS-aided communications cannot be analyzed and designed without accounting for the challenges and perspectives offered by near-field propagation, as for any active and passive EM structure in the environment. Unlike the situations traditionally investigated, where IRSs are assumed to work in far-field conditions with respect to base stations and user positions, the presence of large IRSs will make the far-field hypothesis no longer valid, enabling the creation of additional artificial multipath components capable of increasing the channel rank [50].

As both reflecting surfaces and antennas can be realized exploiting metamaterials, interesting opportunities could arise by considering EM-based signal processing techniques, i.e., move part of the PHY layer operations from the digital domain to the analog/EM domain, thus obtaining a good balance between performance, complexity and latency [52]. In fact, the flexibility offered by metamaterials paves the way to shift some functionalities that are typically performed using digital circuits directly at the EM level (e.g., spatial Fast Fourier Transform (FFT), frequency-dependent beam steering) with the purpose to tackle complexity issues and reduce significantly the latency, as the processing would be realized at the speed of light.

### 4.2 MAC protocols

Traditional MAC protocols cannot be directly applied to IIoT scenarios working at THz, but must be redesigned taking into account all the peculiarities of THz frequencies, such as the problem of limited communication distances, frequency selectivity, deafness and propagation delays, that can be larger than packet transmission times and cannot be neglected at such frequencies. In addition, hidden terminal problem should be carefully considered due to the very short-range nature of THz communications, especially when low-complexity devices are involved, leading to a high probability that devices cannot hear each other.

In a typical IIoT scenario, the PLC may be equipped with multiple antennas, since it has no strict requirements in terms of miniaturization, while sensors, which are low-complexity devices, might have only one radiating element. As a result, the PLC can generate directive beams, to gather data from sensors located in different areas of the machine. The different beams present in the 3D space may be swept in a time-division fashion, brought to a Spatial Time Division Multiple Access (STDMA), or in a frequency-division fashion, resulting in a Spatial Frequency Division Multiple Access (SFDMA) [53].

 

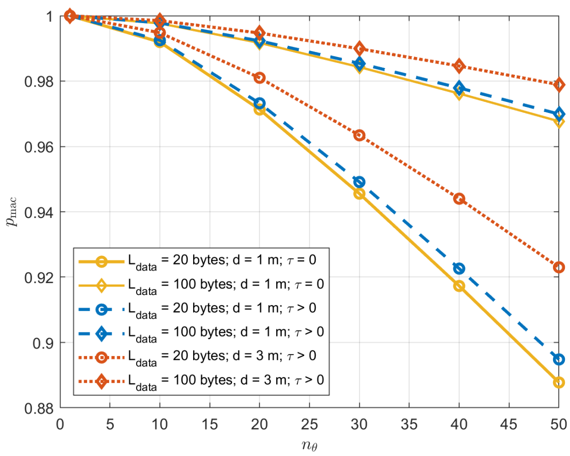


**Fig. 5** – Packet success probability at MAC layer, $p_{\text{mac}}$, as a function of the number of nodes in a beam $n_\theta$, the maximum PLC-node distance $d = 1$ m and 3 m, the data packet size $\text{L}_{\text{data}} = 20$ and 100 bytes, and by also considering the benchmark case where propagation delays are neglected, that is, $\tau = 0$ for a fixed $d = 1$ m

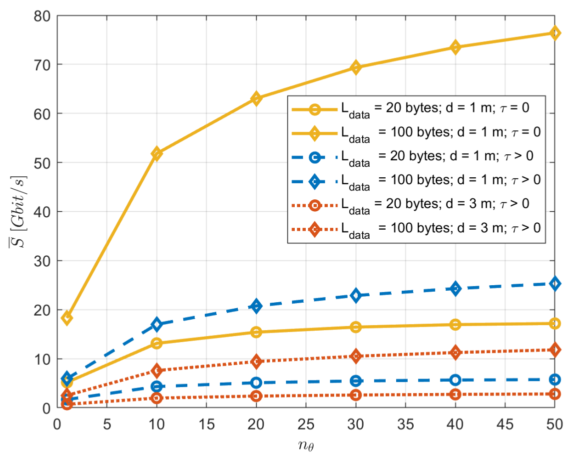


**Fig. 6** – Average network throughput, $\overline{S}$, as a function of $n_\theta$, maximum PLC-node distance $d = 1$ m and 3 m, the data packet size $L_{\text{data}} = 20$ and 100 bytes, and by also considering the benchmark case where prop agation delays are neglected, that is, $\tau = 0$ for a fixed $d = 1$ m

In both cases, interference among sensors belonging to the same beam (i.e., illuminated at the same time, and/or using the same frequency resource) may be present and proper MAC protocols should be devised to limit this interference [36]. Among the possible protocols, we envisage CSMA-based protocols, OCDMA and NOMA.

As far as CSMA, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) with RTS and CTS packets exchange is one feasible solution. Indeed, the use of back-off algorithms allows us to decrease collisions that may be dramatic in a scenario where sensors belonging to the same beam are all triggered at the same time to start the communication (i.e., the instant when the beam is properly steered toward them); while the use of RTS/CTS packets is needed to improve the performance in the presence of the hidden terminal problem. Indeed, since sensors are equipped with omnidirectional antennas, they have a very short reception range and the number of hidden sensors may be notable. The CSMA/CA protocol may be analytically modeled with a semi-Markov chain, according to three main assumptions:

- **Assumption 1**: Constant and independent collision probability of packets transmitted by the different nodes, regardless of the number of retransmissions already suffered.
- **Assumption 2**: Constant and independent probability of finding the channel-free, regardless of the back-off slot and number of retransmissions already suffered.
- **Assumption 3**: Independence between the two types of collisions, the first between RTS packets and the second between RTS and CTS.

Specifically, the model should take into account all the packet transmission durations (e.g., RTS, CTS, and data), and especially the presence of propagation delays, which may have a huge impact on the performance metrics when considering the THz band. This is shown in two examples of numerical results, in terms of success probability at MAC layer $p_{\text{mac}}$ and average network throughput $\overline{S}$. In particular, $p_{\text{mac}}$ is the probability that an RTS packet, which is generated by a generic node in the network, is correctly received by the GW; while $\overline{S}$ is defined as the number of information bits per unit of time which are successfully received by the GW at the MAC layer. Then, in Fig. 5 we show $p_{\text{mac}}$, as a function of the number of nodes in one beam, $n_\theta$, by varying the maximum PLC-node distance $d$, the data packet size $L_{\text{data}}$, and by also considering the benchmark case where propagation delays are neglected, that is, $\tau = 0$. The first effect of propagation delays is an advantage: $p_{\text{mac}}$ increases with $d$, meaning that longer propagation delays help in reducing collisions. Indeed, in the analytical model we assume synchronized transmissions (i.e., all nodes start transmitting data at the same time), which can be guaranteed in real systems in several ways, e.g., through properly enlarging the different protocol phases, or by means of an initial synchronization process [36]. In this way, the distributions of nodes in a sufficiently wide space allows us to increase the probability that packets transmitted simultaneously reach the PLC in different instants without colliding, thanks to the non-negligible propagation delays.

On the other hand, the disadvantage is in terms of average network throughput $\overline{S}$, shown in Fig. 6 as a function of $n_\theta$, that decreases by increasing the propagation delay. This is due to the fact that for higher $d$, the PLC needs more time to capture the data packets sent from nodes.

These two graphs show that for an uplink intra-machine communication, propagation delays at THz frequencies cannot be neglected, but the CSMA/CA protocol, if properly modeled can guarantee good performance in terms of success probability at MAC layer and network throughput.

 

Another possible protocol to be used to limit interference among sensors in the same beam is OCDMA, which inherits the OCDM principle, where a single user transmits $N$ information-bearing chirp waveforms in the same symbol time and occupying the same band; however, in the OCDMA paradigm, the PLC assigns one chirp to each sensor. Therefore, each node transmits just one chirp per symbol time, and the PLC exploits the chirp orthogonality to retrieve the different information content coming from the overlapping $N$ chirps [36]. Nevertheless, this mechanism requires a tight synchronization between node transmissions to preserve chirp orthogonality. However, at THz frequencies, it can be difficult to synchronize users in time, since transmissions last few tens of nanoseconds. Moreover, to ensure synchronization, sensors have to start transmitting at proper instants, depending on their distance from the PLC (the so-called timing advance concept). Remarkably, the distance distribution should be known a priori, which is not always the case, when sensors are mounted on the movable part of the machine. Hence, these drawbacks can be solved by using CSMA/CA in the uplink, while OCDMA can be used in the downlink to avoid the synchronization issues and thus to take full advantage of OCDMA. In the downlink, the PLC can send commands to the actuators to adjust some physical parameters of the environment (e.g., temperature, humidity, movement, etc…) that are not in line with expectations. To this aim, the PLC assigns one chirp to each user, thus multiplexing $N$ devices in the same time-frequency slot. The actuators will then retrieve their information content by means of parallel correlators.

Finally, in NOMA, power-domain multiplexing could be implemented, with different power coefficients allocated to sensors, according to channel conditions to achieve a high system performance. In this case, at the PLC, successive interference cancellation is applied to decode the signals one by one until the desired one is obtained, providing a good trade-off between system throughput and fairness.

Identifying the most proper MAC protocol to be used is not an easy task, because it strictly depends on the type of application to be implemented and on the stringent requirements to be met, such as latency, reliability, throughput, and high-precision positioning (achieved thanks to ISAC). We envisage a network where different MAC protocols will be used simultaneously in separate areas, and the selection could be done via exploiting Artificial Intelligence (AI)-based algorithms. Another important contribution will be the joint design of PHY/MAC to take advantage of the possibility to perform beam focusing in near-field conditions which allows a better interference mitigation than beam steering in far-field conditions [54].

## 4.3 Integrated sensing and communication

ISAC is a new interesting paradigm involving the merging of communications and localization of active (cooperating) and/or passive (non-cooperating) subjects with the same signal set, thus enabling the saving of bandwidth and resources in general [40].

Due to the already-discussed propagation happening within the near-field when operating with THz bands, novel opportunities offered by near-field localization will be of interest, thus adding increased accuracy with respect to traditional far-field approaches based only on angle-of-arrival and time-of-arrival estimation. In this case, in fact, single-anchor localization becomes feasible [55, 56], thanks to the depth resolution of large antenna arrays coming from the possibility of focusing of the radiated/sensed EM field in a specific region (spot) of the environment (beam with finite depth [47, 57]). Due to the large operating frequency, a careful investigation of the relationship among CSI and positioning is needed. In fact, the estimation of the CSI is usually one of the most critical tasks in wireless communications, and when operating in the near field the channel is even more informative, thereby increasing the estimation complexity. In fact, classical estimation algorithms with low pilot overhead rely on the channel sparsity in the angular domain (i.e., they exploit the far-field planar-wavefront assumption); differently, in near-fear channel conditions, sparsity can be exploited only considering channel estimation in the polar domain (i.e., accounting for the actual spherical wavefront) [58]. On the other hand, when moving at THz frequencies, obstacles may completely block the signal and multipath components become sparse so that communication is mainly enabled by LOS conditions. As a consequence, the CSI is expected to be highly correlated to the geometric configuration of antennas, i.e., their relative position and orientation. In such a case, performing CSI estimation according to ad-hoc approaches accounting for the near-field channel characteristics (e.g., [58]) enables localization as a by-product, thus making CSI and localization intimately linked and enabling us to tackle them jointly.

Finally, a disruptive use of THz-based propagation will concern its *imaging* capability, i.e., enhanced sensing of the surroundings capable of providing a map of the environment similar to that obtained with photography [59]. In this sense, additional Key Performance Indicators (KPIs) and performance metrics concerning the resolution should be considered, characterizing the performance which can be obtained with different frequency bands and operating bandwidths, in addition to more traditional metrics such as localization/tracking accuracy and outage. As an example, in Fig. 7 the resolution limit in meters as a function of the antenna size in centimeters is reported for different frequencies in the THz band. Resolution is computed from the traditional Rayleigh diffraction limit usually considered in optics, assuming a target pixel at a certain distance from the antenna of a given aperture.[1] In particular, it can be noticed that cm-resolution (or better) can be achieved when exploiting 1-10 THz frequency bands for targets even at a 20 m distance, when considering antennas of practical size, for example below 10 cm.

[1] As before, in the case of a large antenna array, the antenna size should indicate that of the whole array, not that of the single array element.

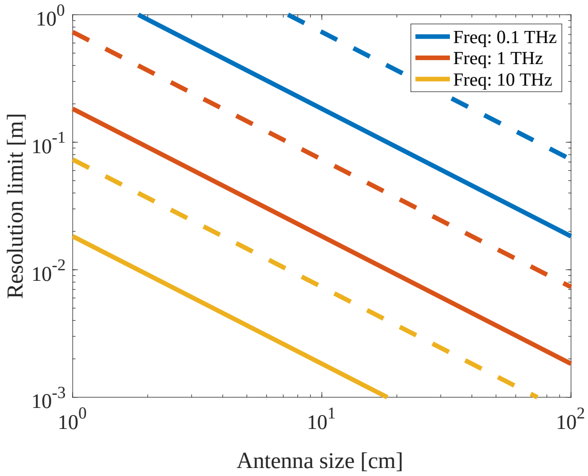


**Fig. 7** – Resolution limit [m] as a function of the antenna size [cm], for different frequencies in the THz band. Continuous lines (—) are for a target at 5 m distance; dashed lines (– –) are for a target at 20 m distance

The high resolution provided by the high carrier frequency and large bandwidth available at THz frequencies will be further enhanced by combining the sensing capabilities of active and passive (IRS) nodes [60]. This approach will allow us to enhance the sensing accuracy by exploiting the presence of multiple points of view. In this direction, a careful investigation of the theoretical performance bounds on localization accuracy of active and/or passive nodes, exploiting the same signal set used for communications, is required.

In order to achieve the soft coverage goal for the network, i.e., the maintenance of communications with different levels of obstruction of the nodes, particular attention could be devoted to stripe IRSs, i.e., long tape-like IRSs that can be easily deployed in the environment and on machines, so that the coverage extension via IRS is very large at least in one dimension, in effect reducing the NLOS occasions and realizing near-field propagation conditions [61].

## 4.4 Multi-goal network optimization

Industrial plants, in particular in manufacturing factories, can be characterized by highly-dynamic time-space evolution of IIoT applications. Within an area of a few hundreds of square meters, separate production processes might coexist and different types of machines might be present. Some of them could be equipped with intra-machine wireless networks to implement motion control applications; others could apply control-to-control requiring inter-machine communications; and some part of the plant might host digital twin paradigms. In some part of the factory there might be UAVs, AGVs or moving robots, while in some others all machines are static. So, the wireless network connecting all machines, sensors, actuators and PLCs might need to address totally different requirements in separate areas of the factory. Moreover, production in manufacturing plants is also characterized by time-varying needs; for maintenance reasons, or due to the steps of a sequential process, machines can change their scheduled activities very often; the presence of humans require fast reaction times to possible dangerous situations. As a result, the requirements set by this multi-goal environment evolve in time and space and the wireless network supporting the production process must be able to follow these evolutions.

As we discussed, THz communications, IRSs and ISACs constitute essential technologies to serve the industrial environment with networks able to fulfill the stringent requirements of IIoT applications. The management of the combination of these disruptive elements in a multi-goal context, however, is complex. The deployment of the wireless network must be done carefully considering the peculiarities of the production process it has to serve; the location of base stations offering connection to the Internet, and of IRSs, requiring precise planning. After deployment, the optimization of all radio resource assignment algorithms and their parameters must be performed having in mind the multi-goal context and the high dynamism of the environment.

From the deployment viewpoint, new planning procedures must be envisaged that include IRSs. The geometric description of the environment must be extremely accurate, to predict all possible LOS/NLOS conditions; in fact, the use of very short wavelengths combined to the complexity of machines make EM prediction a very challenging process. However, this can be facilitated by the fact that normally computer-aided management of these machines require a precise digital description of their geometries, which can be used for the sake of EM prediction applying deterministic modeling tools (e.g. ray tracing).

Much more complex is the optimization of the multi-goal network performance after deployment. There are basically three ways to manage this process:

1. As it is still done today for mobile radio systems, all network elements are configured according to a default set of parameters and algorithms, and then optimization is performed step-by-step observing the evolution of network KPIs; in a complex scenario like the manufacturing plants, this process might be non-trivial and converge towards rather suboptimal states.

2. The self-organizing network paradigm is brought to its highest level, introducing AI tools that observe the network and take decisions regarding the use of algorithms and their parameters in real time; the peculiarity and variety of the multi-goal network we are discussing, impose the use of multi-agent deep reinforcement tools, and possibly of federated learning.

 

3. Rather than asking the IoT network to react to the space-time evolving requirements of the IIoT applications, the network control is integrated with the network of PLCs that determine the schedule of events and production steps on the machines; this way, the wireless network can optimize its configuration not only by reacting to unexpected changes, but also accounting for the planned processes.

In all cases, new PHY-MAC cross-layer approaches to devise goal-oriented scheduling schemes, able to allocate the radio resources available over multiple links with the purpose of satisfying the (possibly conflicting) requirements posed by the connected devices, are required. The inclusion of active and passive (IRSs) nodes in the same network pose new challenges; the integration of communication and sensing requirements further increases the complexity of radio resource assignment algorithms.
THz-tailored MAC protocols must be designed from a network-level perspective. The key objective is the optimization of intelligent multi-goal mesh networks, capable of fulfilling seamlessly different requirements in different areas of the network.
The integration of localization techniques based on ISAC, is not only useful at the application level; indeed, the information on the position of nodes can be used, when suitably combined to the knowledge of the plant map, for the purpose of network real-time optimization.

## 5. CONCLUSIONS

THz networks are very promising to make the current and next industrial revolution possible. At the same time, they pose several challenges that need to be addressed both at the theoretical and technological levels. In this paper, we have provided an overview of these challenges along with possible solutions and research directions that encompass multidisciplinary aspects ranging from EM theory, information theory, signal processing, and network theory.

## ACKNOWLEDGEMENT

This work was supported, in part, by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU, partnership on “Telecommunications of the Future” (PE00000001 - program “RESTART”), and by the EU Horizon project TIMES (Grant no. 101096307).

## REFERENCES

[1] Jay Lee, Behrad Bagheri, and Hung-An Kao. “A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems”. In: *Manufacturing Letters* 3 (Jan. 2015), pp. 18–23. ISSN: 2213-8463.

[2] 5G-ACIA. “5G for Industrial Internet of Things (IIoT): Capabilities, Features, and Potential”. In: *ZVEI* (Nov. 2021).

[3] J. Cheng, W. Chen, F. Tao, and C. Lin. “Industrial IoT in 5G environment towards smart manufacturing”. In: *Journal of Industrial Information Integration* 10 (June 2018), pp. 10–19.

[4] NGMN Alliance. *” 5G E2E Technology to Support Verticals URLLC Requirements”*. 2020.

[5] 5G-ACIA. *”5G for Automation in Industry”*. 2019.

[6] 5G-CLARITY. “Use Case Specifications and Requirements”. In: *Deliverable D2.1* (2020).

[7] S. Ghafoor, N. Boujnah, M. H. Rehmani, and A. Davy. “MAC protocols for terahertz communication: A comprehensive survey”. In: *IEEE Communications Surveys & Tutorials* 22.4 (2020), pp. 2236–2282.

[8] S. Priebe and T. Kurner. “Stochastic modeling of THz indoor radio channels”. In: *IEEE Trans. Wireless Commun.* 12.9 (2013), pp. 4445–4455.

[9] H. Elayan, O. Amin, R. M. Shubair, and M. Alouini. “Terahertz communication: The opportunities of wireless technology beyond 5G”. In: *2018 International Conference on Advanced Communication Technologies and Networking (CommNet)*. Apr. 2018, pp. 1–5.

[10] F. Lemic, S. Abadal, W. Tavernier, P. Stroobant, D. Colle, E. Alarc n, J. Marquez-Barja, and J. Famaey. “Survey on Terahertz Nanocommunication and Networking: A Top-Down Perspective”. In: *IEEE Journal on Selected Areas in Communications* 39.6 (2021), pp. 1506–1543.

[11] Z. Chen, X. Ma, B. Zhang, Y. Zhang, Z. Niu, N. Kuang, W. Chen, L. Li, and S. Li. “A survey on terahertz communications”. In: *China Communications* 16.2 (2019), pp. 1–35.

[12] D. C. Nguyen, M. Ding, P. N. Pathirana, A. Seneviratne, J. Li, D. Niyato, O. Dobre, and H. V. Poor. “6G Internet of Things: A Comprehensive Survey”. In: *IEEE Internet of Things Journal* 9.1 (2022), pp. 359–383.

[13] E. Dahlman, S. Parkvall, and J. Sk ld. *5G NR : the next generation wireless access technology*. London, United Kingdom : Academic Press, an imprint of El-sevier, 2021.

[14] Davide Dardari, Andrea Conti, Ulric Ferner, Andrea Giorgetti, and Moe Z Win. “Ranging with ultrawide bandwidth signals in multipath environments”. In: *Proceedings of the IEEE* 97.2 (2009), pp. 404–426.

[15] G. Gil, J. Y. Lee, and D. Cho. “Estimation of Path Loss Parameters of a Sub-Terahertz Wireless Channel Using Monostatic Radar”. In: *IEEE Access* 9 (2021), pp. 52654–52663.

[16] J. M. Jornet and I. F. Akyildiz. “Channel Modeling and Capacity Analysis for Electromagnetic Wireless Nanonetworks in the Terahertz Band”. In: *IEEE Transactions on Wireless Communications* 10.10 (2011), pp. 3211–3221.

[17] C. Han and I. F. Akyildiz. “Distance-aware multi-carrier (DAMC) modulation in Terahertz Band communication”. In: *2014 IEEE International Conference on Communications (ICC)*. 2014, pp. 5461–5467.

[18] C. Bosso, P. Sen, X. Cantos-Roman, C. Parisi, N. Thawdar, and J. M. Jornet. “Ultrabroadband Spread Spectrum Techniques for Secure Dynamic Spectrum Sharing Above 100 GHz Between Active and Passive Users”. In: *2021 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*. 2021, pp. 45–52.

[19] A. A. Boulogeorgos, A. Alexiou, T. Merkle, C. Schubert, R. Elschner, A. Katsiotis, P. Stavrianos, D. Kritharidis, P. Chartsias, J. Kokkoniemi, M. Juntti, J. Lehtomaki, A. Teixeira, and F. Rodrigues. “Terahertz Technologies to Deliver Optical Network Quality of Experience in Wireless Systems Beyond 5G”. In: *IEEE Communications Magazine* 56.6 (2018), pp. 144–151.

[20] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Madanayake, S. Mandal, A. Alkhateeb, and G. C. Trichopoulos. “Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond”. In: *IEEE Access* 7 (2019), pp. 78729–78757. ISSN:2169-3536.

[21] Q. Xia, Z. Hossain, M. J. Medley, and J. M. Jornet. “A Link-layer Synchronization and Medium Access Control Protocol for Terahertz-band Communication Networks”. In: *IEEE Trans. on Mob. Comp.* (2019), pp. 1–1.

[22] Anique A. and Sinem C. E. “Directional MAC protocol for IEEE 802.11ad based wireless local area networks”. In: *Ad Hoc Networks* 69 (2018), pp. 49–64.

[23] R.R. Choudhury, Xue Y., R. Ramanathan, and N.H. Vaidya. “On designing MAC protocols for wireless networks using directional antennas”. In: *IEEE Transactions on Mobile Computing* 5.5 (2006), pp. 477–491.

[24] Haitao Wu, Yong Peng, Keping Long, Shiduan Cheng, and Jian Ma. “Performance of reliable transport protocol over IEEE 802.11 wireless LAN: analysis and enhancement”. In: *Proceedings.Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies*. Vol. 2. 2002, 599–607 vol.2.

[25] Jaehyuk Choi, Joon Yoo, and Chong-kwon Kim. “A novel performance analysis model for an IEEE 802.11 wireless LAN”. In: *IEEE Communications Letters* 10.5 (2006), pp. 335–337.

[26] X. Li and Q. Zeng. “Influence of Bit Error Rate on the Performance of IEEE 802.11 MAC Protocol”. In: *2007 IEEE Wireless Communications and Networking Conference*. 2007, pp. 367–372.

[27] B. Jang and M. L. Sichitiu. “IEEE 802.11 Saturation Throughput Analysis in the Presence of Hidden Terminals”. In: *IEEE/ACM Transactions on Networking* 20.2 (2012), pp. 557–570.

[28] B. Nardelli and E. W. Knightly. “Closed-form throughput expressions for CSMA networks with collisions and hidden terminals”. In: *2012 Proceedings IEEE INFOCOM*. 2012, pp. 2309–2317.

[29] X. Ouyang and J. Zhao. “Orthogonal chirp division multiplexing”. In: *IEEE Transactions on Communications* 64.9 (2016), pp. 3946–3957.

[30] P. Zhu, X. Xu, X. Tu, Y. Chen, and Y. Tao. “Anti-multipath orthogonal chirp division multiplexing for underwater acoustic communication”. In: *IEEE Access* 8 (2020), pp. 13305–13314.

[31] X. Lv, J. Wang, Z. Jiang, and W. Jiao. “A novel PAPR reduction method for OCDM-based radar-communication signal”. In: *2018 IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G)*. 2018, pp. 1–3.

[32] A. A. A. Solyman, H. Attar, M. R. Khosravi, V. G. Menon, A. Jolfaei, V. Balasubramanian, B. Selvaraj, and P. Tavallali. “A Low-Complexity Equalizer for Video Broadcasting in Cyber-Physical Social Systems Through Handheld Mobile Devices”. In: *IEEE Access* 8 (2020), pp. 67591–67602.

[33] L. Giroto de Oliveira, M. de Lima Filomeno, H. V. Poor, and M. Vidal Ribeiro. “Orthogonal Chirp-Division Multiplexing for Power Line Sensing via Time-Domain Reflectometry”. In: *IEEE Sensors Journal* 21.2 (2021), pp. 955–964.

[34] R. Bomfin, M. Chafii, and G. Fettweis. “Low-Complexity Iterative Receiver for Orthogonal Chirp Division Multiplexing”. In: *2019 IEEE Wireless Communications and Networking Conference Workshop (WCNCW)*. 2019, pp. 1–6.

[35] A. Solyman, H. Attar, M. R. Khosravi, and B. Koyuncu. “MIMO-OFDM/OCDM low-complexity equalization under a doubly dispersive channel in wireless sensor networks”. In: *International Journal of Distributed Sensor Networks* 16.6 (2020), p. 1550147720912950.

[36] Chiara Buratti, Giampaolo Cuozzo, and Roberto Verdone. “OCDMA: a MAC Protocol for Industrial Intra-machine TeraHertz Network”. In: *Journal of Infrared, Millimeter, and Terahertz Waves* (2022), pp. 1–26.

[37] M. Hassan, M. Singh, and K. Hamid. “Survey on NOMA and Spectrum Sharing Techniques in 5G”. In: *2021 IEEE International Conference on Smart Information Systems and Technologies (SIST)*. IEEE. 2021, pp. 1–4.

 

[38] B. Makki, K. Chitti, A. Behravan, and M. Alouini. "A survey of NOMA: Current status and open research challenges". In: *IEEE Open Journal of the Communications Society* 1 (2020), pp. 179–189.

[39] O. Maraqa, A. Rajasekaran, S. Al-Ahmadi, H. Yanikomeroglu, and S. Sait. "A survey of rate-optimal power domain NOMA with enabling technologies of future wireless networks". In: *IEEE Communications Surveys & Tutorials* 22.4 (2020), pp. 2192–2235.

[40] C. De Lima, D. Belot, R. Berkvens, A. Bourdoux, D. Dardari, M. Guillaud, M. Isomursu, E. S. Lohan, Y. Miao, A. N. Barreto, M. R. K. Aziz, J. Saloranta, T. Sanguanpuak, H. Sarieddeen, G. Seco-Granados, J. Suutala, T. Svensson, M. Valkama, B. Van Liempd, and H. Wymeersch. "Convergent Communication, Sensing and Localization in 6G Systems: An Overview of Technologies, Opportunities and Challenges". In: *IEEE Access* 9 (2021), pp. 26902–26925.

[41] Z. Xiao and Y. Zeng. "Waveform Design and Performance Analysis for Full-Duplex Integrated Sensing and Communication". In: *IEEE Journal on Selected Areas in Communications* 6 (2022), pp. 1823–1837.

[42] C. Sturm and W. Wiesbeck. "Waveform Design and Signal Processing Aspects for Fusion of Wireless Communications and Radar Sensing". In: *Proceedings of the IEEE* 99.7 (2011), pp. 1236–1259.

[43] M. Lotti, G. Pasolini, A. Guerra, M. Caillet, R. D'Errico, and D. Dardari. "Radio Simultaneous Localization and Mapping in the Terahertz Band". In: *WSA 2021 - International ITG Workshop on Smart Antennas*. Nov. 2021.

[44] D. Dardari and N. Decarli. "Holographic Communication Using Intelligent Surfaces". In: *IEEE Communications Magazine* 59.6 (2021), pp. 35–41.

[45] Davide Dardari. "Communicating with large intelligent surfaces: Fundamental limits and models". In: *IEEE Journal on Selected Areas in Communications* 38.11 (2020), pp. 2526–2537.

[46] Emil Björnson, Luca Sanguinetti, Henk Wymeersch, Jakob Hoydis, and Thomas L. Marzetta. "Massive MIMO is a reality - What is next?: Five promising research directions for antenna arrays". In: *Dig- ital Signal Processing* (2019). ISSN: 1051-2004. URL:http : / / www . sciencedirect . com / science /article / pii / S1051200419300776 (visited on 12/01/2020).

[47] N. Decarli and D. Dardari. "Communication Modes With Large Intelligent Surfaces in the Near Field". In: *IEEE Access* 9 (2021), pp. 165648–165666.

[48] E. Björnson, H. Wymeersch, B. Matthiesen, P. Popovski, L. Sanguinetti, and E. de Carvalho. "Reconfigurable Intelligent Surfaces: A signal processing perspective with wireless applications". In: *IEEE Signal Processing Magazine* 39.2 (2022), pp. 135–158.

[49] M. Di Renzo, A. Zappone, M. Debbah, M.-S. Alouini, C. Yuen, J. de Rosny, and S. Tretyakov. "Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and road ahead". In: *IEEE Journal Selected Areas in Communications* (2020).

[50] Ö. Özdogan, E. Björnson, and E. G. Larsson. "Using Intelligent Relecting Surfaces for Rank Improvement in MIMO Communications". In: *arXiv e-prints*, arXiv:2002.02182 (Feb. 2020), arXiv:2002.02182. arXiv: 2002.02182 [eess.SP].

[51] A. Abrardo, D. Dardari, and M. Di Renzo. "Intelligent Relecting Surfaces: Sum-Rate Optimization Based on Statistical Position Information". In: *IEEE Transactions on Communications* 69.10 (2021), pp. 7121–7136.

[52] M. Barbuto, Z. Hamzavi-Zarghani, M. Longhi, A. Monti, D. Ramaccia, S. Vellucci, A. Toscano, and F. Bilotti. "Metasurfaces 3.0: a New Paradigm for Enabling Smart Electromagnetic Environments". In: *IEEE Transactions on Antennas and Propagation* (2021), pp. 1–1.

[53] E. R. Castillo, P. Harati, I. Kallfass, P. Hügler, C. Waldschmidt, and S. Shiba. "Spatial-frequency-scanning data transmission for mmW multi-user wireless communication systems". In: *2017 47th European Microwave Conference (EuMC)*. 2017, pp. 220–223.

[54] H. Zhang, N. Shlezinger, F. Guidi, D. Dardari, M. F. Imani, and Y. C. Eldar. "Beam Focusing for Near-Field Multi-User MIMO Communications". In: *IEEE Transactions on Wireless Communications* (2022), pp. 1–1.

[55] F. Guidi and D. Dardari. "Radio Positioning with EM Processing of the Spherical Wavefront". In: *IEEE Transactions on Wireless Communications* 20.6 (June 2021), pp. 3571–3586.

[56] A. D. J. Torres, A. D'Amico, L. Sanguinetti, and M. Z. Win. *Cramér-Rao Bounds for Near-Field Localization*. 2021. URL:https://arxiv.org/abs/2104.14825.

[57] E. Björnson, Ö. T. Demir, and L. Sanguinetti. "A Primer on Near-Field Beamforming for Arrays and Reconigur able Intelligent Surfaces". In: *2021 55th Asilomar Conference on Signals, Systems, and Computers*. 2021, pp. 105–112.

[58] Mingyao Cui and Linglong Dai. "Channel Estimation for Extremely Large-Scale MIMO: Far-Field or Near-Field?" In: *IEEE Transactions on Communications* 70.4 (2022), pp. 2663–2677.

 

[59] H. Sarieddeen, N. Saeed, T. Y. Al-Naffouri, and M. Alouini. "Next Generation Terahertz Communications: A Rendezvous of Sensing, Imaging and Localization". In: *arXiv e-prints*, arXiv:1909.10462 (Sept. 2019), arXiv:1909.10462. arXiv: 1909 . 10462 [eess.SP].

[60] A. Elzanaty, A. Guerra, F. Guidi, and M. Alouini. "Reconigur able Intelligent Surfaces for Localization: Position and Orientation Error Bounds". In: *IEEE Transactions on Signal Processing* 69 (2021), pp. 5386–5402.

[61] D. Dardari, N. Decarli, A. Guerra, and F. Guidi. "LOS/NLOS Near-Field Localization With a Large Reconigur able Intelligent Surface". In: *IEEE Transactions on Wireless Communications* 21.6 (2022), pp. 4282–4294.

## AUTHORS

**Sara Cavallero** received a B.Sc in electronics and telecommunications engineering and an M.Sc with honors in telecommunications engineering from the University of Bologna, Italy, in 2018 and 2021, respectively. She is currently pursuing a Ph.D. in electronics, telecommunications, and information technologies engineering (ETIT) at the University of Bologna. Her research activity is focused on the design and modeling of MAC protocols for Industrial Internet of Things applications working at THz frequencies and the development of scheduling optimization algorithms of 5G NR networks to promote URLLC. She is also studying mathematical models based on Markov chains for the deployment of MAC protocols. She is the winner of "Premio Mela d'Oro", Fondazione Marisa Bellisario, telecommunications engineering new graduate section.

**Nicolò Decarli** received an M.S. degree in telecommunications engineering (with honors), and a PhD degree in electronics, telecommunications and information technologies from the University of Bologna, Italy, in 2009 and 2013, respectively. Between 2012 and 2013 he was a visiting student at the Laboratory for Information and Decision Systems (LIDS) of the Massachusetts Institute of Technology (MIT), USA. In 2020 he joined the Institute of Electronics, Computer and Telecommunication Engineering (IEIIT) of the National Research Council of Italy (CNR). His research interests include wireless communication systems and techniques, and signal processing.

**Giampaolo Cuozzo** received a B.Sc with honors in electronics and telecommunications engineering and an M.Sc with honors in telecommunications engineering from the University of Bologna, in 2017 and 2019, respectively. He is currently pursuing a Ph.D. in electronics, telecommunications, and information technologies engineering (ETIT) at the University of Bologna. His research activity is focused on the study, development and validation of wireless networks for the Industrial Internet of Things, with a particular focus on MAC protocols for THz-based systems and scheduling optimization algorithms for 5G NR networks. He is also involved in experimental activities that exploit current wireless technologies, like 5G, LoRa, Zigbee and NB-IoT.

**Chiara Buratti** received an M.Sc. degree in telecommunications engineering from the University of Bologna, Italy. She is an assistant professor with the University of Bologna. Since 2006, when she started her Ph.D., she has been involved in the research related to wireless networks for the Internet of Things, with particular reference to MAC and routing protocol design. She is currently a principal investigator of the COST Innovators' Grant IG15104, IMMUNet. She has been the main proponent of the Cost Action CA20120, INTERACT, and she is currently vice-chair and grant holder of the Action. She has been chair of the EWG on IoT of the Cost Action IRACON, Dissemination Manager for the FP7 WiserBAN Project, and responsible for the EuWIn@Bologna laboratory, created within the FP7 NoE Newcom#. She has coauthored more than 90 research papers.

**Davide Dardari** is a full professor at the University of Bologna, Italy. He has been a research afiliat e at the Massachusetts Institute of Technology, USA. His interests are in wireless communications, smart radio environments, localization techniques and distributed signal processing. He published more than 250 technical papers and played several important roles in various National and European Projects. He received the IEEE Aerospace and Electronic Systems Society's M. Barry Carlton Award (2011) and the IEEE Communications Society's Fred W. Ellersick Prize (2012). He is senior member of the IEEE where he was the chair of the Radio Communications Committee and Distinguished Lecturer (2018-2019) of the IEEE Communication Society. Currently, he is a senior member of the Editorial Board of the IEEE Signal Processing Magazine. He served as an editor for IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS from 2006 to 2012 and as guest editor for several Journals.

**Roberto Verdone** is a full professor at the University of Bologna, since 2001. He is the director of WiLab, the Italian Laboratory of Wireless Communications of CNIT. He is also co-director of the Joint Innovation Center on "Intelligent IoT for 6G" with Huawei. His main research interests are on the evolution from 5G to 6G, and the Internet of Things. He published 200 scientiic papers and few books on various aspects of wireless communications.