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Evaluation methodology for 6G sensing-assisted communication system performance

ANDREA RAMOS[1], ARTURO MROZOWSKI[1], DANAISY PRADO-ALVAREZ[1], JOSE F. MONSERRAT[1], YUNHAO ZHANG[2], ZIMING YU[2], AND YAN CHEN[2]

[1]iTEAM Research Institute, Universitat Politècnica de València, 46022 Valencia, Spain

[2]Huawei Technologies Co., Ltd., China

Corresponding author: Andrea Ramos (e-mail: anrapil@iteam.upv.es)

ABSTRACT Nowadays, Integrated Sensing and Communication (ISAC) is receiving significant attention in the frame of the Sixth Generation (6G). To assess the performance of future candidate ISAC technologies and to be able to compare them with each other, the standardization of evaluation methodologies is necessary. This paper introduces a suitable methodology for evaluating sensing-assisted communication systems. For this purpose, features similar to those included in the International Telecommunications Union (ITU) recommendation have been adopted, mainly geometry-based stochastic channel modeling and Key Performance Indicator (KPI) selection. The key elements of this evaluation methodology are the existence of a correlation between the sensing and the communication channels and the need for a spatial consistency model to obtain spatially correlated stochastic channels using the geometry-based stochastic model (GBSM). Considering these elements allows a wide range of usage scenarios to be evaluated within the ISAC framework. Finally, to clarify the evaluation procedure, a sensing-assisted channel estimation use case has been presented as an example of the applicability of the proposed methodology. Promising results are presented, where the ISAC solution can outperform a conventional communication system in terms of throughput.

INDEX TERMS 6G, ISAC, sensing capabilities, sensing-assisted communication.

I. INTRODUCTION

The increasing demand for high-speed connections with low latency, massive device connectivity, low power consumption, and high network reliability requirements have driven Fifth Generation (5G) systems to improve mobile communication capabilities [1]. 5G services have been geared towards human-centric applications and with applications for autonomous cars, smart buildings, and vertically developed industries. Given the evident digital transformation, next generation communication systems (NGCS) is expected to emphasize connecting people and things, enabling a fully intelligence-connected society. Therefore, Sixth Generation (6G) will usher in a new era of connected intelligence marked by the introduction of artificial intelligence (AI) and sensing as the two main novel usage scenarios [2]. Consequently, this leads to the foundation of new technology that will shape 6G networks. A vital pillar related to sensing is that its functionality will play an essential role in improving communication systems [3]. Hence, Integrated Sensing and Communication (ISAC) systems are well-positioned candidates to become a native technology for 6G networks.

ISAC systems are mainly based on the coexistence of sensing and communication capabilities in a single system that will allow sharing of scarce resources, such as hardware and spectrum [4]. This joint architecture will open up a range of promising and novelty applications, catering to both communication-assisted sensing and sensing-assisted communication.

On the one hand, the communication system as a sensor will employ radio waves' transmission, reflection, and scattering to obtain helpful information from the environment, introducing new services such as high-accuracy localization, imaging, and tracking [2]. On the other hand, the use of sensing information to improve communication will bring appealing benefits in terms of reducing channel estimation resources, optimizing beam management (beam tracking [5]), or identifying the most robust paths to the receiver (Rx) under Non Line of Sight (NLoS) conditions [6].

In the state of the art, some works delve into the analysis of current developments and the challenges inherent in this technology, as exemplified in reference [7]. Another interesting article is [8], which evaluates selected use cases based on analytical system models, or [9], which discusses the benefits of possible sensing-assisted communication use cases.

Despite all the attention ISAC is receiving, there is currently a lack of contributions proposing a methodology for evaluating ISAC systems. An effective evaluation methodology is a vital compass to guide the improvement and growth of any system. Having a structured and reliable evaluation methodology is important because it allows the research community to assess the current state to identify strengths and weaknesses, set clear objectives, and measure performance towards the desired achievement. So far, works on simulation methodology have focused on ISAC functionalities, advantages, and presentation of techniques that enhance communications through sensing [5]. Therefore, it is necessary to introduce evaluation criteria considering aspects related to signal processing and channel modeling, among others, specially oriented to study how sensing can be exploited for the benefit of communication.

Delving into further details regarding the construction of a methodology, the International Telecommunications Union (ITU) [10] has emphasized that a crucial element is a suitable channel model. Analytical or discrete channel models have been used so far within the ISAC framework [11]–[13]. Parameters such as Angle of Departure (AoD), Angle of Arrival (AoA), pathloss, and delays have been generated without considering the geometrical characteristics of the scenario. Given the complexity of sensing applications due to the required geometrical accuracy, the conventional channel models do not seem to fit these requirements.

Being map-specific, ray tracing (RT)-based channel models offer a deterministic approach, enabling the accurate study of propagation conditions. Indeed, prior contributions such as [14] have used a deterministic channel model to emulate ISAC. However, opting for them may involve a high computational cost. Moreover, from the standardization point of view, more scalable and flexible channel models are expected to be considered. In this direction, the Third Generation Partnership Project (3GPP) has included a geometry-based stochastic model (GBSM) in its specifications [15] for the communication channel model.

GBSMs have proven to be useful and powerful tools in which propagation paths are generated from probabilistic functions derived from channel measurement campaigns conducted in real scenarios, thus geometrically presetting the distribution of effective scatterers, i.e., the objects on which the set of rays are incident. This way, a fairly accurate characterization of the physical channels can be obtained from GBSM because, like the deterministic model, it considers the scenario's geometry. Additionally, GBSM can be used in different propagation scenarios and needs less computational resources compared to RT-based methods.

This paper presents a methodology for evaluating sensing-assisted communication systems considering GBSM as a type of channel modeling suitable for emulating ISAC systems. The main elements of this methodology lie in characterizing the propagation condition for sensing channel modeling, i.e., considering the correlation between the sensing and the communication channels and ensuring that both channels are spatially correlated. This way, a consistent channel evolution is achieved over time, and scenarios where users are expected to receive similar channel contributions, e.g., when considering user mobility or multiple nearby users, can be properly assessed.

To show the applicability of the proposed methodology, a sensing-assisted communication use case in a simple scenario is also introduced. For this purpose, the 3GPP channel model [15] is used for communications, while the GBSM model from [16] has been used for sensing characterization.

The remainder of the paper is organized as follows. Section II reviews the concept of sensing-assisted communications. Section III summarizes the main components of the evaluation methodology proposal. Section IV presents the results obtained after applying the methodology to assess a sensing-assisted communication use case. The results are compared with some benchmarks, highlighting the impact of considering the proposed methodology's main elements. Finally, in Section V, some concluding remarks are drawn.

II. SENSING-ASSISTED COMMUNICATIONS

Initially, sensing capabilities were introduced as a separate service, deriving valuable applications such as localization and mapping, imaging, or human activity recognition, among others [2], [9]. However, in recent years, it has become more evident that sensing can improve the performance of existing communication systems in different ways, so this approach is expected to be fully exploited. Therefore, several use cases are reviewed in this section to give readers a general understanding of the sensing-assisted communication framework. One specific use case is given to highlight the practical applicability of the proposed methodology.

A. SENSING-ASSISTED RESOURCE ALLOCATION

Given the ever-increasing demand for requirements in wireless communication networks, resource allocation (RA) efficiency on a service basis is important for overall performance. This process is considered challenging as it is user-centric to acquire better Quality of Service (QoS) [17]. In general, RA of a wireless communication system is defined mainly in terms of power control, spectral efficiency, energy efficiency, or spectrum allocation, among others. Numerous techniques have been applied to support the requirements of usage scenarios from 5G networks. Nevertheless, the use of ISAC allows for the redefinition of these techniques due to the prior knowledge of the user's location. For instance, spectrum reuse allows for higher performance and data rates when using a communication-only system. However, mutual interference is expected as the number of users increases in a scenario. Therefore, knowing the users' specific requirements and their location or trajectory, which can be estimated from sensing echo signals, it is possible to design bandwidth allocation schemes for each user, depending on the available spectrum [18].

The same rationale can be applied in scenarios such as vehicle-to-infrastructure (V2I), where high mobility can lead to connection drops. By predicting the trajectory through sensing, the roadside units (RSU) can prepare spectrum, power, and data resources in advance [5], [6]. Meanwhile, the authors of [19] believe in improving position estimation for multiple users by applying the Cramér–Rao bound (CRB). This approach minimizes localization errors and increases the data rate value in downlink (DL) communication, outperforming the conventional water-filling design.

B. SENSING-ASSISTED BEAM MANAGEMENT

With the increasing number of antennas in massive MIMO (mMIMO) and the use of narrower beam patterns in higher frequencies to cope with higher losses, beam management techniques are becoming a trending topic. Beam management focuses on the procedures for selecting and maintaining the transmitting and receiving beams. To obtain a beam pair for transmitter (Tx) and Rx and be able to initialize the communication, some delay, pilot signaling, and signal processing are introduced, significantly impacting overall system performance. As the number of possible beams increases, the complexity of the problem grows exponentially, and the effective performance drops. Therefore, multiple solutions are being proposed in the literature to reduce the beam pair searching time, including algorithms that simplify the beam pair search, using prior information to aid the beam training, machine learning approaches [20], and beam tracking.

The introduction of sensing and location capabilities in the communication scheme has enabled the generation of novel technologies to boost legacy beam management. These novel approaches reduce pilot signaling, suppress uplink (UL) feedback, increase spectrum efficiency, and minimize signal processing costs. Some interesting works on this topic can be found in [5], [21]–[26]. Using the prior information and the sensing information, the set of possible beams is significantly reduced, the tracking of the optimal beams is eased, and the system can also benefit from the sensing signal to be aware of the context. Moreover, the authors in [5], [23], [27] consider employing beam tracking and prediction, which ensures integration and coordination gains in these procedures.

C. SENSING-ASSISTED CHANNEL ESTIMATION

Acquiring a reliable channel estimate is a critical element in ensuring effective communication. Ideally, this procedure should involve frequent estimations, particularly in systems with many antenna ports or scenarios characterized by rapid channel fluctuations. Nonetheless, this estimation process often necessitates allocating pilot resources within a frame for channel estimation instead of data transmission, thereby introducing overhead in throughput, as fewer bits are transmitted per frame. Efficient estimation is a prerequisite for facilitating swift user access to resources while minimizing overhead consumption. Within this context, the integration of sensing capabilities can confer distinct advantages by enhancing channel acquisition through leveraging prior knowledge of the environment.

This paper presents a fast channel acquisition use case as an applicable example of the evaluation methodology for sensing-assisted communication systems. This use case addresses the estimation of the communication channel leveraging the information available from sensing. The aim is to replace the pilot-based channel estimation procedure using the knowledge of the echoes from sensing. For this alternative method to successfully enable data transmission, the information provided by the communication pilots and the sensing echoes must be similar. Hence, it is essential that both communication and sensing channels exhibit correlation based on the inherent fact that they share common multipath components (MPCs). The discussion on channel correlation will be further elaborated in the subsequent section.

III. EVALUATION METHODOLOGY

The ITU defines an evaluation methodology as a set of the necessary tools, steps, parameters, and procedures designed to assess a communication system on a technical basis. The establishment of unified guidelines in the form of a methodology makes it possible to assess systems fairly since the results in terms of performance obtained from the evaluation procedure applied to a given system are comparable to others. Regarding the elements that should be part of an evaluation methodology for wireless communication systems, at a minimum, it must include an appropriate selection of Key Performance Indicators (KPIs) to quantify system performance, criteria on how these KPIs will be measured, and a channel model to have realistic modeling of the propagation condition [10]. The determination of the latter two allows the replicability of the evaluation.

Consequently, when considering new ISAC designs, it seems reasonable to follow the above guidelines, intended for communication-only systems, to design an evaluation methodology for sensing-assisted communication systems since one of their main goals is to boost communication performance by leveraging sensing capabilities. Therefore, similar considerations to those described above are followed in this work.

Fig. 1 summarizes the fundamental elements considered for this work. Firstly, the main features related to the characterization of the sensing channel in Section III-A are presented, i.e., considering the correlation between sensing and communication channel and the spatial consistency. Then, in Section III-B, some KPIs are introduced to illustrate the performance achieved by the system, together with the criteria for measuring them. Finally, the step-by-step procedure to evaluate a sensing-assisted communication system for a

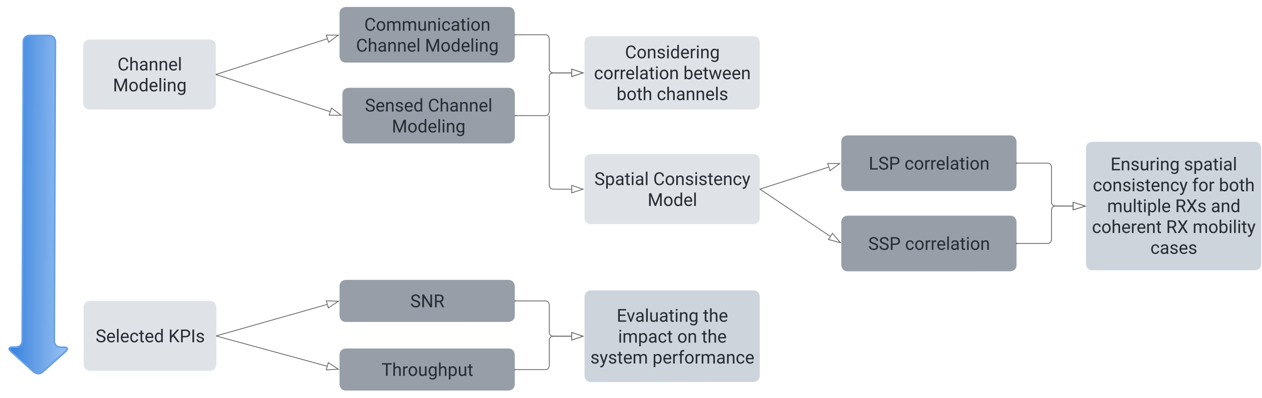

FIGURE 1. Summary of the main elements considered for evaluating sensing-assisted communication systems.

given use case is provided in Section III-C.

A. SENSING CHANNEL MODELING

When evaluating the performance of an ISAC system, both the communication channel and the sensing channel must be considered if accurate conclusions about system performance are to be drawn. In the case of the radio channel in conventional communication systems, channel models such as the 3GPP GBSM [15], WINNER II [28], or QuaDRiGa [29] emulate the electromagnetic wave propagation considering the geometric aspects of the scenario. This replication allows predicting channel behavior with very close fidelity to real conditions [10]. Thus, a similar perspective to the sensing channel is conducted for ISAC. This paper focuses on monostatic sensing, where the Tx and the Rx are placed in the same location. The sensing channel features are presented as follows.

1) Correlation with communication channel

Within an analysis of ISAC, the authors in [30] employed sensing devices integrated into the infrastructure of RSU. The sensing performance correlated highly with the communications one, achieved by aligning angular information in the measurements. The azimuth power spectrum was used to assess the power originating from different angles, revealing substantial similarities between both systems.

The concept of correlation between the sensing and the communication channel might also be evident in applications such as simultaneous localization and mapping (SLAM) integrated into 5G radio systems. For instance, the study conducted in [31] used such correlation to enhance environment reconstruction, providing an advanced mapping solution that enables more effective tracking against potential changes in the radio environment.

While the aforementioned contributions focused on different objectives, both concluded a realistic correlated behavior of communication and sensing channels and relied on it. This is a solid motivation to model ISAC systems using a GBSM model, given that if communication and sensing channels are modeled based on the geometry of the scenario, both would be characterized by the same scenario setup, meaning that an identical set of obstacles would influence signal propagation similarly in both cases. Furthermore, sensing and communication channels share the same fraction of the transmission path between the Tx and the scatterers or backscatter points. Fig. 2 shows the commonalities between communication paths (green dashed lines) and sensing paths (blue dashed lines). Given these inherent shared MPCs, a correlation between the two channels can be inferred. Some similar strategies are presented in the literature, such as the ones in [16], [32]–[34].

Modeling the sensing channel to ensure correlation with the communication channel can instigate new strategies, such as filtering the echo trajectories based on this correlation [16]. This approach might guarantee that the sensing channel retains the most accurate contributions related to the environment. Consequently, greater benefits can be derived from echoes without additional communication resources. In summary, not considering the existing correlation between the sensing and the communication channels may lead to wrong conclusions in assessing 6G candidate technologies.

2) Spatial consistency

As already pointed out, correlation is a key element to enable the evaluation of ISAC systems. In addition to the correlation between the sensing and the communication channels, a proper evaluation of the potential performance of a sensing-assisted communication system requires a spatially consistent channel. In this context, spatial consistency (SC) can be understood as a procedure to guarantee spatial correlation between channel realizations, i.e., to generate matching channels for receivers that are on a similar distance from the Tx, a smooth channel evolution for a Rx moving around a nearby area, or even receivers close to each other can share identical scatterers. The receivers experiment with similar propagation conditions, so channel parameters such as delays and angles

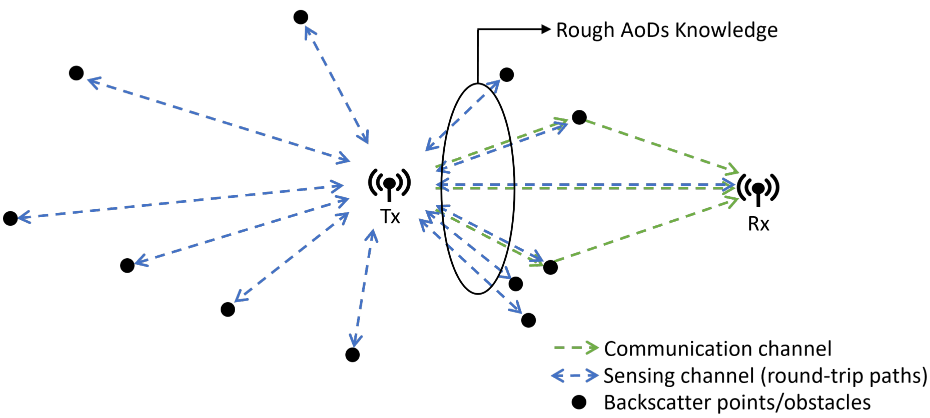

FIGURE 2. Sensing channel cluster geometry based on 3GPP GBSM, adjusted from [16], illustrates the correlation between communication and sensing channels.

are consistent. Such situations need to be considered when modeling the channel since scenarios with multiple receivers and mobility are expected to be the ones to reflect the potential benefits of ISAC.

One of the significant drawbacks of GBSMs in dealing with mobility or multiple receivers is their drop-based nature. A drop can be defined as a still representation of the channel impulse response between the Tx and the Rx at a given time. Although SC is intrinsic to some parameters included in the GBSMs, e.g., distance-dependent path loss, the environment's geometry is not used to identify scatterers that give rise to the different propagation paths. Instead, the effective scatterers are distributed in a geometry determined by several random processes and probability functions derived from channel measurement campaigns and divided into two abstraction layers: the large-scale fading, which is characterized by large scale parameters (LSPs), and the small-scale fading, described by small scale parameters (SSPs). Therefore, whereas SC is inherent to deterministic models since the physical environment is known and this information is used in simulations, drop-based GBSMs need to be adjusted. These models already include methods to ensure LSP correlation, but SSPs remain uncorrelated.

Regarding the large-scale fading model, LSPs refer to parameters whose variation is only significant over longer distances. In other words, these LSPs, e.g., delay and angular spreads and shadow fading, remain constant for several meters; therefore, there is a need to generate spatially correlated parameters. A common approach to model such correlation, and the one followed in the 3GPP GBSM, is a two-step procedure introduced in [28], in which the influence of exponential auto-correlation for each LSP and cross-correlation between all LSPs is generated separately.

As for the small-scale fading model, it characterizes the MPCs that a Rx experiences at a given spatial position by generating clusters that are defined by a set of SSPs. Some of the SSPs considered in the 3GPP GBSM are cluster delays, powers, AoDs and AoAs for both azimuth and elevation dimensions, and polarization phases. These SSPs are calculated from the combination of one or more random variables drawn from a specific probability distribution defined through a LSP (e.g., cluster delays are derived from a uniform random variable and the delay spread). For this reason, even if LSPs are correlated, the cluster generation procedure produces uncorrelated MPCs and, as a result, uncorrelated channel realizations.

The 3GPP TR 38.901 [15], in which the GBSM is described, also features a collection of extensions, among them one that enables SC. This method combines a two-dimensional (2D) filtered random process, which aims to generate correlated cluster and ray-specific random variables, together with two alternatives, namely Procedure A and Procedure B, to replace the step-wise generation of SSPs. In Procedure A, cluster delays and angles are geometrically updated at each location. In contrast, in Procedure B the probability distributions of the random variables used in the generation of delays are angles are modified, as well as the cluster powers generation method. Hence, in one way or another, steps of the original channel model related to generating cluster delays, powers, and angles are replaced.

For the proposed channel model in this work, SC is implemented as indicated in Procedure A. Details on the implementation of this model are described in Appendix A. This procedure considers the velocity vector of the Rx and the time elapsed between channel realizations to update delays and angles from the previous ones. An update distance constraint is set to 1 m for these velocity and time parameters. Therefore, for the model to behave properly, there should not be more than 1 m distance between receivers, or a Rx should not have moved more than 1 m between consecutive channel realizations. Additionally, the implementation method presented in Appendix A assumes that the Tx has no mobility.

B. KEY PERFORMANCE INDICATORS

Usually, KPIs for ISAC evaluation are divided into two different categories: information-theoretic and estimation-theoretic metrics [35]. On the one hand, information-theoretic focuses on channel capacity performance metrics, e.g., mutual information (MI), and KPIs derived by Shannon's theorem. Although the authors of [35] present MI as a promising candidate for evaluating ISAC, they also conclude that there are still some open problems in this regard. On the other hand, estimation-theoretic metrics include the CRB, Mean Square Error (MSE), or detection probability.

For the present study, two metrics are chosen to evaluate the proposed use case as an example: the Signal to Noise Ratio (SNR) and the Throughput. Firstly, the SNR is selected to evaluate the impact on the system performance by sensing-assisted communication. Secondly, the throughput is used to quantify the improvement that can be achieved by the sensing-assisted solution due to the faster channel acquisition or the overall sensing gain.

The SNR at the Rx side and the throughput experienced by the user have been calculated following eq. (1) and (2), respectively.

$$SNR = \frac{p|\mathbf{H}\mathbf{w}\mathbf{w}^H\mathbf{H}^H|}{N_0} \tag{1}$$

$$Throughput = \frac{\tau_c - \tau_p}{\tau_c} B \log\left(1 + SNR\right) \tag{2}$$

In the above equations, $\mathbf{H}$ is the channel matrix, $\mathbf{w}$ can be any suitable precoder, p denotes the transmitted power, N_0 refers to the noise power, τ_c is the coherence interval length, τ_p is the training phase length, and B denotes the system bandwidth.

C. SYSTEM EVALUATION METHODOLOGY

After reviewing the fundamental components to be considered in an evaluation methodology for sensing-assisted communication systems, it is important to describe the evaluation procedure. Fig. 3 depicts the stages of this procedure. The step-by-step operation is as follows:

1) *Use case requirements*. A clear description of the use case, including its main requirements, should be a starting point for establishing an appropriate configuration or a precise implementation. This block addresses the system implications derived from the use case and the necessary modifications to be made.
2) *Scenario setup*. The environment, network layout, and antenna array parameters are established. This step refers to the definition of the geometrical conditions of the scenario, together with the antenna configuration. The existence of Line of Sight (LoS) propagation condition is also defined at this stage.
3) *Initialize channel model parameters*. In this step, it is decided whether to simulate the traditional communication channel or the sensing channel. Accordingly, either the original 3GPP GBSM or the modified model for the sensing channel is used. That being said, non-geometrical parameters, such as frequency, number of clusters, or channel fading, are also defined.
4) *Start test environment*. The system simulation starts after configuring all the parameters and setting the scenario.

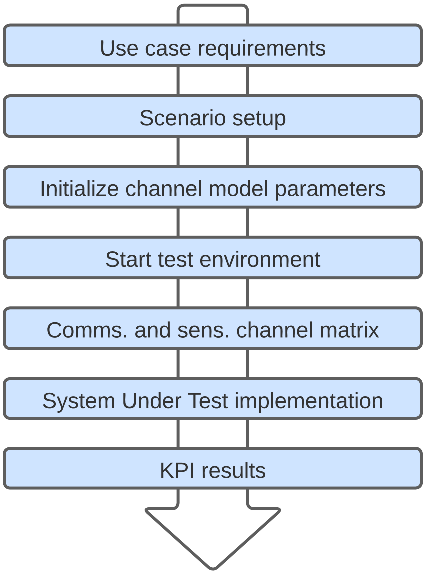

FIGURE 3. Outline of the stages that make up the evaluation methodology.

5) *Communication and sensing channel matrix*. The communication and sensing channel coefficients are generated and structured as a Channel Impulse Response (CIR) matrix of size $N_t \times N_r$, where N_t is the number of transmitting antennas, and N_r is the number of receiving antennas.
6) *System Under Test (SUT) implementation*. Within this stage, the necessary modifications identified at the beginning of the procedure are implemented, e.g., beamformer designs, tracking or localization algorithms, or signal processing techniques, among others.
7) *KPI results*. SNR and $Throughput$ results are obtained from the simulation. Other KPIs of interest to the use case can be added to provide additional information on system performance evaluation.

IV. ANALYSIS AND EVALUATION

This section follows the evaluation procedures described in Section III-C and discusses the numerical results of the sensing-assisted channel estimation use case described in Section II-C. Eventually, Section IV-C presents a performance comparison among several benchmarks and the use case method.

A. SIMULATION SCENARIO

The evaluation scenario consists of a 20 m × 20 m indoor scenario shown in Fig. 4. In this scenario, the Tx is located in the center and equipped with 64 antenna elements distributed in an 8 × 8 Uniform Planar Array (UPA) at a height of 6 m, whereas the single-antenna of the communication Rx is 1.5 m high. Initially, the communication Rx is placed in the center of the stage and moves to the upper right corner with a constant speed of 3 km/h, with LoS propagation condition

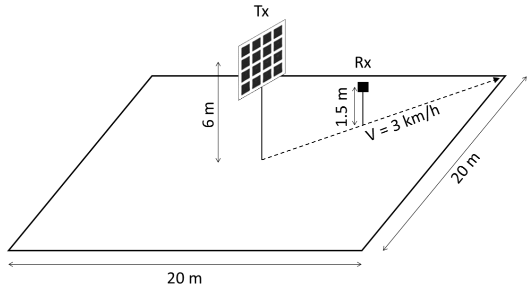

FIGURE 4. Simulated scenario.

throughout the entire trajectory. The working frequency is 28 GHz, and the available bandwidth is 100 MHz. Table 1 summarizes the parameters used to carry out the simulations.

TABLE 1. Parameter settings for the simulations.

Parameters	Value
Frequency	28 GHz
Bandwidth	100 MHz
Transmit power	21 dBm
Scenario dimensions	20 m × 20 m
Tx antenna height	6 m
Rx antenna height	1.5 m
Tx antenna configuration	UPA 8 × 8
Rx antenna elements	Single antenna
Rx noise figure	9 dB
Tx/Rx antenna pattern	Omnidirectional
Rx speed	3 km/h
Communication channel model	3GPP TR 38.901
Sensed channel model	López-Reche *et al.* [16]
Baseline scenario	Indoor Hotspot (InH)
Spatial consistency model	3GPP - Procedure A
Frame duration	10 ms [36]
Number of simulations	100

B. USE CASE ASSUMPTION

Following the SUT implementation (step 6, Section III-D) of the proposed methodology, a beam training technique has been designed to select the transmitted codebook using sensing information. The sensing channel (Echo reception in Fig. 5) is used to estimate the geometry of the scenario and the user location [5], [6] represented by its angular information. This information is used to identify the most suitable beam in the codebook. Since the ISAC solution can retrieve the same information from data echoes as from pilot echoes, in later frames, the Tx does not require the transmission of sensing-specific pilots. Therefore, this approach can substitute conventional beam training techniques in a communication-only system.

It should be noted that both communication-only or sensing-assisted communication may require feedback signaling to share the common ground to establish the communication link between Tx and Rx. Thus, the feedback stage is neglected in the performance study conducted in this use case.

In order to select the beam, the Tx needs to know the channel and the available set of precoders. On the one hand, for the latter, the Tx creates a set of precoding matrices as follows:

$$w_n = e^{-i2\pi\frac{d}{\lambda}(n_x cos(\phi)sin(\theta)+n_y sin(\phi)sin(\theta))};$$
$$n_x \in 1,\ldots,N_x, n_y \in 1,\ldots,N_y \quad (3)$$

$$\mathbf{w} = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}, \quad (4)$$

where d is the distance between antenna elements, λ is the wavelength of the carrier, and θ and ϕ are the elevation and azimuth LoS angles, respectively. n_x and n_y denote the coordinate index pair of each antenna element in a UPA of N total antenna elements configured in a $N_x \times N_y$ distribution, where n_x and n_y correspond to the horizontal and vertical indexes of the array, respectively, and n is the precoder index which sweeps the vertical and horizontal array indexes of the UPA. For the numerical analysis, the azimuth and elevation are sampled from 0 to 180 degrees with a step of 5 degrees. The spatial power spectrum is given by

$$\hat{n} = \arg\max_n |\mathbf{w}^H \mathbf{H}_{\text{sen}}|^2, \quad (5)$$
$$w^{\text{sen}} = w_{\hat{n}}, \quad (6)$$

which determines the weight of every precoder created at every angle of the sweeping range. Thus, the ideal precoder is selected by the highest power in the scanning process, being $\mathbf{H}_{\text{sen}}$, the sensing CIR matrix. The latter is constructed under the assumption that the Tx has an approximate knowledge of the Rx position (as mentioned in [16]). This allows for the precise filtering of echo contributions. Consequently, in this case, the ideal precoder is selected based on the echoes associated with the user or those nearby.

Assuming that the Channel State Information (CSI)-based procedure performs beam selection every 10 ms of the frame duration (the duration of the frame), it can be naturally deduced that the performance may decrease compared to a system that constantly updates the beam selection and performs the data transmission simultaneously, as is the case with the sensing-assisted solution.

C. BENCHMARKS

Four solutions are compared to provide a comparative analysis of the proposed methodology. (1) *SAC* refers to *sensing-assisted communication* and is the solution proposed in this paper, including the correlation between sensing and communication channels and SC. (2) *CSI-based* beam selection refers to a conventional beam training solution as in [37]. It analyzes all available beams in the predefined codebook using communication system resources. This procedure is

FIGURE 5. Frame structure in a DL transmission.

defined in Fig. 5, in which a significant part of the resources are used to find the best beam. After the beam selection, the Tx sends a downlink feedback signal to the Rx informing of the chosen beam and the required parameters to establish the communication link. Communication can begin since the Tx and the Rx already have the information to transmit. SC has been considered for this benchmark. (3) *SAC without correlation* is a system similar to (1) in which correlation between the communication and the sensing channel is not included [38], i.e., two independent GBSM models are used for the communication and sensing channels. (4) *SAC without SC* refers to a model in which GBSM is used, including channel correlation, but without any guarantee of spatial consistency. As explained in Section III-A2, the absence of SC is a major drawback in dealing with mobility or multiple receivers. Therefore, this benchmark considers the correlation between the channels without the generation of spatially consistent channel realizations, as done, for instance, in [32]–[34].

D. NUMERICAL RESULTS

After delving into the use case and mentioning the possible vulnerabilities in a sensing-assisted communication system without the crucial elements of the proposed methodology, this section provides a comparative analysis of the four solutions discussed before.

Fig. 6 illustrates the Cumulative Distribution Functions (CDFs) of the SNR of the studied schemes. *SAC without correlation* and *SAC without SC* have obtained lower levels of SNR as compared with the other two schemes. *SAC without correlation* emulates a sensing channel that generates a different backscatter distribution from the communication channel. Consequently, the echo information to assist the communication system is inaccurately applied, which results in this degradation.

On the other hand, since there is no coherent mobility in the solution of *SAC without SC*, the channel realizations at each instant of the trajectory are generated differently, i.e., the SSPs are generated spatially uncorrelated in each time slot. This method introduces variations in the channel gain that negatively impact system performance. The smooth channel evolution is required to make the best of the sensing channel estimations.

Comparing the proposed *SAC* solution with the applied methodology and conventional *CSI-based* beam selection, it can be observed that *SAC* slightly outperforms the *CSI-based* scheme by 0.17 dB on the median. The *SAC* solution does not introduce a significant enhancement in terms of SNR. Still, it saves many resources dedicated to channel estimation, which will impact $Throughput$.

Fig. 7 shows the $Throughput$ CDFs for the four solutions. The conventional communication system employs a *CSI-based* beam selection process, and resources within the transmitted frame are utilized. This process might introduce an overhead of 18%, as defined in [39] for CSI acquisition. In contrast, for any SAC solution, the beam selection process co-occurs with the data transmission process. This results in negligible overhead as the Tx leverages echo information for optimal precoder selection, as Fig. 5 shows. Even considering no overhead for both *SAC without correlation* and *SAC without SC*, they failed to achieve satisfactory levels of $Throughput$ due to the mistaken channel estimation.

The comparison between *CSI-based* and proposed *SAC* reveals that even with the slight enhancement in terms of SNR level experienced when using the *SAC* solution, the reduced overhead allows the *SAC* approach to yield a 25.38% enhancement in terms of $Throughput$ over the *CSI-based* beam selection method. The *CSI-based* beam selection process inherently penalizes the experienced data rate as it uses many pilots before data transmission occurs. The beam selection and link establishment procedure is simplified by taking advantage of the available sensing information, resulting in an almost overhead-free solution. In this case, communication would be more reliable and could be applied to more complex use cases and scenarios.

V. CONCLUSION

This work has proposed an evaluation methodology for sensing-assisted communication systems, for which two key points have been identified during its description. Firstly, channel modeling is essential to include in a methodology

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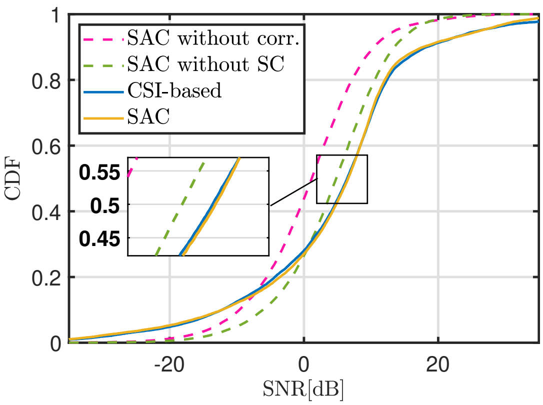

FIGURE 6. SNR performance for the beam selection use case.

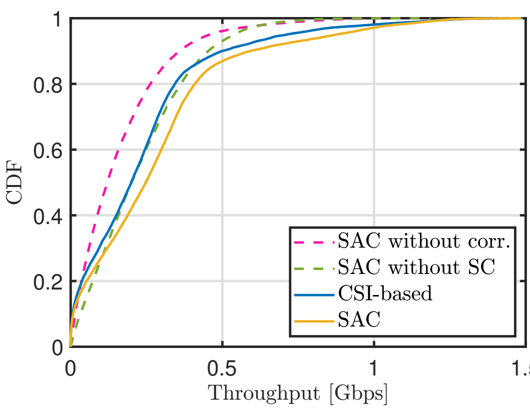

FIGURE 7. Throughput performance for the beam selection use case.

proposal. Thus, to this extent, suitable models that capture the specificities of both sensing and communication channels and replicate the existing correlation between them are necessary. GBSMs are an interesting choice due to their flexibility and accuracy, given their limited resource requirements. Secondly, appropriate KPIs need to be selected to show the system's performance under evaluation. In this case, SNR and throughput have been chosen to quantify the robustness and efficiency of sensing-assisted communication links.

A sensing-assisted beam selection use case has been described and studied as an example to which the proposed methodology for sensing-assisted communication systems can be applied. The results remark the importance of considering the sensing channel modeling features suggested by the proposed methodology, i.e., modeling the correlation between sensing and communication channels and their spatial consistency.

Moreover, the convergence of both systems can be advantageous over established communication systems by harnessing the fast access and low overhead that ISAC envisions. It should be noted that the use case presented in this paper refers to a simplified environment. However, the sensing-assisted communication system is likely better exploited in complex scenarios, e.g., when the channel varies rapidly, as overhead reduction is essential in these cases. Further research is required for these complex cases, including NLoS scenarios, since more complex sensing algorithms are needed.

In general, establishing an evaluation methodology adds credibility to the performance evaluation of any system, as ITU has already done with legacy communication systems in the past. The proposed methodology in this work is a first step towards a reasonable evaluation of ISAC solutions, which will contribute to the growing ISAC field. Future works might build on this proposal since the described methodology is based on general assumptions, which opens up the possibility of applying it to assess different use cases and ISAC system designs.

APPENDIX A 3GPP SPATIAL CONSISTENCY MODEL

Procedure A of the spatial consistency (SC) model presented in the Third Generation Partnership Project (3GPP) TR 38.901 [15] modifies the step-wise method to generate a radio communication channel by replacing the operations to generate small scale parameters (SSPs). On the one hand, equations to generate cluster delays and angles in steps 5 and 7 in the 3GPP geometry-based stochastic model (GBSM) now consider the velocity vector of the receiver (Rx), $\mathbf{v}_{\text{rx}}$, and the time elapsed between channel realizations, Δt, to update delays and angles from the previous ones, rather than generating new, uncorrelated sets of these parameters derived from probability distributions.

On the other hand, random variables used in the generation of other SSPs that are still calculated in the same way are conveniently treated to ensure that they are correlated to those used in a previous channel realization so that the corresponding SSPs will also be correlated. The changes introduced to the standard procedure are described below.

A. GENERATE UPDATED CLUSTER DELAYS

The following method replaces Step 5 of the 3GPP GBSM. At the initial instant, t_0, cluster delays are calculated as

$$\tilde{\boldsymbol{\tau}}_n\left(t_k\right) = \boldsymbol{\tau}_n\left(t_0\right) + \tau_\Delta\left(t_0\right) + \frac{d_{3\text{D}}\left(t_0\right)}{c}, \tag{7}$$

where $\boldsymbol{\tau}_n\left(t_0\right)$ are the cluster delays calculated as in step 5 of the standard procedure, $\tau_\Delta\left(t_0\right)$ is either 0 in Line of Sight (LoS) condition or the minimum of non-normalized delays generated earlier, $\boldsymbol{\tau}'_n\left(t_0\right)$, in Non Line of Sight (NLoS), $d_{3\text{D}}$ denotes the three-dimensional (3D) distance between transmitter (Tx) and Rx, and c is the speed of light. Then, at the k_{th} time epoch, t_k, cluster delays are updated as

$$\tilde{\boldsymbol{\tau}}_n\left(t_k\right) = \tilde{\boldsymbol{\tau}}_n\left(t_{k-1}\right) - \frac{\hat{\mathbf{r}}_{\text{rx},n}\left(t_{k-1}\right)^T \mathbf{v}_{\text{rx}}\left(t_{k-1}\right)}{c}\Delta t, \tag{8}$$

where $\hat{\mathbf{r}}_{\text{rx},n}\left(t_{k-1}\right)^T$ is the transpose of the spherical unit vector, which is defined as

$$\hat{\mathbf{r}}_{\text{rx},n}\left(t_{k-1}\right) = \begin{bmatrix} \sin\left(\theta_{n,\text{ZOA}}\left(t_{k-1}\right)\right)\cos\left(\phi_{n,\text{AOA}}\left(t_{k-1}\right)\right) \\ \sin\left(\theta_{n,\text{ZOA}}\left(t_{k-1}\right)\right)\sin\left(\phi_{n,\text{AOA}}\left(t_{k-1}\right)\right) \\ \cos\left(\theta_{n,\text{ZOA}}\left(t_{k-1}\right)\right) \end{bmatrix}. \tag{9}$$

In (9), $\theta_{n,\text{ZOA}}$ and $\phi_{n,\text{AOA}}$ are the angles of arrival in the elevation and azimuth dimensions are specific to each cluster, respectively. Finally, the delay normalization step is replaced by

$$\boldsymbol{\tau}_n(t_k) = \tilde{\boldsymbol{\tau}}_n(t_k) - \min\left(\{\tilde{\boldsymbol{\tau}}_n(t_k)\}_{n=1}^{N}\right). \quad (10)$$

The normalized delays are then used in the cluster powers generation (step 6 of the 3GPP procedure).

B. GENERATE UPDATED CLUSTER DEPARTURE AND ARRIVAL ANGLES

The following method replaces the method to generate cluster departure and arrival angles described in step 7 of the 3GPP GBSM. At the beginning of the simulation, cluster delays are calculated as in the standard procedure. Then, at time t_k, cluster arrival angles in the azimuth and elevation dimensions are updated as

$$\begin{aligned}\boldsymbol{\phi}_{n,\text{AOA}}(t_k) &= \boldsymbol{\phi}_{n,\text{AOA}}(t_{k-1}) \\ &\quad - \frac{\mathbf{v}_{\text{rx}}(t_{k-1})^T\hat{\boldsymbol{\phi}}}{c\cdot\tilde{\boldsymbol{\tau}}_n(t_{k-1})\sin(\boldsymbol{\theta}_{n,\text{ZOA}}(t_{k-1}))}\Delta t,\end{aligned} \quad (11)$$

$$\boldsymbol{\theta}_{n,\text{ZOA}}(t_k) = \boldsymbol{\theta}_{n,\text{ZOA}}(t_{k-1}) - \frac{\mathbf{v}_{\text{rx}}(t_{k-1})^T\hat{\boldsymbol{\theta}}}{c\cdot\tilde{\boldsymbol{\tau}}_n(t_{k-1})}\Delta t, \quad (12)$$

with $\tilde{\boldsymbol{\tau}}_n(t_{k-1})$ being the non-normalized spatially consistent cluster delays calculated in (8). $\hat{\boldsymbol{\phi}}$ and $\hat{\boldsymbol{\theta}}$ are the spherical unit vectors defined as

$$\hat{\boldsymbol{\phi}} = \begin{bmatrix} -\sin(\boldsymbol{\phi}_{n,\text{AOA}}(t_{k-1})) \\ \cos(\boldsymbol{\phi}_{n,\text{AOA}}(t_{k-1})) \\ 0 \end{bmatrix}, \quad (13)$$

$$\hat{\boldsymbol{\theta}} = \begin{bmatrix} \cos(\boldsymbol{\phi}_{n,\text{AOA}}(t_{k-1}))\cos(\boldsymbol{\theta}_{n,\text{ZOA}}(t_{k-1})) \\ \cos(\boldsymbol{\theta}_{n,\text{ZOA}}(t_{k-1}))\sin(\boldsymbol{\phi}_{n,\text{AOA}}(t_{k-1})) \\ -\sin(\boldsymbol{\theta}_{n,\text{ZOA}}(t_{k-1})) \end{bmatrix}. \quad (14)$$

Similarly to (11) and (12), cluster departure angles are updated as

$$\begin{aligned}\boldsymbol{\phi}_{n,\text{AOD}}(t_k) &= \boldsymbol{\phi}_{n,\text{AOD}}(t_{k-1}) \\ &\quad + \frac{\mathbf{v}'_{n,\text{rx}}(t_{k-1})^T\hat{\boldsymbol{\phi}}}{c\cdot\tilde{\boldsymbol{\tau}}_n(t_{k-1})\sin(\boldsymbol{\theta}_{n,\text{ZOD}}(t_{k-1}))}\Delta t,\end{aligned} \quad (15)$$

$$\boldsymbol{\theta}_{n,\text{ZOD}}(t_k) = \boldsymbol{\theta}_{n,\text{ZOD}}(t_{k-1}) + \frac{\mathbf{v}'_{n,\text{rx}}(t_{k-1})^T\hat{\boldsymbol{\theta}}}{c\cdot\tilde{\boldsymbol{\tau}}_n(t_{k-1})}\Delta t, \quad (16)$$

where $\hat{\boldsymbol{\phi}}$ and $\hat{\boldsymbol{\theta}}$ are the spherical unit vectors in (13) and (14), but replacing arrival angles with $\phi_{n,\text{AOD}}(t_{k-1})$ and $\boldsymbol{\theta}_{n,\text{ZOD}}(t_{k-1})$. $\mathbf{v}'_{n,\text{rx}}$ is a per cluster transformation of the Rx velocity vector given by

$$\mathbf{v}'_{n,\text{rx}}(t_{k-1}) = \begin{cases} \mathbf{v}_{\text{rx}}(t_{k-1}) & \text{for LoS} \\ \mathbf{R}_{n,\text{rx}}\cdot\mathbf{v}_{\text{rx}}(t_{k-1}) & \text{for NLoS} \end{cases} \quad (17)$$

with $\mathbf{R}_{n,\text{rx}}$ being a combination of rotation matrices defined in the SC model (Procedure A).

C. GENERATE CORRELATED RANDOM VARIABLES

Whereas cluster delays and angles follow a different procedure to be calculated, the rest of SSPs, i.e., cluster powers, cross-polarization power ratios (XPR), and initial random phases, are generated following steps 6, 9, and 10 of the 3GPP GBSM, respectively. However, in order to ensure that these SSPs are also spatially consistent, it is necessary to correlate the random variables used in their calculation. The generation of spatially consistent cluster and ray-specific random variables is based on the distance-dependent exponential auto-correlation function given by

$$R(\Delta x) = e^{-\frac{|\Delta x|}{d_{cor}}}, \quad (18)$$

where $|\Delta x|$ is the two-dimensional (2D) distance from the last position in which the channel was updated, and d_{cor} is the correlation distance, a specific parameter to each of the scenarios defined in the 3GPP GBSM. Once the auto-correlation is calculated, a random variable, y_k, correlated to its previous realization, y_{k-1}, with correlation R can be generated as follows:

$$y_k = R(\Delta x)y_{k-1} + \sqrt{1-R^2}z, \quad z \sim N(0,1) \quad (19)$$

In (19), it is assumed that y is a random variable drawn from the standard Gaussian distribution. However, if random variables from other probability distributions are needed, e.g., random variables drawn from a uniform distribution are assigned as random phases of each ray, they can be obtained by applying known transformations to the above result.

Moreover, other considerations when implementing the SC model include sorting the delays as described in step 5 of the 3GPP GBSM after applying the SC procedure, keeping the sign of the cluster angles generated at the beginning of the simulation throughout it. The random coupling of rays performed in Step 8 and sub-cluster delays do not change either.

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ANDREA RAMOS received the M.Sc. degree in Telecommunication Technologies, Systems, and Networks from the Universitat Politècnica de València (UPV) in 2019. She is currently doing her Ph.D. in telecommunications engineering at the Institute of Telecommunications and Multimedia Applications (iTEAM). Her research focuses on propagation channel models for industrial networks, especially for novel integrated sensing and communication (ISAC) technology. Her work is supported by the Spanish Ministry of Science, Innovation, and University.

ARTURO MROZOWSKI received the B.Sc. degree in Telecommunication Engineering and the M.Sc. degree in Telecommunication Technologies, Systems, and Networks from the Universitat Politècnica de València (UPV), Spain, in 2020 and 2023, respectively. Since December 2020, he has been a Researcher with the iTEAM Research Institute, UPV. He was involved in the European 5G-CARMEN project focused on 5G for connected and automated road mobility, participating in simulation activities. His research interests include integrated sensing and communication (ISAC), wireless communication channel modeling, and vehicular networks.

DANAISY PRADO-ALVAREZ graduated in Electronics and Telecommunication Engineering in 2015 at Technological University of Havana “José Antonio Echeverría”, Cuba. She received her M.Sc. degree in Telecommunication Technologies, Systems, and Networks and her Ph.D. degree in Telecommunications from the Universitat Politècnica de València (UPV) in 2017 and 2022, respectively. In 2018, she joined the iTEAM Research Institute of the Universitat Politècnica de València, Valencia, Spain. Her current research interests are focused on 5G&6G wireless technologies design, channel modeling, network planning and resource allocation.

PROF. JOSE F. MONSERRAT [SM] is a full professor and Vice President of the Universitat Politècnica de València, the first technical university in Spain. His research focuses on the design of beyond 5G wireless systems and their performance assessment. He has been involved in several European Projects, like METIS/METIS-II where he led the simulation activities, or currently 5G-CARMEN and 5G-SMART. He co-edited the Wiley book “Mobile and wireless communications for IMT-Advanced and beyond” and the Cambridge book “5G Mobile and Wireless Communications Technology”. Jose Monserrat is a senior member of the IEEE and has published more than 60 journal papers. His research team comprises 5 Postdoctoral fellows, 8 Ph.D. students, and 2 Master students. Jose F. Monserrat has served as the European Parliament and the World Bank Group advisor in the vehicular 5G communications topic.

YUNHAO ZHANG received her B.Sc. and Ph.D. degrees from Southeast University and Shanghai Jiao Tong University in China in 2014 and 2019, respectively. He joined Huawei Technologies Co., Ltd. in Shanghai in 2019. He is now senior engineer in wireless technology laboratory, 2012 laboratory of Huawei. His current research interests include the new use cases, novel channel models and evaluation methodologies for the 6G new scenarios e.g. integrated sensing and communication (ISAC).

ZIMING YU was born in Jiangxi, China on October 6, 1986. He received the B.S. degree in telecommunication from Jiangxi University of Science and Technology, Jiangxi, China, in 2005. He received the M.S. degree in mobile communication from Chongqing University of Posts and Telecommunications, Chongqing, China, in 2009. He joined the wireless technology laboratory, 2012 laboratory, Huawei technologies CO., LTD, Chengdu, China in 2012. His research involves millimeter wave channel measurement, sounder system design and channel modeling. His current research interests include the THz channel propagation modeling, integrated communication and sensing channel research.

YAN CHEN received her B.Sc. and Ph.D. degrees from Chu Kochen Honored College and Institute of Information and Communication Engineering from Zhejiang University in 2004 and 2009, respectively. She was a visiting researcher at Hong Kong University of Science and Technology from 2008 to 2009. She joined Huawei Technologies Shanghai in 2009 and from 2010 to 2013, she was the project manager and technical leader of Huawei internal Green Radio project studying energy efficient solutions for wireless networks and also served as technical leader of the Green Transmission Technology (GTT) project at GreenTouchTM Consortium. Since 2013, she is one of the key technical leaders on 5G air interface design and the related 3GPP standardization in Huawei, focusing on multiple access including NOMA transceivers, grant-free massive access, and ultra-reliable and low-latency communications. Now she is leading the 6G vision study in Huawei. Her research interests include novel 6G use cases and key capabilities such as collaborative robotics, new enabling technologies and architectures such as integrated sensing and communication (ISAC), network for distributed learning and inference, next generation multiple access (NGMA), as well as system level evaluation methodologies for new usage scenarios. She won the IEEE Communication Society Award for Advances in Communication in 2017.