On Integrated Cooperative Radio Sensing for Spatial Electromagnetic Analysis in 6G

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March 18, 2024

Abstract

Reliable analysis of the electromagnetic situation in a particular area is critical for wireless technology applications. With the increased number of devices and exploration of the new frequency bands, sensing helps, inter alia, in interference and radio resource management. Additionally, it facilitates the classification of signals to detect jammers and distinguish between legal and anomalous transmitters. This paper discusses the cooperative sensor network as a technology candidate for 6G. Specifically, we describe a possible architectural extension of the future cellular networks to obtain and utilize spectrum awareness. Several applications are systematically reviewed in this context, including dynamic spectrum sharing for coexistence in unlicensed bands, spectrum monitoring for signal detection and classification, and emitter localization. Qualitative and quantitative examples of possible performance improvements in cellular networks with the proposed approach are presented. Finally, we highlight the open research topics and challenges to solve for such a cooperative sensor network.
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Index Terms—6G, cooperative sensor network, LBT, NR-U, emitter localization, spectrum monitoring, WSN

I. INTRODUCTION

Radio sensing can provide the system with a vast amount of useful information about the environment which can potentially be used by the system for various tasks of the future radio. It is widely accepted that sensing advances will be adapted for 6G; numerous ways to integrate radio sensing technology with communications systems are currently discussed in the research community. For example, the integration of radar, often referred to as integrated sensing and communications (ISAC), enables obtaining information about the physical environment. The state-of-the-art reviews on this technology can be found in [1]–[3]. Next to radar sensing, sensing for channel sounding is used to determine propagation channel characteristics [4], [5]. A novel concept of obtaining location-specific channel characteristics and to construct a so-called channel knowledge map is described in [6]. However, radio sensing is not limited to measurements of the physical world’s properties.

The air is nowadays packed with electromagnetic waves transferring energy and information, and the trend is increasing. For example, according to [7], there are already more than 15 billion IoT devices in 2023, and this number will be doubled by the end of the decade when the 6G rollout is supposed to begin. At the same time, the radio spectrum is a valuable and limited natural asset that should be used as efficiently as possible.
of the electromagnetic situation in a specific area. Strictly speaking, the term 'spectrum sensing' is used in cognitive radio (CR) community to denote the process of finding licensed users or unoccupied parts of the spectrum; here, it is used in a broader way, meaning getting knowledge about the EM situation (electromagnetic awareness) in a passive way. Fig. 1 also emphasizes authors’ vision of radio sensing as a distributed process, as it adds another level of awareness. Clearly, observation of the same area from different points of view improves understanding of the environment, both physical and electromagnetic. The key contributions of our paper are as follows:

- We describe and justify a potential implementation of the complementary cooperative sensor network as a 6G radio access network (RAN) infrastructure helper, which, to the best of authors’ knowledge, has not been considered yet;
- Focusing on spectrum analysis, we provide an overview of relevant technologies that can be integrated into such sensor nodes, and the direction of future research in the context of the proposed architecture.

The rest is structured as follows. Chapter II discusses the potential use of a cooperative sensor network that can take over many EM-analysis tasks currently performed by existing communications network infrastructure and users, and potential advantages of its implementation. Chapter III overviews EM sensing applications, focusing on CR with spectrum monitoring and emitter localization (both blind and devise-based) as valuable helpers. Chapter IV exemplifies the potential benefits of the proposed cooperative sensor network. Finally, chapter V highlights research topics for future work and challenges to be overcome.

II. COOPERATIVE SENSOR NETWORK: VISION AND FUNDAMENTAL ARCHITECTURE

Spectrum sensing applications are often limited just to the estimation at a single point by a device that usually has a somewhat limited sensing capability. However, a reliable wireless system should rely on more than an ego view. Discussed in the literature, distributed approaches are based on collaborative sensing performed by numerous sensor units [9]. We discuss an approach where the sensing and signal processing functionalities are handed over to a dedicated cooperative sensor network that consists of several spatially distributed sensor nodes and a central signal processing entity (CSPE). Constructing a radio environment map (REM) that considers every possible parameter observable by sensor nodes could be an essential step toward advanced spectrum awareness for 6G.

The introduced approach requires the installation of additional infrastructure, which can be rather diverse in price, depending on functionality. Reduced complexity networked sensor nodes which are capable just of detecting power are rather cheap and affordable. Integrating all the aforementioned features, such as high-quality spectrum monitoring with the feature to detect anomaly transmitters, perform spectrum allocation and precise localization in a highly productive distributed supplement system promises performance improvement; however, extension of already existing infrastructure can be expensive and requires long-term investments. These factors make the implementation of the collaborative sensor network concept feasible and interesting, first of all, as a solution for industrial radio systems or campus networks. In the future, with the development of technology, this concept may find broader applications, and, for example, to be integrated into the public cellular networks. However, importance of keeping balance between technical feasibility, costs and futuristic vision should not be neglected.

A fundamental architecture for collaborative spectrum monitoring over the entire radio access network (RAN) is provided in Fig. 2. In this figure, cellular network nodes and participants like remote radio heads (RRH), a baseband unit (BBU) connected with a core network, and user equipment (UE), as well as connections between them, are shown in black, whereas the collaborative sensor network elements named as passive radio sensors (PRS) and CSPE are colored in green. Geographically distributed sensors, each with a limited range of action, cover the whole area of interest; additionally, supplement by sensors moving along the predefined trajectories can be considered in specific environments. In WSN, optimal sensor placement is critical [10]; in the proposed architecture, sensor placement needs to be done additionally considering the most vulnerable parts of the cellular network w.r.t. interference, handover, or jammer attacks. PRSs can be placed, e.g., at the cell edges or collocated with RRH. Individual sensors collect information relevant to the EM analysis and share it with the CSPE. CSPE’s role is to fuse sensor data and create a 2D or 3D REM. To construct a REM that covers the whole area of interest based on sensor measurements at only several points, interpolation methods need to be utilized. Subsequently, a REM
is shared with the communications network. BBU then uses this information to make an optimal decision on, for example, radio resource allocation, scheduling, handover, or user blacklisting.

III. RELEVANT SENSING APPLICATIONS: OVERVIEW AND ROLE IN THE COOPERATIVE SENSOR NETWORK

By the term passive radio sensing, we mean techniques that allow analyzing the EM situation without sending any signal, unlike conventional active radar sensing or channel sounding, which require the transmission of predefined signals. An inherent advantage of the passive sensing is the possibility of extracting information with no additional spectrum or time spent on transmission, just by listening. Then such information can be processed by the sensor itself or transmitted to a CSPE. Finally, CSPE makes a centralized decision based on the data collected from multiple distributed sensors, getting benefits from spatially diverse measurements.

In this chapter, we review three crucial applications of passive radio sensing. First, sensing to discover the presence of a particular user in cellular networks, and to perform dynamic spectrum sharing and interference management. The second application in focus is monitoring the environment to determine unauthorized users or anomalous transmitters, e.g., jammers. Finally, we review methods to localize emitters for a specific area, an essential step for REM construction.

A. Coexistence in Wireless Networks

For a long time, cellular communications systems operated only in licensed frequencies below 3 GHz, thus avoiding massive interference from radar and other wireless systems. However, in order to increase capacity, several frequency bands were introduced in unlicensed spectrum (so-called LTE-U), and particularly the 5 GHz Industrial, Scientific, and Medical (ISM) band, where they coexisted with Wi-Fi and some kinds of aeronautical and maritime radio-navigation radars [11]. In this chapter, we survey the existing methods to share the same or overlapping frequency bands in communications and radar systems that base on spectrum sensing.

1) Cellular Networks: LTE-LAA and NR-U: As explained above, spectrum sensing is the term widely used in CR technology, usually denoting the process of detecting primary users on air. Initially, the concept of CR is an extension of Software Defined Radio introduced by Mitola in his Ph.D. dissertation [12]. A state-of-the-art review article by Agrawal et al. [13] also describes CR basics and outlines architectures.

Nowadays, spectrum sensing is a crucial part of modern wireless communications in unlicensed bands for both cellular and Wi-Fi. In both cellular and Wi-Fi technologies, the detection process is called LBT; additionally, the Wi-Fi access is based on carrier-sense multiple access with collision avoidance (CSMA/CA) protocol. In general, the cognitive cycle consists of three phases: spectrum sensing, processing of the information, and, depending on the decision on channel occupancy, the transmission or leaving the channel ’idle’ for the rest of the cycle.

The focus of this paper is on cellular applications unless otherwise noted, therefore we will use the 3GPP vocabulary in the following discussion. The 3GPP specification defines four priority classes (denoted by p) of LBT in NR-U [14], distinguished by backoff time, contention window (CW), during which the channel sensing is performed, and channel occupation time (COT), during which a device is allowed to transmit. Technical information on procedures for shared spectrum access can be found in [14], whereas the comprehensive discussion on state-of-the-art is provided by [15]. The channel access delay and collision rate of coexisting devices depend on the
maximal and minimal values of the contention window. The application defines priority classes; a higher real-time capability (i.e., lower latency) requirement corresponds to less sensing time, less channel COT, and a higher priority class, whereas a lower prior class is more suitable for large volumes of non-critical data. Based on [14], major time-relevant parameters of the channel access priority classes in the downlink are summarized in Table I.

![Diagram of Busy Channel Transmission Opportunity](image)

**Fig. 3.** An example of the CAT4-LBT channel access process in NR-U (according to [14]).

<table>
<thead>
<tr>
<th>$p$</th>
<th>$m_p$</th>
<th>$CW_{\text{min}}$</th>
<th>$CW_{\text{max}}$</th>
<th>$T_{COT_{\text{max}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>3 µs</td>
<td>7 µs</td>
<td>2 ms</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>7 µs</td>
<td>15 µs</td>
<td>3 ms</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>15 µs</td>
<td>63 µs</td>
<td>8 or 10 ms</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>15 µs</td>
<td>1023 µs</td>
<td>8 or 10 ms</td>
</tr>
</tbody>
</table>

The defer duration $T_d$ consists of the duration $T_i = 16 \mu s$ ($T_i$ includes an idle sensing slot duration $T_{sl}$ at the beginning of $T_i$), followed by $m_p$ consecutive sensing slot durations $T_{sl}$ (a basic $T_{sl}$ equals 9 µs) [14]. Being different in technical details, LBT-based access techniques are conceptually similar for various cellular and Wi-Fi standards. Fig. 3 illustrates the channel access procedure in NR-U for the category CAT4.

Multiple access (MA) in unlicensed frequency bands has some issues listed below:

- Collisions due to the hidden node problem result in increased interference. It leads to a reduction in signal-to-noise ratio and throughput;
- Consuming radio resources: MA requires sensing and signal processing resulting in reduced time for transmission and throughput;
- MA increases complexity of the communications devices due to additional mandatory functionality;
- MA requires additional protocol design;
- Difficulties in choice of the sensing threshold in different scenarios;
- Significant latency due to collision avoidance protocols.

2) **Radar Interference**: Most of radar systems do not utilize any radio access scheme, transmitting uncoordinatedly. However, increasing spectrum congestion and a growing number of devices that use radar technology (for example, vehicles) increase the importance of interference limitation between radars and other wireless systems. The negative impact of interference on radar systems includes ghost targets and increased noise floor [16]. Ghost targets appear due to coherent interference that may occur due to strong multipath and disturbance from other radars with similar or the same parameters. Such a phenomenon leads to wrong peaks in the range-Doppler map, resulting in false detections. The noise floor increases due to incoherent interference. It happens when the receiver is affected by strong signals of different structure, e.g., waveform design. Increased noise floor results in missed detections.

Similarly to communications, there are different approaches in literature for radars to avoid or mitigate interference, including spatial, time, and code division [17]–[19]. RF spectrum sensing also plays a significant role in the emerging concept of cognitive radar [20], which is based on the perception-action cycle, likewise CR. The potential cooperation and interference avoidance of new radar systems with other RF systems is discussed in [11] and [21]. However, the actual implementation of interference-free radars is still under investigation.

### B. Spectrum Monitoring and Jammer Detection

The most straightforward application of getting knowledge about electromagnetic situation is **spectrum monitoring**, which is often considered to be an intrinsic part of the critical infrastructure. Spectrum monitoring includes techniques to analyze and classify the signals in a certain area of interest. It aims to detect interfering or jamming emitters and to trigger some countermeasure steps in order to guarantee a particular level of SINR or security for authorized participants. For example, spectrum monitoring is a crucial component providing aviation safety [22], which is widely used at airports and pilot cabins. Spectrum monitoring, however, is also used in cellular networks [23].

Standard spectrum sensing, discussed in Chapter III-A1, only gives information about the occupancy of a specific frequency range and can be seen as an operation with binary output (either free or occupied status). With the trend of increasing the level of heterogeneity of the wireless networks, additional information about the radio environment becomes even more critical. For example, detecting unauthorized sources of EM radiation can be used to change the system state and execute the necessary actions (e.g., blacklisting). RF signal classification can be seen as a kind of spectrum sensing which provides not only information about the occupancy of a specific frequency range but also about the type of the signal. Hence, with the help of signal classification, interference management and differentiation between friendly and hostile radios can be significantly improved [24]. If the decision about a channel’s status depends only on the detected energy, jammers can easily block the resources through constant transmission. The knowledge about the signal structure may be associated with particular kinds of transmitters, say, 4G LTE, Wi-Fi, 5G NR, or automotive radar. If these transmitters are identified as licensed or legal wireless network participants, the orchestration between them can be refined such that the unintentional interference gets canceled or minimized; in case of the signal type which
does not belong to the network or unrecognized signal, the corresponding device can be treated as a jammer, which has to be localized and neutralized.

State-of-the-art methods to analyze the EM situation based on an analytical approach are listed below (for a detailed overview, see [25]).

- Energy detection;
- Matched filtering based signal detection;
- Covariance based signal detection;
- Waveform-based detection;
- Cyclostationarity-based detection.

Matched filtering-based signal detection and waveform-based detection are capable of finding the presence of a particular technology and can be used for signal classification. In addition, nowadays there is extensive research on machine learning algorithms for signal classification. For example, in [26] and [27] authors describe deep learning-based approaches to detect and classify RF signals. However, the advantages of machine learning (ML) for the task of signal classification in practice are to be explored yet.

C. Emitter Localization

Compared with the localization of objects for future cellular networks, which is widely discussed in the research community (see Chapter I), emitter localization often seems to be overlooked. However, knowledge about the position of emitting devices in the area can be used in many different ways, from radio resource allocation to faster countermeasures against jammers.

In wireless networks, there are two conceptual approaches for localization: in the first, devices with unknown coordinates (called agents) localize themselves by processing the signals from transmitters with known coordinates (anchors), and in the second, localization is done by the anchor nodes based on signal analysis from the wireless network agents. Since the collaborative sensor network introduced in Chapter II consists of anchor nodes that perform EM analysis, the second approach is in the focus.

Early localization services in cellular networks were promoted by governmental bodies in the U.S. and Europe and focused on emergency use. Initial accuracy requirements defined by FCC for E911 service (ranging from 50 m to 300 m in the horizontal dimension, depending on the scenario), defined in the late 1990s, were crossed only in the mid-2010s. A holistic survey on cellular localization methods from 1G to 4G as well as the early vision of 5G is provided in [28].

Three main localization methods are described below.

- **Received Signal Strength (RSS)-based localization** is the simplest method based on distributed power measurements and subsequent computation of the emitter’s position [29]. RSS-based methods work even when there is no line of sight. In addition, RSS measurements can be used to localize the emitters and construct REMs relatively straightforwardly, relying on EM power measurements relation at different points and subsequently using various interpolation methods.

Standard RSS-based localization algorithms use different models to capture the power variations in the received signal then to derive spatial relationships based on power levels measured by distributed sensors. A popular propagation model is given by

\[
P_r (\text{dBm}) = P_t (\text{dBm}) + K (\text{dBm}) - 10 \alpha \log_2 \left( \frac{d}{d_0} \right) + \Psi_{\text{ant}}
\]

where \( P_r (\text{dBm}) \) is the received power, \( P_t (\text{dBm}) \) is the transmit power, \( K (\text{dBm}) \) is a constant depending on the antenna characteristics and the average channel attenuation, \( \alpha \) is the path loss exponent, \( d_0 \) is a reference distance for the antenna far-field, and \( \Psi \) is a Gaussian-distributed random variable representing shadow fading.

However, path loss, shadowing effects, and multipath fading depend on a specific scenario, and standard models often fail to provide reasonable precision due to their too-generic nature. For environments and scenarios that include complex propagation structures or dynamic changes, data-driven approaches seem to be a more promising solution. ML-based localization algorithms that utilize RSS are explored in [30] and [31], studying a single and multiple emitter localization respectively. Equipment from different manufacturers produces non-consistent RSS measurements under the same conditions due to design discrepancy, resulting in a lack of localization consistency. This is another argument favoring using a sensor network consisting of standardized nodes.

- **Time-of-flight-based localization** methods are based on measuring the signal propagation time between the agent and anchors and converting them into ranges, which can then be used for position estimation. To estimate the position, at least three range measurements are needed (trilateration); more measurements usually produce a more accurate assessment (multilateration). This is a standard positioning approach used in global navigation satellite systems, with satellites acting as anchors.

- **Angle of arrival-based localization** uses angular measurements between anchors and an agent. To estimate angles, nodes have to be equipped with arrays of antennas. At least two measurements are needed. This approach is used for geolocation in cellular networks [32].

RSS-based localization methods are often referred to as **blind**, highlighting the contrast with another two approaches that require some prior knowledge of the signal structure of the emitter to be localized.

IV. ELECTROMAGNETIC AWARENESS AND PERFORMANCE IMPROVEMENT: EXAMPLES

Generally speaking, sensing applications discussed in the Chapter III are developing in parallel. Today’s spectrum monitoring and methods used for radio access in unlicensed frequency bands have some weaknesses. For example, unlicensed access has an inherent problem: as shown in the previous chapter, a communications node must stop transmitting while performing spectrum sensing. Then, spectrum sensing is
performed by smartphones, which have limitations in sensitivity and capability to detect transmitters in the region of interest. In this chapter, we discuss these two issues and ways to overcome them with a help of a cooperative sensor network in detail.

A. Solve Hidden Node Problem

The disability to obtain a reliable picture of spectrum usage in the surroundings often turns into interference due to the so-called hidden node problem. This problem occurs when a transmitting node does not know about the existence of another node (the ”hidden node”) while transmitting to a third node placed within the accessible range of both nodes. The hidden node problem causes complications in the Medium Access Control (MAC) layer because multiple nodes send data to the certain access point simultaneously, resulting in interference and reduced throughput.

The existing hidden node solutions (for example, a so-called ’request to send/clear to send” protocol in Wi-Fi) introduce significant latency, which is inappropriate in ultra-reliable low latency communications with millisecond or even sub-millisecond latency requirements. Yang and Kang in [33] consider a group-wise LBT protocol that coordinates efforts of several base stations, increasing area capacity in the dynamic spectrum sharing environment; however, this approach is sub-optimal because it relies on already existing communications infrastructure, and is only applicable in the downlink.

The cooperative sensor network can be used for collaborative RF emission sensing, signal analysis, and localization. With an optimally placed, optimal number of nodes with sufficient sensitivity, such a network significantly improves spectral awareness in many ways. Measurement at particular points can be interpolated to the whole area of interest such that we get knowledge about relevant signal strengths at every point, i.e., a REM can be constructed. Sensors placed with accounting for possible ‘dead zones’ can help to overcome problems of limited individual sensor sensitivity or shadowing. Fig. 4 schematically illustrates and describes the distributed sensing approach to get a more reliable emitter detection, and thus to solve the hidden node problem.

B. Improve Spectrum and Energy Efficiency

Wireless communications in the unlicensed bands rely on the LBT procedure reviewed in the chapter III. It has an intrinsic disadvantage: a significant amount of time is spent on periodic sensing and making a decision. It results in wasted transmission opportunities. A cooperative sensor network could solve this issue and thus improve spectrum utilization. Sensor nodes permanently sniff the EM situation in a particular area and then send the results to the CSPE, which periodically updates the REM. The REM is then shared with the BBU, which can send commands or trigger signals to the communications network participants (UEs and RRHs). These commands, generated at the end of the REM update cycle, can subsequently trigger the events relevant to dynamic spectrum sharing in unlicensed bands in a centralized way. This approach can not only improve spectrum utilization but also can reduce computational load on communications nodes. These improvements are schematically shown and explained in greater detail in Fig. 5.

To be more specific, let’s consider a scenario in which a user transmits in an unlicensed band that is permanently free. Based on values from Tab. I, in the best case (for $p = 1$, $m_p = 1$, $CW = 3 \mu s$, $T_{COT} = 2$ ms), approximately 98.5 percent of the cycle is used for transmission, thus losing 1.5 percent on spectrum sensing. In contrast, for the worst case ($p = 4$, $m_p = 7$, $CW = 3 \mu s$, $T_{COT} = 2$ ms), we get around 87.9 percent of the cycle used for transmission, spending 12.1 percent on unnecessary spectrum sensing, which can be avoided with the dedicated cooperative sensor network.
V. OPEN RESEARCH CHALLENGES

This paper introduces an assistive cooperative sensor network and overviews the relevant technologies. However, it is important to recognize not only the opportunities, but also the challenges associated with integrating diverse technologies into a holistic system. There are multiple research questions to be studied and trade-offs to be estimated. Below we present directions in which such a cooperative sensor network can be further explored and evaluated in greater detail.

1) **Optimal sharing of signal processing duties:** The information captured by sensors can be pre-processed before transmission to the CSPE to reduce the amount of data. Optimal sharing of signal processing duties between individual sensor nodes and CSPE facilitates avoidance of the fronthaul links, and thus is of paramount importance.

2) **Synchronization:** Reliable synchronization in time for sensing, computing, and communicating components is essential in wireless sensor networks [34]. The integration of a cooperative sensor network with a 5G NR network additionally raises the question of precise coordination between CSPE and the BBU, where the connection between cellular and collaborative networks exists.

3) **Application of artificial intelligence (AI):** AI and ML are planned to be included in 3GPP specifications already in the upcoming Release 19, and 6G is supposed to be AI-native by design [35]. As shown in Chapter III, spectrum sensing and relevant research communities are also exploring data-driven approaches as promising alternatives to standard statistical models. Design of a reliable framework for ML-based solutions to analyze the EM situation, as well as collection (or synthesis) of sufficient amount of trustworthy data for training such algorithms, is a hot research topic. A fresh spectrogram data set that can be utilized, e.g., for ML-based signal classification, is provided in [36]; however, getting a proper dataset for a particular scenario usually remains a unique handmade process.

4) **Estimation of energy efficiency:** The sensor network needs to be powered. Energy consumption issues and energy efficiency of such a system are important performance indicators. Energy efficiency can be described as the number of correctly received data packets over the energy spent. As discussed in Chapter IV, a collaborative sensor network has a clear potential of increased throughput, thus compensating for additionally consumed energy. However, an analysis of this trade-off and a fair comparison with the standard cellular approach should be done.

5) **Timing and scheduling:** Orchestration of such a complex system that integrates variety of technologies will require precise timing and scheduling, including protocol design for physical and MAC layers. Optimal strategies for sharing information between sensor nodes and CSPE to avoid interference with other services are to be studied. In this context, the use of different technology to connect the sensor nodes to a network such that it does not contribute to the overall interference in the region of interest can be considered.

6) **Update rate:** Modern wireless networks include many mobile users, and the EM situation in the region of interest is dynamically changing. Therefore, REM produced by a collaborative sensor network has to be regularly updated to provide the cellular network with relevant and fresh information. Necessary REM update rate for different applications and achievable update rate are to be investigated.

7) **Integrating radar sensing:** Possible integration of radar sensing in to a collaborative sensor network, such that the network is capable of detection passive objects and add spatial awareness level (as shown in Fig. 1).

8) **Integrating channel state information:** Possible integration of estimation of channel state information that will provide information about propagation conditions (as shown in Fig. 1).

9) **PHY sensor design:** PHY level design of an individual sensor node w.r.t. needs of future cellular network requirements (e.g., consider necessary instantaneous analysis bandwidth of an individual sensor). Infrastructure sensors that monitor the spectrum might differ from simple average power meters to complicated wideband spectrum analyzers.

10) **Optimal number and placement of sensors:** Trade-offs between the number of sensors, their performance capabilities, and achievable overall system performance is a classical problem for WSN [10]. Intuitively, the higher the number of sensors, the better the performance. However, integrating additional sensors increases the implementation costs, and the performance gets close to saturation at some point. Thus, the optimal number of sensors for a particular area of interest to reach the necessary performance is to be determined.

11) **Different frequency ranges:** 5G NR includes different frequency bands. In addition to the traditional for cellular communications sub-6 GHz, a millimeter wave range has been added. Moreover, the terahertz frequency range is under consideration for 6G and beyond wireless networks [37]. Thus, the cooperative sensor network needs to be considered with respect to different frequency ranges. It is a more sophisticated scenario due to the massive use of high-gain directional antennas, making some classical algorithms irrelevant (e.g., RSS-based localization described by Eq. 1).

12) **Security:** Miscellaneous security issues should be researched for such a collaborative sensor network, including detecting a jammer in the region of interest, jamming attacks on sensor nodes, and detecting malicious nodes [38]. In addition, potential countermeasures have to be investigated. This can also contribute to the concept of resilience and security by design, widely discussed concerning the 6G.

VI. CONCLUSION

In this article, we accentuate the need for spectral awareness in cellular networks, in addition to widely discussed radar functionality. We start by proposing a vision and fundamental architecture of the collaborative sensor network for 6G. Then we provide an overview of relevant technologies that could be integrated. In this context, we discuss the capabilities and show the advantages of spectrum sensing in unlicensed bands, spectrum monitoring, and emitter localization. In future cellular networks, interference management, jammer detection, and emitter localization can be done by a proposed collaborative...
sensor network, thus providing multiple benefits. With concrete examples, we demonstrate how this approach solves the notorious hidden node problem and reduces the computational burden on communications devices. Finally, open research problems and directions for future studies related to implementing such a collaborative sensor network are introduced.

ACKNOWLEDGMENT

The authors acknowledge the financial support by the Federal Ministry of Education and Research of Germany in the project "Open6GHub" (grant number: 16KIS005).

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