Distributed 5G NR-Based Integrated Sensing and Communication Systems: Frame Structure and Performance Analysis

1st Shengnan Shi, 2nd Ziyang Cheng, 3rd Linlong Wu, 4th Zishu He, 5th Bhavani Shankar
School of Information and Communication Engineering, University of Electronic Science and Technology of China, China
Interdisciplinary Center for Security, Reliability and Trust (SnT), University of Luxembourg, Luxembourg
E-mail: zycheng@uestc.edu.cn; dsn@std.uestc.edu.cn

***Abstract*—This paper discusses a distributed Integrated Sensing and Communication (ISAC) network based on 5G NR. Each BS in the cellular network adopts half-duplex operation, and every three adjacent BSs construct a cooperative sensing system. Based on the 5G NR standard frame configuration, we develop a new procedure and protocol to support the proposed ISAC network. Under this network, we analyze the performance of both sensing and communication in practical scenarios. Simulations show the effectiveness of the proposed ISAC network.**

***Index Terms*—integrated sensing and communication (ISAC), 5G New Radio (NR), distributed sensing, frame structure, OFDM.**

I. INTRODUCTION

With the emergence and development of the fifth-generation (5G) wireless communication technology, the integrated sensing and communication (ISAC) system, which aims to implement both sensing and communication functionalities on the same hardware platform, has become a new research hotspot [1]. The ISAC has shown a great superiority in alleviating frequency band congestion and reducing hardware cost, and has been regarded as one of the key technologies in autonomous vehicular networks, perceptive mobile networks, and so on.

To construct an ISAC network, most published works consider having each BS individually responsible for the sensing and communication tasks within a cell. This requires the BS to support full-duplex (FD) operation and also requires advanced transmit and receive schemes for simultaneous sensing and communication [2]. However, the FD operation can cause severe self-interference, which is aroused by the signal leakage directly from the transmit antenna to the receive antenna and can significantly degrade the sensing and communication performance [3]. Although some self-interference suppression methods have been proposed recently, they are not yet mature enough for practical application.

In this paper, we propose a novel ISAC scheme, which reserves the half-duplex (HD) operation for BSs and can be implemented in an emerging 5G New Radio (NR) network without any challenging modifications. As a key trick, the proposed scheme arranges different frame structures for every three adjacent BSs to ensure that at any time, only one BS works in DL mode and the other two BSs work in UL mode. By doing so, the three adjacent BSs construct a distributed sensing system and thereby realize the physical separation of sensing transmitter and receiver. On this basis, the proposed ISAC scheme performs a complete sensing by utilizing three discontinuous OFDM symbols in one time-slot, while also performing DL and UL communication in a time-division multiplexed (TDD) manner. Both theoretical analysis and numerical simulation show that the proposed scheme is well compatible with the 5G NR standard and can be flexibly applied to various actual scenarios.

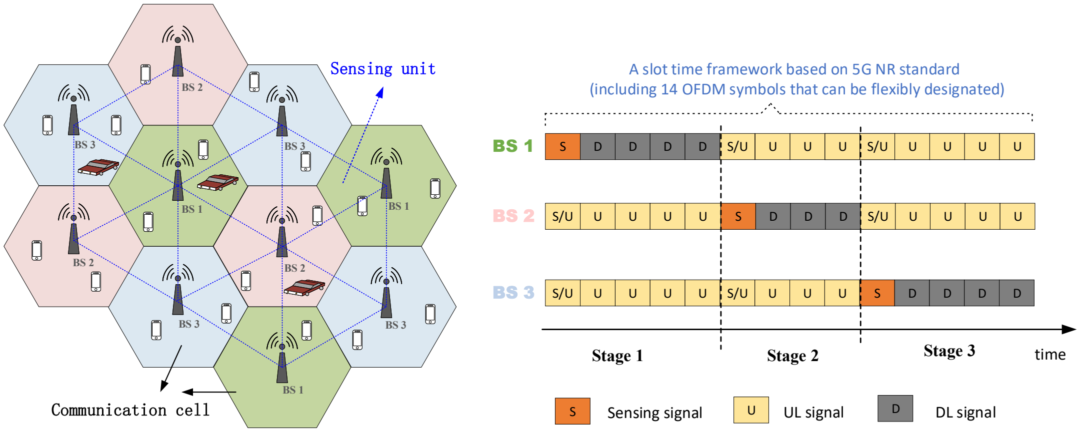
Notations: Standard lower-case letters represent the constants or variables. Boldface letters in lower-case and upper-case denote the column vectors and matrices, respectively. $\mathbb{C}^{n\times m}$ denotes the $m\times m$ complex space. $\mathbb{E}(\cdot)$ is the expectation of a random variable. $(\cdot)^H$ denotes complex conjugate transpose operation. $fft(\cdot)$ means to perform the fast Fourier transform on a vector.

II. SYSTEM DESIGN AND SIGNAL MODEL

A. Operating mechanism

Fig. 1(a) shows a typical cellular network, where a BS equipped with N_{BS} antennas is placed at the center of a hexagonal cell and is supposed to serve multiple single-antenna users (UEs) in the cell. In this work, we attempt to discuss an ISAC scheme, which allows the BS to preserves HD operation and can be easily implemented without complex design on the transceiver. The operation mechanism of the proposed scheme is concluded as follows:

Basic BS sensing unit First, all BSs in the network are divided into three groups. As shown in Fig. 1(a), BSs in the same color cell are formed into a group. By doing so, every three adjacent BSs belong to different groups and cooperate to perceive a prescribed area, i.e., the equilateral triangle enclosed by them. There, we use the expressions of *(sensing) unit* and *(communication) cell* to avoid confusion. The former is a triangle represented by the dotted blue line and the latter is a hexagon represented by the solid black line. It can be seen that each BS is associated with six sensing units but only one communication cell. From another point of view, the perception work of a unit is charged by three BSs while the communication task in a cell is handled by one BS.



(a) (b)

Fig. 1. (a) Diagram of the proposed ISAC network and (b) frame structures of different set of BS.

Interleaved frame structures The key to implementing collaborative sensing is to wisely design the frame structure for BSs. As shown in Fig. 1(b), the proposed ISAC scheme assigns different frame structures to different groups, which can be easily supported by 5G NR technology. With this setting, a time-slot is partitioned into three stages. At any stage, only one group of BSs operate in DL mode, employing the first OFDM symbol to emit a sensing signal and the other symbols to transmit DL information. At the same time, the other two groups of BSs work in UL mode, receiving the sensing signal in the first symbol duration and the UL signal throughout the whole stage. To make a distinction, the first symbol of each stage is called as the sensing symbol in the rest of this paper.

Sensing scheme For the sensing task, every three adjacent BSs form a distributed sensing system to perceive the associated unit. Such a distributed sensing system consists of one transmitter and two receivers, and is dynamic throughout a time-slot because the sensing transceiver changes at each stage. As shown in Fig. 1(b), the sensing work is carried out thrice in a time-slot, which produces six different sets of results to jointly characterize the scenario prevailing in the unit, i.e., two sets are respectively yielded at two receivers in each sensing.

Communication scheme For the communication task, each BS conducts UL or DL communication with the UEs in its cell. With the switching of stages, the two types of communication are performed in a TDD manner. However, one special point is that the DL communication is hanging in sensing symbol duration, while the UL communication can be kept.

Based on the above discussion, the operation scheme of the proposed ISAC network within the regular symbol duration can be embedded in a conventional 5G communication network. Therefore, this part will not be discussed in this paper. On the other hand, distributed sensing and UL communication are simultaneously carried out in sensing symbol duration, which raises some new technical issues to be addressed. For example, reasonable beamforming scheme and signal processing method are required by the BS to handle the two tasks. Regarding this, the transceiver signal model of the BS, as well as the beamforming and processing methods, will be investigated in the following. Notice that the discussion will be conducted for one sensing unit and one sensing symbol duration, since the extension to the whole network is straightforward.

B. Signal Model

The signal model for a certain sensing symbol over M time-slots will be discussed. To facilitate the expression, we use T-BS and R-BS to distinguish the transmitting BS and receiving BS. Besides, the discussion is conducted based on the following two *Assumptions*:

(i) There is one LOS path and several NLOS paths between two BSs, and the same between each BS and each UE. All channel information is assumed to be known and is invariant for at least M time-slots.

(ii) Under the premise of system synchronization, the following arrangements can be implemented by using the transmit-timing advance technique [4]. That is, for an R-BS, the sensing signal sent by the T-BS and propagated through the LOS path arrives at the same time as the UL signal sent by the users in its cell.

Denote the sensing symbol transmitted by the k-th sub-carrier as $\mathbf{s}_k \in \mathbb{C}^{N_s \times 1}$ (with N_s being the number of data stream) and define $\mathbf{F}_k \in \mathbb{C}^{N_{BS} \times N_s}$ to represent the corresponding transmit beamforming matrix, then, the baseband sensing signal transmitted by T-BS is

$$x(t) = \sum\nolimits_{k=1}^{K} \mathbf{F}_k \mathbf{s}_k e^{j2\pi k \Delta f t}, \tag{1}$$

where Δf is the sub-carrier interval. $x(t)$ is first reflected by targets and then be received by two R-BSs. Thereby, the distributed sensing system can also be regarded as two bi-static systems, and each bi-static system has a dedicated effective sensing area (ESA). A detailed explanation of ESA will be given in Section III. Here, we proceed to derive the received signal model of R-BS. Considering one of the R-BSs and its corresponding bi-static system, we assume that there are L targets located in its ESA. For the l-th target, φ_l, θ_l, τ_l and $f_{d,l}$ respectively represent the angle of departure (AOD) at T-BS, angle of arrival (AOA) at R-BS, time delay and Doppler frequency. Besides, we also assume that the R-BS has Q UEs in its cell. Then, in the m-th time-slot, the frequency-domain signal received by the R-BS on the k-th sub-carrier is

$$\mathbf{y}_{k,m} = \sum\nolimits_{l=1}^{L} \alpha_l \mathbf{d}_r(\varphi_l)\mathbf{d}_t^H(\theta_l)\mathbf{F}_k\mathbf{s}_k e^{j2\pi k\Delta f\tau_l} e^{j2\pi f_{d,l} mT_s} + \mathbf{G}_k\mathbf{F}_k\mathbf{s}_k + \sum\nolimits_{q=1}^{Q}\mathbf{h}_{q,k}u_{q,k,m} + \mathbf{n}_{k,m}, \quad (2)$$

where T_s is the duration of a time-slot and α_l represents the complex coefficient. $\mathbf{d}_r(\cdot)$ and $\mathbf{d}_t(\cdot)$ are the steering vectors of R-BS and T-BS, respectively. $u_{q,k,m}$ is the communication symbol transmitted by the q-th UE. $\mathbf{G}_k$ is the general channel matrix between T-BS and R-BS (constructing as *Assumption* 1), and $\mathbf{h}_{q,k}$ is the channel between the q-th UE and R-BS. $\mathbf{n}_{k,m} \sim \mathcal{N}(\mathbf{0}, \sigma^2\mathbf{I})$ represents the additive white Gaussian noise.

Next, two separate signal processing branches are developed for R-BS to obtain target information and UL symbol, respectively.

1) Signal processing for sensing: Following [5], we assume that the AODs and AOAs of the targets (i.e., θ_l and φ_l) are known or well estimated by the BSs and thereby mainly introduce how to acquire range and Doppler information in this work. With the information of φ_l, a set of receive beamformers $\mathbf{w}_{k,l}$ can be designed to spatially separate the sensing signals reflected from different targets. As a consequence, the separation process towards the l-th target will produce

$$z_{k,m,l} = \sum\nolimits_{l=1}^{L} \alpha_l \mathbf{w}_{k,l}^H \mathbf{d}_r(\varphi_l)\mathbf{d}_t^H(\theta_l)\mathbf{F}_k\mathbf{s}_k e^{j2\pi k\Delta f\tau_l} e^{j2\pi f_{d,l} mT_s} + \mathbf{w}_{k,l}^H\mathbf{G}_k\mathbf{F}_k\mathbf{s}_k + \sum\nolimits_{q=1}^{Q}\mathbf{w}_{k,l}^H\mathbf{h}_{q,k}u_{q,k,m} + \mathbf{w}_{k,l}^H\mathbf{n}_{k,m}. \quad (3)$$

Then, matched filtering is performed on $z_{k,m,l}$ to obtain

$$\tilde{z}_{k,m,l} = \frac{z_{k,m,l}}{\mathbf{d}_t^H(\theta_l)\mathbf{F}_k\mathbf{s}_k} = \alpha_l \mathbf{w}_{k,l}^H \mathbf{d}_r(\varphi_l) e^{j2\pi f_k\tau_l} e^{j2\pi f_{d,l} mT_s} + \sum\nolimits_{l'\neq l} \bar{\beta}_{k,l,l'} e^{j2\pi f_k\tau_{l'}} e^{j2\pi f_{d,l'} mT_s} + \tilde{\beta}_{k,l,m}, \quad (4)$$

where

$$\bar{\beta}_{k,l,l'} = \frac{\alpha_l' \mathbf{w}_{k,l}^H \mathbf{d}_r(\varphi_{l'})\mathbf{d}_t^H(\theta_{l'})\mathbf{F}_k\mathbf{s}_k}{\mathbf{d}_t^H(\theta_l)\mathbf{F}_k\mathbf{s}_k}, \quad (5)$$

$$\tilde{\beta}_{k,l,m} = \frac{\mathbf{w}_{k,l}^H\mathbf{G}_k\mathbf{F}_k\mathbf{s}_k + \sum_{q=1}^{Q}\mathbf{w}_{k,l}^H\mathbf{h}_{q,k}u_{q,k,m} + \mathbf{w}_{k,l}^H\mathbf{n}_{k,m}}{\mathbf{d}_t^H(\theta_l)\mathbf{F}_k\mathbf{s}_k}$$

characterize the residuals of unwanted components for estimating the information of the l-th target.

Finally, τ_l and $f_{d,l}$ are estimated by performing FFT on the frequency and time domains, respectively, i.e.,

$$\hat{\tau}_l = fft\left([\tilde{z}_{1,1,l}, \tilde{z}_{2,1,l}, \ldots, \tilde{z}_{K,1,l}]\right), \quad (6a)$$

$$\hat{f}_{d,l} = fft\left([\tilde{z}_{1,1,l}, \tilde{z}_{1,2,l}, \ldots, \tilde{z}_{1,M,l}]\right). \quad (6b)$$

2) Signal processing for UL communication: To recover the UL symbol $u_{q,k,m}$, a combiner $\boldsymbol{\xi}_{q,k}$ should be designed to process $\mathbf{y}_{k,m}$, resulting that

$$\hat{u}_{q,k,m} = \boldsymbol{\xi}_{q,k}^H \mathbf{h}_{q,k} u_{q,k,m} + \gamma_{q,k,m}, \quad (7)$$

where

$$\gamma_{q,k,m} = \boldsymbol{\xi}_{q,k}^H\Big(\sum\nolimits_{q'\neq q}\mathbf{h}_{q',k}u_{q',k,m}\Big) + \boldsymbol{\xi}_{q,k}^H\mathbf{G}_k\mathbf{F}_k\mathbf{s}_k + \boldsymbol{\xi}_{q,k}^H\mathbf{n}_{k,m} + \boldsymbol{\xi}_{q,k}^H\Big(\sum\nolimits_{l=1}^{L}\mathbf{d}_r(\varphi_l)\mathbf{d}_t^H(\theta_l)\mathbf{F}_k\mathbf{s}_k e^{j2\pi f_k\tau_l} e^{j2\pi f_{d,l} mT_s}\Big) \quad (8)$$

is the interfering component for extracting $u_{q,k,m}$.

C. Transceiver Beamforming Scheme

To obtain good parameter estimation and UL communication performance, beamformers and combiners ($\mathbf{F}_k$, $\mathbf{w}_{k,l}$, $\boldsymbol{\xi}_{q,k}$) should be wisely designed so that the interfering components ($\bar{\beta}_{k,l,l'}$, $\tilde{\beta}_{k,l,m}$ and $\gamma_{q,k,m}$) can be well suppressed. There, we introduce a simple but effective beamforming scheme.

First, the beamformer of transmitting BS is designed to generate multiple beams directed at targets. That is,

$$\mathbf{F}_k(:, l) = \mathbf{d}_t(\theta_l), \;\; l = 1, \ldots, \tilde{L}, \quad (9)$$

where $\tilde{L}$ is the total number of targets located in the ESAs of two bi-static systems formed in the current sensing.

Then, the receive beamformers $\mathbf{w}_{k,l}$ and $\boldsymbol{\xi}_{q,k}$ are respectively designed based on the minimum variance distortionless response (MVDR) criterion [6] and minimum mean square error (MMSE) criterion [7], implementing spatial separation of the UL signal and target echoes.

Remark: Notice that the above discussion are conducted for perceiving one sensing unit. However, as we mentioned before, a BS is associated with and should take charge of six sensing units. Therefore, the antenna array of a BS is divided into several sub-arrays to separately implement the perception in different sensing units. Accordingly, the above content can be flexibly applied to each sub-array.

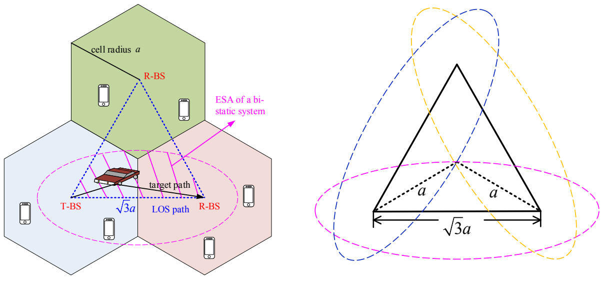
III. SENSING CAPABILITY OF THE PROPOSED ISAC SCHEME

In this section, we first explain the aforementioned concept of ESA. Followed with it, the sensing and communication capabilities of the proposed ISAC scheme are analyzed, showing how they are affected by the signal frame configuration.

A. Effective Sensing Area

As the OFDM signal is used, a prerequisite for ensuring the justification of (2) is that the sensing signal reflected by the target can be fully captured for FFT at R-BS. With Assumption (ii), the network is supposed to set the FFT window based on the time delay of the LOS path between transceive BSs. Therefore, the time delay difference between the LOS path and the target path should be less than a cyclic prefix (CP) duration. Consequently, we can define the ESA of a bi-static system as Fig. 2(a), which is the overlapping area of the sensing unit and an ellipse. The ellipse has two foci respectively located at T-BS and R-BS, and the sum of distances from the point on the ellipse to the two foci is $\sqrt{3}a + cT_{cp}$, where T_{cp} is the CP duration and a is the radius of the communication cell.

Based on the above discussion, T_{cp} cannot be set too small, otherwise, the coverage of ESA is extremely limited. But a large T_{cp} can also reduce the communication rate. Thus, it is necessary to specify the effect of T_{cp} on the capabilities of communication and sensing, in order to guide the frame configuration setting of the proposed ISAC scheme.



(a) (b)

Fig. 2. (a) the ESA of a bi-static system, (b) the critical condition to guarantee that all targets in a sensing unit can be effectively detected within a time-slot.

B. Sensing and Communication Capabilities

While T_{cp} affects the communication rate, it also confines the communication cell size given by the following considerations. In the proposed scheme, a bi-static system is expected to only form beams towards targets within its ESA, so as to avoid inter symbol interference. Therefore, to ensure that the three perceptions performed in a time-slot can cover the whole sensing unit, the critical condition is illustrated in Fig. 2(b). That is, the three ellipses associated with the three bi-static systems intersect at the center of the sensing unit. Accordingly, we can deduce that the cell radius a and the CP duration T_{cp} should satisfy $T_{cp} \geq (2a - \sqrt{3}a)/c$. Thereby, for a given T_{cp}, the maximum cell size a_{max} that can ensure full sensing is

$$a_{max} = cT_{cp}/(2-\sqrt{3}). \tag{10}$$

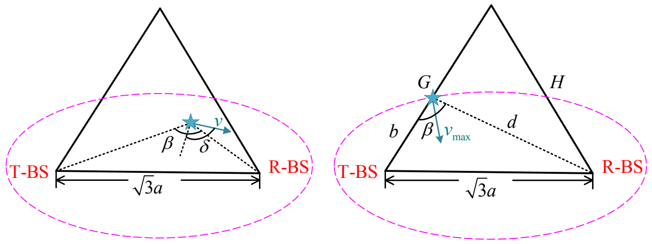
In addition, T_{cp} also affects the sensing capability in terms of the maximum detectable velocity. For a bi-static system, the Doppler frequency of a target is $f_d = \frac{2v}{\lambda}\cos(\beta/2)\cos(\delta)$, where v is the radial velocity of the target, β is called as bi-static angle, δ is the angle between the target moving direction and the centerline of the bi-static angle, as shown in Fig. 3(a). Therefore, assuming that the maximum detectable velocity is v_{max}, the maximum Doppler frequency $f_{d,\max}$ will appear in the case of Fig.3(b), i.e., a target with speed of $v_{\max}$ moves along the centerline of the bi-static angle at point G or H. Because in such a case, $\cos(\delta) = 1$ and β takes minimum value (denoted as β_{min}) within ESA. Accordingly, we have

$$f_{d,\max} = 2v_{\max}\cos(\beta_{\min}/2)/\lambda. \tag{11}$$

Then, the maximum detectable velocity is given as follows.

$$2v_{\max}\cos(\beta_{\min}/2)/\lambda = f_{d,\max} = 1/2T_s$$
$$\Rightarrow v_{\max} = \frac{\lambda}{4T_s\cos(\beta_{\min}/2)}. \tag{12}$$

Notice that $\cos(\beta_{\min}/2)$ can be calculated based on the geometric knowledge, which is related to a and T_{cp}. The above analysis reveals that the maximum detectable velocity is determined jointly by the CP duration T_{cp}, the time-slot length T_s and the communication cell size a.



(a) (b)

Fig. 3. (a) the relationship between Doppler frequency and velocity in a bi-static system is $f_d = \frac{2v}{\lambda}\cos(\beta/2)\cos(\delta)$, (b) a case where the target provides the maximum achievable Doppler frequency

IV. Numerical Results

A. Practicality Analysis based on 5G NR Standard

In this part, the communication and sensing capabilities of the proposed ISAC scheme are studied under the 5G NR standard, which provides five different frame configurations distinguished by μ. Fig.4 concludes the maximum cell size corresponding to each configuration, which spans from 320m to 5.2km. This result indicates that the proposed scheme can support various cell sizes that may appear in actual scenarios. Besides, Fig.4 also depicts the detectable velocity under different frame configurations and cell sizes. Note that each line ends at the corresponding maximum cell size. These results provide a basic guideline for using the proposed ISAC scheme. That is, setting a small u can support the detection of fast-moving targets in small-scale cells. On the other hand, when selecting a large u, the proposed scheme can be used for detecting slow-moving targets in large-scale cells.

μ	T_s (ms)	T_{cp} (us)	$a_{\max}$ (km)
0	1	4.69	5.25
1	0.5	2.34	2.62
2	0.25	1.17	1.31
3	0.125	0.57	0.64
4	0.0625	0.29	0.32

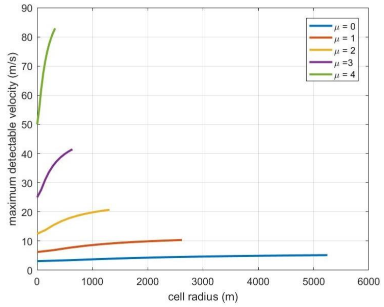
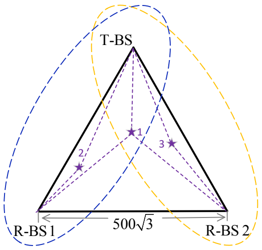


Fig. 4. The maximum cell size and maximum detectable velocity under different frame configurations

B. Signal Processing Result

Now, we evaluate the effectiveness of the beamforming and signal processing methods developed in Section II. We consider a 5G NR cellular network, where the cell radius is 500m. In each cell, there are two single antenna users and one BS equipped with N_{BS}=10 antennas. The frame configuration of the signal follows the 5G NR standard with $u = 3$. The distribution of targets in a sensing unit is depicted in Fig.5.

Fig. 6 shows the target detection results obtained at two R-BSs. It can be seen that the information of target 1 is obtained by two R-BSs, since it falls in the overlapping area of the two ESAs. The information of targets 2 and 3 are respectively



Target	Distance difference to LOS path	Radial velocity
1	90.75m	20m/s
2	14.18m	10m/s
3	8.71m	15m/s

Fig. 5. Distribution of targets in the considered sensing unit

obtained by R-BS 1 and R-BS 2. According to the figure, all target information is well estimated, and the interference components are effectively suppressed. Besides, Fig. 7 is given to evaluate the UL communication performance with respect to the bit error rate, where the SNR is defined as the power ratio of the UL signal to other components. The above results indicate that the sensing and UL communication can be well implemented at the same time.

V. CONCLUSION

In this work, we discuss an ISAC implementation scheme in a cellular network. By exploiting the interleaved frame structure, a dynamic distributed sensing network is constructed by the BSs, which can complete a global perception in three discrete symbol durations. Besides, a transmit beamforming scheme and a receiver processing architecture are developed so that the UL communication can be maintained during sensing symbol durations. We also discuss how the communication and sensing capabilities of the proposed scheme are affected by the signal frame configuration. Simulations show that, by wisely setting frame configuration (e.g. adopting the 5G NR standard), the proposed ISAC scheme can satisfy the various requirements developed in the application scenarios.

VI. ACKNOWLEDGMENT

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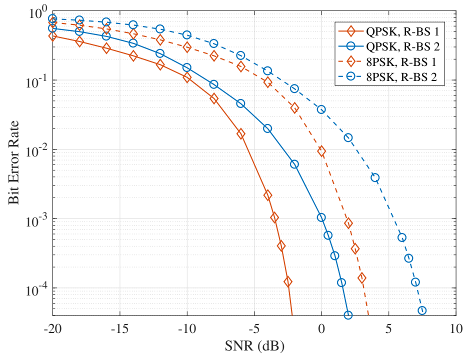

Fig. 7. Bit error rate of communication versus the SNR.

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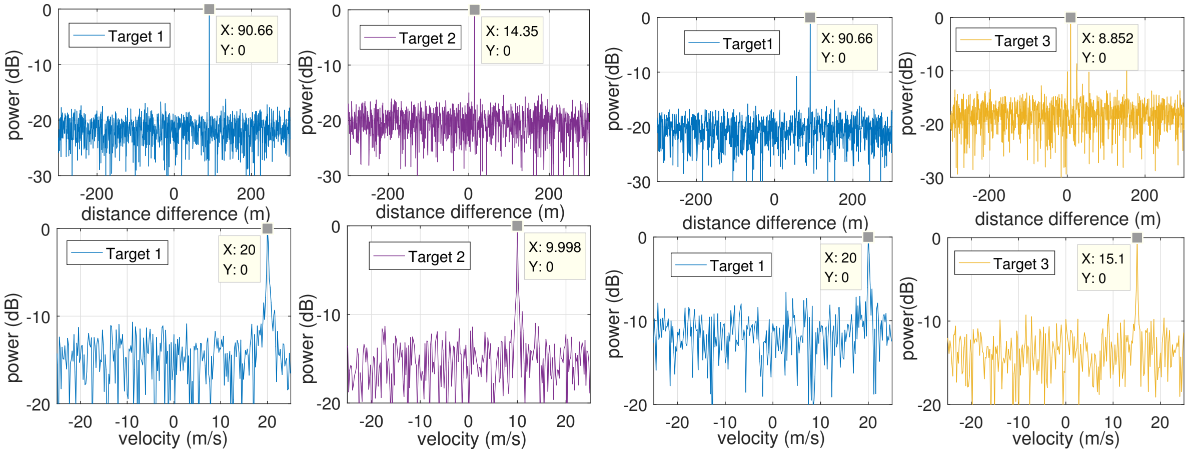

(a)

(b)

Fig. 6. (a) Distance and velocity of targets 1 and 2 measured by R-BS 1, (b) distance and velocity of targets 1 and 3 measured by R-BS 2.