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Non-orthogonal multiple access based cooperative spectrum sharing between MIMO radar and MIMO communication systems

Mohamed Rihan [a,b], Lei Huang [a,*]

[a] Multi-dimensional Signal Processing Lab., College of Information Engineering, Shenzhen University, Shenzhen, 518060, China
[b] Department of Electronics and Electrical Communications Engineering, Faculty of Electronic Engineering, Menoufia University, Shibin Al-Kawm 21974, Egypt

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ABSTRACT

During the last decade, spectrum sharing between different wireless technologies has been suggested as a promising solution to the spectrum scarcity problem. However, with the increasing growth of mobile devices and data rate hungry applications, it becomes a necessity to find more innovative spectrum sharing solutions. This paper proposes a novel three-phases non-orthogonal multiple access (NOMA)-based spectrum sharing strategy between multi-user MIMO (MU-MIMO) communication (comm) systems and collocated MIMO radars. The proposed strategy exploits a win–win relationship between the MIMO radar and MIMO comm systems. The MIMO radar wins the improvement of its performance in terms of probability of detection through the delegation of its transmission to the base-station (BS) that has better channels with the targets. On the other hand, the comm system improves its sum-rate throughput and outage performance through sharing the spectrum originally assigned to the radar. The proposed cooperative spectrum sharing strategy is examined in terms of sum-rate throughput and outage probability for the comm system, and the probability of detection for the MIMO radar. Simulation results are presented to illustrate that the proposed spectrum sharing strategy outperforms the state-of-the-art approaches to spectrum sharing between the MIMO radar and MIMO comm systems.

1. Introduction

In recent years, the demand for high bandwidth/high data rate wireless connectivity has skyrocketed, leading to unprecedented consumption and occupancy of the spectral resources assigned for wireless communication (comm) services [1]. Accordingly, it is of significant importance for the network operators to expand the capacity of their cellular networks to avoid congestion and overloading so as to guarantee quality of service. It is very interesting for the industry, mobile network operators, and academia to study spectrum sharing, especially with the case of some federal comm services that under-utilize their spectral bands, i.e., radar and TV services [2].

All the regulatory agencies worldwidly consider the spectrum as a scarce resource. Accordingly, there are significant efforts to better utilize the spectrum and it will continue hard with the approaching deployment of the fifth generation (5G) mobile comm networks [3]. For instance, the federal communications commission (FCC) focuses on developing solutions that are able to share the spectrum with different federal spectrum users, such as defense and civilian radars, public sector, and mobile operators [3]. Specifically, the FCC as well as national telecommunication and information administration (NTIA) have proposed the sharing of 150 MHz of the spectrum in the 3.5 GHz band, previously assigned to radar applications, with comm applications [2]. Despite all these efforts, a great challenge that cannot be ignored when dealing with spectrum sharing solutions is the mutual electromagnetic interference resulting from the co-existence of wireless system on the same spectral band [1–3].

Towards finding a solution to the interference problem and accordingly the data rate/capacity scaling requirements, non-orthogonal multiple access (NOMA) with successive interference cancellation (SIC) is strongly elected by many researchers and organizations to be the radio access technology for the next generation mobile networks [4–7]. Generally, NOMA can be used to allow multiple users to share their temporal, spectral, and spatial resources via power or code domain multiplexing [4]. The work in [8] highlights another degree of freedom (DoF) to the NOMA schemes by exploiting the co-existence of orthogonal frequency division multiple access (OFDMA) and single carrier frequency division multiple access (SC-FDMA) signals. This co-existence is achieved by revealing the characteristics of both OFDMA and SC-FDMA signals in the frequency and power domains [8].

* Corresponding author.
E-mail address: dr.lei.huang@ieee.org (L. Huang).

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During the last decade, numerous efforts had been done to develop solutions for spectrum sharing between comm systems and MIMO radars. Among these works, the authors in [9] concentrate on the MIMO radar side, where they designed the radar waveform to be in the null space of the interference channel between the MIMO radar and the BS of a single-cell comm system. Additionally, this work is extended in [10] to work with multi-cell cellular comm scenarios. In this case, the designed radar waveform is designed to be in the null space of the interference channel with the largest null space dimension. Another concept for achieving efficient spectrum sharing between the comm system and the MIMO radar is the use of ZF-like beamforming at both systems' nodes [11]. Numerous other works are based on the concept of null space projection (NSP) [9–16]. The principle behind the NSP is projecting the information signal of one of the two systems, either radar or communication, onto the null space of the interference channel between the two systems. Unfortunately, all the aforementioned approaches do not consider mutual and cooperative design of the spectrum sharing problem between the two systems, as well as, the achieve lower spectrum efficiency levels due to the employment of traditional orthogonal multiple access techniques. Accordingly, next generation networks will be in severe need to more spectrum efficient solutions that take care of the figure of merits of both systems, which is the main target of the proposed approach in this article.

Up to the best of our knowledge, spectrum sharing for the co-design of radar and communication systems was first introduced in [17–20]. Compared to legacy spectrum sharing designs in [9–16], the co-design approach is able to achieve an improved spectral efficiency through the optimum management of much more number of design degrees-of-freedom (DoFs). The integrated co-design approach always requires the exchange of some physical layer information between the two systems. For example, the two systems would have to share their channel state information (CSI) through a central node which manages the transmissions and signaling schemes for both systems. For successful operation of the co-design approach, certain degree of cooperation between the two systems could be maintained. Although an additional overhead would be incurred by the cooperation, the performances of radar and comm systems can be significantly enhanced because the interference signals between the two systems are efficiently suppressed and the limited spectrum resources are reused. Additionally, in [19], we have presented a two-tier alternative optimization framework to achieve peaceful coexistence between MIMO radar and MIMO comm with an optimum performance for both systems. The proposed framework in [19] employs the concept of interference alignment (IA) to get ride of the harmful interference between the two systems, and accordingly, maximize both the signal-to-interference-plus-noise ratio (SINR) at MIMO radar receiver and the average sum-rate of MIMO comm system. Specifically, the proposed framework is used to jointly optimize the transmit and receive beamforming filters for both systems aiming to provide an optimum co-design in terms of the SINR and the average sum rate throughput of the MIMO radar and MIMO comm system, respectively.

In this article, we propose a cooperative NOMA-based spectrum sharing strategy between MU-MIMO comm systems and MIMO radar. The motivation behind this spectrum sharing strategy is to achieve a two-way beneficial relationship between the two systems. The MIMO radar can make use of the wide coverage of the comm network to enhance its detection performance, and, at the same time, use its highly elevated BSs for early warning. On the other hand, the comm system can share the frequency band originally assigned for MIMO radar services. To this end, it is necessary to employ advanced signal processing techniques in the comm branch to get rid of the harmful interference between the two systems, and on top of these solutions is the newly adopted NOMA transmission technology with its well-known spectrum efficiency as well as its accompanying SIC technique. The main contributions in our article can be summarized as follows:

- A three-phase cooperative NOMA-based spectrum sharing strategy will be proposed to efficiently use the under-utilized radar frequency band by hosting transmissions from the comm system which can help the MIMO radar system to detect far targets with which, it has very poor channels.
- Evaluating the performance of the proposed spectrum sharing strategy through studying the target probability of detection of the MIMO radar and the outage probability as well as the sum-rate throughput of the comm system.
- Deriving a closed-form expression for the outage probability of the comm system in case of implementing the proposed spectrum sharing strategy.
- Comparing the proposed strategy with the state-of-the-art spectrum sharing techniques in the literature of MIMO-radar-MIMO-comm spectrum sharing.

The remaining sections are organized as follows: Section 2 introduces the system model of the proposed spectrum sharing approach and the common interference issues arising with the coexistence scenarios of both the MIMO radar and MIMO comm systems for which the given model applies. Then, the proposed NOMA-based cooperative spectrum sharing transmission strategy is addressed in Section 3. This is followed by exploiting the superiority of the proposed approach for both systems in terms of sum-rate throughput and outage probability for the comm system, and the target probability of detection for the MIMO radar in Section 4. Simulation results are presented in Section 5 and Section 6 concludes our work.

Notation: Vectors and matrices are written in boldface lower-case and upper-case letters, respectively. The $\mathbf{A}^\dagger$ is referred to as the complex Hermitian transpose of matrix $\mathbf{A}$. The symbols $\mathrm{tr}(\mathbf{A})$ and $\|\mathbf{A}\|_2$ represent the trace and 2-norm of matrix $\mathbf{A}$, respectively. The matrix $\mathbf{I}_n$ stands for the identity matrix of size $n \times n$. The $\mathbf{x} \sim \mathcal{CN}(\mu, \Sigma)$ means that $\mathbf{x}$ is complex Gaussian distributed with mean μ and covariance matrix Σ. The mathematical expectation is denoted as $\mathbb{E}[\cdot]$. The expression $\sigma^2_{max}(\mathbf{H})$ refers to the maximum eigenvalue of the matrix $\mathbf{H}$.

2. System model

Consider a cooperative spectrum sharing environment between a collocated MIMO radar and a multi-user MIMO (MU-MIMO) comm network as shown in Fig. 1. Specifically, assume a collocated MIMO radar that uses a transmit uniform linear array (ULA) of M_t antennas and a receive ULA of M_r antennas, and the inter-element distances of the transmit and receive ULAs are half-wavelength. Without loss of generality, we assume that the arrays have the same number of elements, i.e., $M = M_t = M_r$, at both the transmitter and receiver of the MIMO radar. The radar is pulsed-based with pulse repetition interval (PRI) T_{PRI} and carrier wavelength λ_c. It is assumed that the far-field targets are with distinct angles $\{\theta_t\}$, target reflection coefficients $\{\beta_t\}$, and Doppler shifts $\{\nu_t\}$. Moreover, they are localized within the same range bin. The MU-MIMO comm system considered here consists of one base-station (BS) that serves a number of K users denoted as UE_k, $k \in \{1, 2, \cdots, K\}$. The BS uses a number of N antennas, and each UE is also equipped with N antennas operating in a half-duplex mode. All channels are assumed to experience independent and identically distributed (i.i.d.) Rayleigh fading. The comm channel between the MIMO radar transmitter and the BS is denoted as $\mathbf{H}_{br} \in \mathbb{C}^{N \times M}$. Moreover, the channel gains from the BS and the MIMO radar transmitter to

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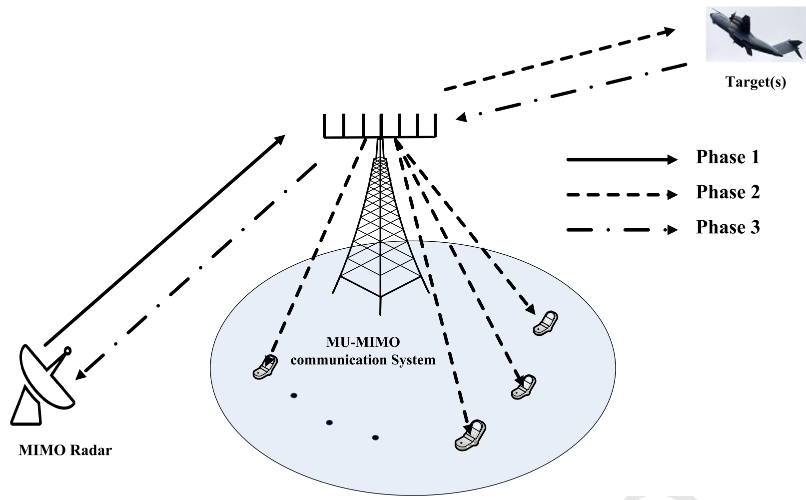

Fig. 1. Multi-user MIMO communication system sharing the spectrum with MIMO radar.

user k is denoted as $\mathbf{H}_{kb}$ and $\mathbf{H}_{kr}$, respectively. The transmit powers of the MIMO radar and BS are denoted by P_r and P_{BS}, respectively, and the background noise is assumed to be a zero-mean, complex Gaussian random variable with variance σ_r^2.

In order to establish the coexistence model between the MIMO radar and MIMO communication, the following assumptions are used in this article:

1. We assume that the two systems transmit narrow-band waveforms with the same symbol period. To make sure that such an assumption is feasible, let us consider an S-band search and acquisition radar with range resolution equal to 300 m (a typical range resolution is between 100 and 600 m [21]). Accordingly, the corresponding pulse duration for the radar system is 2 μs. On the other hand, symbol duration of 2 μs is quite typical in modern cellular communication systems [22]. The transmitted signal is considered as narrow-band if the channel coherence bandwidth is larger than the signal bandwidth [22–24]. In a macro-cell, typical values for the channel coherence bandwidth are of the order of 1 MHz [25], which is much larger than the signal bandwidth of 0.5 MHz (or symbol interval 2 μs). Thus, the narrow-band assumption is typically valid.
2. We assume that the radar and communication receivers sample their data in a time synchronous manner. For example, the range resolution for an S-band search and acquisition radar is typically between 100 m and 600 m [21]. Thus, the range resolution is $cT_b/2 = 300$ m, where $c = 3 \times 10^8$ m/s denotes the speed of light, and $T_b = 2$ μs is the radar pulse duration. In order to obtain identical symbol rate for two systems, the communication symbol duration should be 2 μs, which corresponds to the signal bandwidth of 0.5 MHz. Therefore, the symbol interval value lies within the range of typical LTE systems [25].
3. We assume that the radar system employs orthogonal waveforms. The employment of orthogonal signals improves the capabilities of the MIMO radars in terms of digital transmit and receive beamformings [26]. Additionally, the use of orthogonal waveform helps to obtain the improved angular resolution, extended array aperture in the form of virtual arrays, increased number of resolvable targets, lower sidelobes, and lower probability of intercept as compared to coherent waveforms [27,28].
4. We consider the target tracking scenario, in which the radar searches for the targets with unknown radar cross-section (RCS) variance in particular directions of interest, given by the set $\{\theta_t\}$, and a range bin of interest [29,30]. In such a scenario, the target parameters have typically been obtained from previous tracking cycles and are used to optimize the transmission for better SINR performance [31].

3. NOMA-based cooperative spectrum sharing between MIMO radar and MIMO comm systems

The proposed spectrum sharing strategy is suitable to scenarios where the MIMO radar has a small radar cross section (RCS) from its target(s), or scenarios in which comm system lies halfway between the MIMO radar and its target(s). In these scenarios, the mutual electromagnetic interference between the MIMO radar and the comm system can affect the signal(s) returned from the target(s) and accordingly degrade its performance. As shown in Fig. 1, the proposed cooperative NOMA-based spectrum sharing transmission strategy consists of three phases. During the first transmission phase, the signal $\mathbf{s}_0$ is transmitted from the MIMO radar transmitter to the BS, the received signal at the BS is given by:

$$\mathbf{y}_{BS}^{(1)} = \sqrt{\mathrm{P}_r}\, \mathbf{H}_{br}\, \mathbf{s}_0 + \mathbf{n}_b, \tag{1}$$

where P_r is the radar transmit power, $\mathbf{n}_b$ is the noise at the BS during the first transmission phase, and $\mathbf{s}_0$ is an orthogonal waveform that satisfies $\mathbb{E}\left(|\mathbf{s}_0|^2\right) = 1$. The signal received at the comm user UE_k can be expressed as:

$$\mathbf{y}_k^{(1)} = \sqrt{\mathrm{P}_r}\, \mathbf{H}_{kr}\, \mathbf{s}_0 + \mathbf{n}_k, \tag{2}$$

where $\mathbf{n}_k$ is the noise at UE_k during the second transmission phase.

During the second transmission phase, namely NOMA-based transmission phase, the BS is acting as an amplify-and-forward (AF) relay, and it is responsible for transmitting the communication signals to the users and at the same time transmit the signal received from the MIMO radar in the steering direction(s) previously assigned or transmitted by the MIMO radar through a backhaul connection between the two systems. Specifically, the BS superimposes the MIMO radar signal together with the comm signals using NOMA in order to achieve both spectral efficiency and interference mitigation. The signal received at user k can be expressed as:

$$\mathbf{y}_k^{(2)} = \mathbf{H}_{kb} \sum_{i=0}^{K} \sqrt{\alpha_i \mathrm{P}_{BS}}\, \mathbf{x}_i + \mathbf{n}_k, \tag{3}$$

where P_{BS} denotes the BS transmit power. The α_i refers to the power allocation coefficient of $\mathbf{x}_i$, $\forall i = 0, 1, \cdots, K$. The vector $\mathbf{n}_k$

refers to the noise at UE_k during the second phase. The signals $\mathbf{x}_i$, $\forall\, i = 1, \cdots, K$ are the comm signals that should be transmitted to the comm users. Additionally, the signal $\mathbf{x}_0$ forwarded by the BS from the MIMO-radar during the second transmission phase is given as:

$$\mathbf{x}_0 = \frac{\mathbf{y}_{BS}^{(1)}}{\sqrt{\mathbb{E}\left[\left|\mathbf{y}_{BS}^{(1)}\right|^2\right]}} = \frac{\mathbf{y}_{BS}^{(1)}}{\sqrt{\text{P}_r \left\|\mathbf{H}_{br}\right\|_2^2 + \sigma_b^2}}, \tag{4}$$

where σ_b^2 is the variance of the Gaussian noise at the BS.

According to the fundamentals of NOMA, an SIC will be carried out at each user UE_k to de-multiplex the signals within the power domain. The signals which allocated more power will be detected first, then SIC can be used to sequentially de-multiplex other signals in descending order of its power level. Specifically, UE_k will first detect UE_i's signal, $i < k$, and then remove the signal from its received superimposed version in a successive manner, while UE_i's signal, $i > k$, will be treated as noise at UE_k.

Since we consider that the MIMO radar tracks T targets and the parameters $\{\beta_t\}$ with distribution $\mathcal{CN}\left(0, \sigma_\beta^2\right)$, denote the complex path-loss for the target t that includes the coefficient of reflection, the propagation-loss, and the RCS of the target. Let the vectors $\mathbf{a}_{tx}(\theta_t)$ and $\mathbf{a}_{rx}(\theta_t)$ be the transmit and receive steering vectors for target t. The transmit steering vector, with equal inter-element spacing of half wavelength can be defined as:

$$\mathbf{a}_{tx}(\theta_t) \triangleq \begin{bmatrix} 1 \\ e^{-j\pi \sin(\theta_t)} \\ e^{-j2\pi \sin(\theta_t)} \\ \vdots \\ e^{-j(M-1)\pi \sin(\theta_t)} \end{bmatrix}. \tag{5}$$

Since the BS array will be used to transmit the MIMO radar signal and receive the signal returns from the targets, then we can assume that $\mathbf{a}(\theta_t) = \mathbf{a}_{tx}(\theta_t) = \mathbf{a}_{rx}(\theta_t)$, and accordingly the transmit-receive steering matrix can be written as:

$$\mathbf{A}(\theta) \triangleq \mathbf{a}(\theta)\ \mathbf{a}^{\dagger}(\theta). \tag{6}$$

In the second transmission phase, the BS transmits the superimposed signals $\sum_{k=0}^{K} \sqrt{\alpha_k \text{P}_{BS}}\, \mathbf{x}_k$ to its served users as well as emits it in the prescribed target direction(s), where $\mathbf{x}_k$ contains the signals to be transmitted to the served users UE_k for $k \in \{1, 2, \cdots, K\}$ or the MIMO radar signal for $k = 0$; i.e. $\mathbf{x}_0 = \mathbf{s}_0$. Without loss of generality, we can assume that the users' channel gains with their BS are ordered descendingly with respect to their maximum eigenvalue, namely, $\sigma_{max}^2(\mathbf{H}_{1b}) \le \cdots \le \sigma_{max}^2(\mathbf{H}_{Kb})$. Additionally, due to the high priority of the MIMO radar signal, we assume that $\alpha_0 \ge \alpha_1 \ge \cdots \ge \alpha_K$ with $\sum_{k=0}^{K} \alpha_k = 1$ [4,6].

During the third transmission phase, the BS is responsible for collecting the returned echo signals from radar targets together with faded version from the superimposed communication signals, then forwarding them all to the MIMO radar for further signal processing procedures. The echo signals from the target received at the BS can be expressed as:

$$\mathbf{y}_{BS}^{(3)} = \beta_t\, \mathbf{A} \sum_{k=0}^{K} \sqrt{\alpha_k \text{P}_{BS}}\, \mathbf{x}_k + \mathbf{n}_{BS}, \tag{7}$$

where $\mathbf{n}_{BS}$ is the noise at the BS during the third phase of the shared spectrum transmission strategy. The signal finally received by the MIMO-radar receiver can be expressed as:

$$\mathbf{y}_r = \mathbf{H}_{cr}^{\dagger} \overline{\mathbf{y}_{BS}^{(3)}} + \mathbf{n}_r, \tag{8}$$

where $\mathbf{n}_r$ is the noise at the MIMO radar receiver during the third transmission phase, and $\overline{\mathbf{y}_{BS}^{(3)}}$ is the normalized version of the signal received by the BS in the second transmission phase, which expressed as:

$$\overline{\mathbf{y}_{BS}^{(3)}} = \frac{\mathbf{y}_{BS}^{(3)}}{\sqrt{\mathbb{E}\left[\left|\mathbf{y}_{BS}^{(3)}\right|^2\right]}} = \frac{\mathbf{y}_{BS}^{(3)}}{\sqrt{|\beta_t|^2 \left\|\mathbf{A}\right\|_2^2 \text{P}_{BS} + \sigma_r^2}}. \tag{9}$$

Through a backhaul-link between the BS and MIMO-radar, the steering parameters and channel state information (CSI) of all comm users' channels can be forwarded together with the returned echo signals to the MIMO-radar. Through an SIC scheme at the MIMO-radar, it is able to easily detect the target echo signals.

4. Performance analysis of the proposed cooperative spectrum sharing strategy

The most important phase in the proposed cooperative spectrum sharing strategy is the NOMA-based cooperative transmission phase. During this phase, SIC is employed at the kth user, and according to (3), the receiving SINR for the UE_k user to detect the UE_i user $(1 \le i \le m \le K)$ is given by

$$\gamma_{i\to k} = \frac{\text{P}_{BS} \left\|\mathbf{H}_{kb}\right\|_2^2 \alpha_i}{\text{P}_{BS} \left\|\mathbf{H}_{kb}\right\|_2^2 \sum\limits_{j=i+1}^{K} \alpha_j + \sigma_k^2}. \tag{10}$$

After all $K-1$ users can be decoded successfully, the received SINR for the Kth is given by

$$\gamma_K = \frac{\left\|\mathbf{H}_{kb}\right\|_2^2 \alpha_K \text{P}_{BS}}{\sigma_K^2}. \tag{11}$$

During the third phase, the BS will act as AF relay which forwards the received echo signals to the MIMO-radar receiver. Together with these echo signals, the BS will send, through a backhaul link to MIMO-radar, the steering parameters and the CSI of all comm users. Accordingly, by employing the SIC stage at the MIMO-radar receiver, the output SINR of the MIMO-radar return signals at the BS can be evaluated as

$$\gamma_{r\to b} = \frac{\beta_t^2 \left\|\mathbf{A}\right\|_2^2 \alpha_0 \text{P}_{BS}}{\beta_t^2 \left\|\mathbf{A}\right\|_2^2 \left(\sum\limits_{k=1}^{K} \alpha_k\right) \text{P}_{BS} + \sigma_{BS}^2}. \tag{12}$$

Finally, based on (8), (9), and (12), the SINR of the received signal at the MIMO-radar receiver at the end of the third phase can be expressed as

$$\gamma_{radar} = \frac{\text{P}_{BS} \left\|\mathbf{H}_{cr}\right\|_2^2 \left\|\mathbf{A}\right\|_2^2 |\beta_t|^2}{\sigma_{BS}^2 \left\|\mathbf{H}_{cr}\right\|_2^2 + \sigma_r^2 \left(\text{P}_{BS} \left\|\mathbf{A}\right\|_2^2 |\beta_t|^2 + \sigma_r^2\right)}. \tag{13}$$

We are now at a position to evaluate the performance of the proposed NOMA-based cooperative spectrum sharing between MIMO-radar and MU-MIMO comm systems in terms of the outage probability and sum-rate throughput of the MU-MIMO NOMA comm system, and the detection probability for the MIMO radar when the two systems are operating in close proximity to each other.

4.1. Detection probability for MIMO-radar in coexistence with NOMA-based MU-MIMO comm system

One of the most important aspects of the MIMO-radar is the target detection probability and the effect of external interference signals on it. In this sub-section, we study the detection probability of the MIMO-radar when it is involved in the proposed cooperative spectrum sharing strategy with the NOMA-based MU-MIMO comm system. Obviously, the interference from the comm network to the MIMO-radar receiver will affect the probability of detection at MIMO-radar receiver. Based on Neyman–Pearson criterion, the asymptotic target detection probability of the MIMO-radar, denoted as P_D, can be evaluated using the generalized likelihood ratio test (GLRT) [32,33] as:

$$\mathrm{P}_D = 1 - \varphi_{\mathcal{X}_2^2(\rho)}\left(\varphi^{-1}_{\mathcal{X}_2^2}(1 - \mathrm{P}_{FA})\right), \tag{14}$$

where P_{FA} is the probability of false alarm. The function $\varphi_{\mathcal{X}_2^2(\rho)}$ denotes the non-central chi-square cumulative distribution function (CDF) with 2 degree-of-freedoms (DoFs). Finally, the function $\varphi^{-1}_{\mathcal{X}_2^2}$ represents the inverse function of the chi-square CDF with 2 DoFs, and ρ is the non-centrality parameter for $\mathcal{X}_2^2(\rho)$, and it is expressed as

$$\rho = \frac{|\beta_t|^2}{\sigma_r^2} M\, \mathrm{P}_r \mathrm{tr}\left(\frac{\mathbf{H}_{cr}\mathbf{H}_{cr}^{\dagger}\mathbf{A}\mathbf{A}^{\dagger}}{\mathbf{H}_{cr}\mathbf{H}_{cr}^{\dagger}/\sigma_r^2 + \mathrm{P}_{BS}\,|\beta_t|^2\,\mathbf{A}\mathbf{A}^{\dagger} + \sigma_r^2\mathbf{I}}\right). \tag{15}$$

It is of great importance here to highlight that the probability of detection for the MIMO radar in [32] is suitable only for white Gaussian noise. However, our proposed model includes both noise and interference, thereby enabling us to develop more efficient spectrum sharing approaches to handle the coexistence issue between radar and comm systems. It should be noted that the resulting interference-plus-noise is still Gaussian distributed with zero mean but non-identity covariance matrix [33]. Accordingly, a whitening-filter is applied in our design to normalize the interference-plus-noise signal, such that the derivation in [32] is still applicable to our design.

4.2. Outage probability for NOMA-based MU-MIMO comm system in coexistence with MIMO-radar

This subsection provides a comprehensive performance analysis, for the comm side, achieved by the proposed cooperative NOMA-based spectrum sharing strategy. As we assume that the BS of the comm system works as an AF relay, the outage probability is directly determined by the event that the instantaneous rates at the destination users are less than the targeted user data rates. At the side of the comm system, the performance is evaluated from an outage event perspective. The outage event occurs when any user fails to decode the signal of other users with lower index, i.e. worse channel users. For instance, the achievable data rate for user k to detect the signal assigned to user i, where $1 \le i < k$, is given by (10). The outage event occurs when $R_{i\to k} < R_i \;\forall\; i = 1, \cdots, K$, where R_i is the targeted data rate of $\mathbf{x}_i$. Subsequently, $\mathbf{x}_i$ can be decoded and removed by user k. This process will be terminated when $\mathbf{x}_k$ can be successfully decoded at UE_k. The achievable rate at UE_k, $k = 1, \cdots, K-1$, is given by

$$\gamma_k = \frac{1}{2}\log_2\left(1 + \frac{\mathrm{P}_{BS}\,\|\mathbf{H}_{kb}\|_2^2\,\alpha_k}{\mathrm{P}_{BS}\,\|\mathbf{H}_{kb}\|_2^2 \sum\limits_{j=k+1}^{K}\alpha_j + \sigma_k^2}\right). \tag{16}$$

Furthermore, the achievable data rate at user K, can be obtained as

$$\gamma_K = \frac{1}{2}\log_2\left(1 + \frac{\mathrm{P}_{BS}\,\|\mathbf{H}_{Kb}\|_2^2\,\alpha_K}{\sigma_K^2}\right). \tag{17}$$

Since the radar target detection and localization information are delay-sensitive, and accordingly, a fixed rate will be transmitted from the BS to the radar, the throughput of the network mainly depends on the outage probability. So, the outage probability is a fundamental metric of comm networks. The outage probability of the comm user UE_k with the proposed NOMA-based cooperative spectrum sharing strategy can be expressed as:

$$\begin{aligned}
\mathrm{P}_{out}^{(k)} &= \Pr\{R_{i\to k} < R_i\} \\
&= \Pr\left\{\frac{1}{2}\log_2\left(1 + \frac{\mathrm{P}_{BS}\,\|\mathbf{H}_{kb}\|_2^2\,\alpha_i}{\mathrm{P}_{BS}\,\|\mathbf{H}_{kb}\|_2^2 \sum\limits_{j=i+1}^{K}\alpha_j + \sigma_k^2}\right) < R_i\right\} \\
&= \Pr\left\{\frac{\mathrm{P}_{BS}\,\|\mathbf{H}_{kb}\|_2^2\,\alpha_i}{\mathrm{P}_{BS}\,\|\mathbf{H}_{kb}\|_2^2 \sum\limits_{j=i+1}^{K}\alpha_j + \sigma_k^2} < 2^{2R_i} - 1\right\} \\
&= \Pr\left\{\frac{z\alpha_i}{z\sum\limits_{j=i+1}^{K}\alpha_j + \frac{1}{\rho}} < c\right\},
\end{aligned} \tag{18}$$

where $\rho = (\mathrm{P}_{BS}/\sigma_k^2)$, $c = 2^{2R_i} - 1$, and $\Pr\{A\}$ denotes the probability of occurrence of the event A. The variable z is equivalent to the square of the channel, i.e., $\|\mathbf{H}_{kb}\|_2^2$. Since we are considering mutually independent Rayleigh fading channels, $\mathbf{H}_{kb}$ $\forall k \in \{1, 2, \cdots, K\}$, their squares can be modeled as exponential random variables with mean $\bar{z}$. As a result, the CDF can be evaluated as

$$\mathrm{P}_{out}^{(k)} = \begin{cases} 1, & \text{if } z \ge \frac{\alpha_k}{\sum_{j=k+1}^{K}\alpha_j} \\ 1 - \exp\left(-\frac{z}{\rho\left(\alpha_k - \left(\sum\limits_{j=i+1}^{K}\alpha_j\right)z\right)}\right), & \text{otherwise} \end{cases} \tag{19}$$

At high SNR, $c/(\rho(\alpha_k - \sum_{j=i+1}^{K}\alpha_j z))$ approaches 0, and the probability of the event, $((z\alpha_i)/(z\sum_{j=i+1}^{K}\alpha_j + 1/\rho)) < c$, can be approximated by using the power series of exponential functions [34] as

$$\mathrm{P}_{out}^{(k)} = 1 - \exp\left(-\frac{c}{\rho\left(\alpha_k - \left(\sum\limits_{j=i+1}^{K}\alpha_j\right)c\right)}\right). \tag{20}$$

Based on the condition that $c < (\alpha_k/(\sum_{j=k+1}^{K}\alpha_j))$, the previous expression in (20) can asymptotically be approximated as

$$\mathrm{P}_{out}^{(k)} = \frac{c}{\rho\alpha_k}. \tag{21}$$

The overall system outage event is defined as the event that any user in the system cannot achieve it targeted data rate, which means that the overall asymptotic outage probability, $\mathrm{P}_{asymptotic}$, is

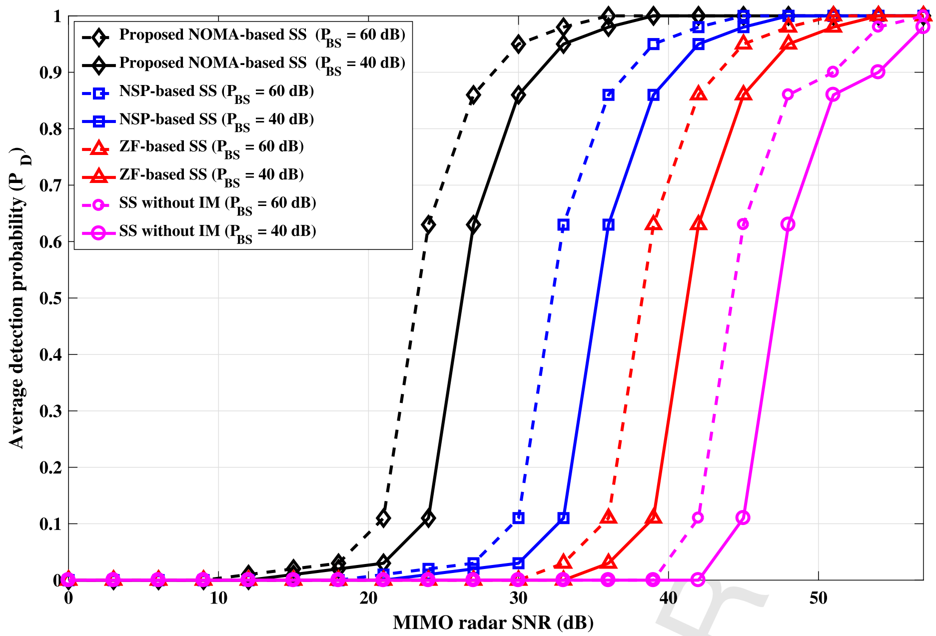

Fig. 2. Average detection probability of the MIMO radar Vs. radar SNR for different spectrum sharing approaches, $\mathrm{P}_{BS} = \{40\ \mathrm{dB}, 60\ \mathrm{dB}\}$, $P_{FA} = 10^{-5}$, $R_i = 2.5$ bps/Hz, $M = 4$, $K = 5$.

$$\mathrm{P}_{asymptotic} \triangleq 1 - \prod_{k=1}^{K} \left(1 - \mathrm{P}_{out}^{(k)}\right). \tag{22}$$

5. Numerical and simulation results

In this section, numerical results are presented to validate the merits of the cooperative NOMA-based spectrum sharing strategy between the MIMO radar and MU-MIMO comm systems. Throughout this section, the proposed cooperative strategy is compared with three other techniques, namely, NSP-based spectrum sharing [9–36] (denoted as NSP-based SS for short), the ZF beamforming based spectrum sharing strategy [37] (denoted as ZF-SS), and the spectrum sharing without interference mitigation (denoted as SS without IM) which corresponds to the situation where the two systems are obliviously operating in close-proximity to one-another, without interference mitigation. It is worth mentioning that the backhaul channel between MIMO-radar and communication systems is used for the exchange of parameters of the systems. These parameters, i.e. channel state information (CSI), are used for the coordination between the two systems to get rid of the harmful interference. In both the NSP-SS and ZF-SS techniques, this step is replaced by pilot signal transmission [9]. These pilot signals can be used to estimate and feedback the channel information between the radar and communication systems. Similar methods can also be used to feedback other configuration parameters [17].

Without loss of generality, this work considers a MIMO radar system with collocated ULA of half wavelength inter-element spacing that transmit Gaussian orthogonal waveforms. We assume that the coefficients of the channels, $\mathbf{H}_{kb}$, are i.i.d. zero-mean and unit-variance circularly symmetric complex Gaussian distributed, i.e., $\mathcal{CN}(0, 1)$. Additionally, the interference channels $\mathbf{H}_{cr}$ and $\mathbf{H}_{kr}$ are Rayleigh fading channels with i.i.d. coefficients drawn from $\mathcal{CN}\left(0, \sigma_r^2\right)$, with $\sigma_r^2 = 0.01$. We assume that the comm system consists of a BS that serves $K = 5$ users, and the users, BS and radar receiver are equipped with the same number of antennas M. It is assumed that the noise power at each comm user is normalized to unity. Since, the identical maximum transmit power is sent from the BS to serve each user, we evaluate the comm signal-to-noise ratio (SNR) in the considered scenario. During the evaluation of our results, we assumed that the time duration of this orthogonal waveform is equal to $L = 16$ symbols or 16 sub-pulse, which is also the number of pulses within the PRI. Also, we assumed that the sub-pulse duration of the radar and the symbol duration of the communication systems are equal to 2 µs. Accordingly, the waveform duration is equal to 32 µs.

The proposed NOMA-based strategy provides a win–win relationship between the two systems. This beneficial relation is tested for the MIMO radar through its target detection probability, that is analyzed in Sub-section 4.1. On the other hand, the strategy is tested for the comm side in terms of both the outage probability, analyzed in Sub-section 4.2, and the sum-rate throughput of the system in bits/sec/Hz (bps/Hz). As we stated earlier, the target detection probability has a direct relationship with the non-centrality parameters, ρ. From (15), the parameter is directly proportional to the number of antennas at the MIMO radar and the square of β_t^2, which is related to the path-loss and RCS of the targets. Additionally, it is directly proportional to the radar transmit power P_r, which in our scenario is related to the BS power budget P_c through the power allocation factor α_0, where $\mathrm{P}_r = \alpha_0 \mathrm{P}_c$. Totally, we can say that, P_D is monotonically increasing function with respect to the non-centrality parameter ρ [33].

In Fig. 2, the average detection probability, P_D, of the MIMO radar is tested in corresponding to the SNR of the MIMO radar at different levels of BS budget, P_{BS}. In this scenario, we assume that $M = 4$, $K = 5$, and $\mathrm{P}_{FA} = 10^{-5}$. Generally, it is obvious that P_D monotonically increases for all the spectrum sharing strategies. However, it is clear that the proposed strategy achieves better P_D than the other strategies at the same SNR. In other words, the proposed strategy achieves the maximum detection probability, for example, when SNR is 45 dB, the detection probabilities $\mathrm{P}_D \approx 0.04$, $\mathrm{P}_D \approx 0.7$, $\mathrm{P}_D \approx 0.95$, and $\mathrm{P}_D \approx 1$ for the SS without IM, ZF-SS, and the proposed SS strategies, respectively. It is observed in Fig. 3 that P_D improves as the radar SNR increases for all approaches. Fig. 3 studies P_D versus the power fraction allocated to the comm users from the BS power budget, namely, $(1 - \alpha_0)$. It is seen from Fig. 3 that P_D is inversely proportional to $(1 - \alpha_0)$ for different BS power budgets, namely, $\mathrm{P}_{BS} = 40$ dB and $\mathrm{P}_{BS} = 60$ dB.

The performance of the comm system implementing the proposed strategy is examined in terms of the outage probability and

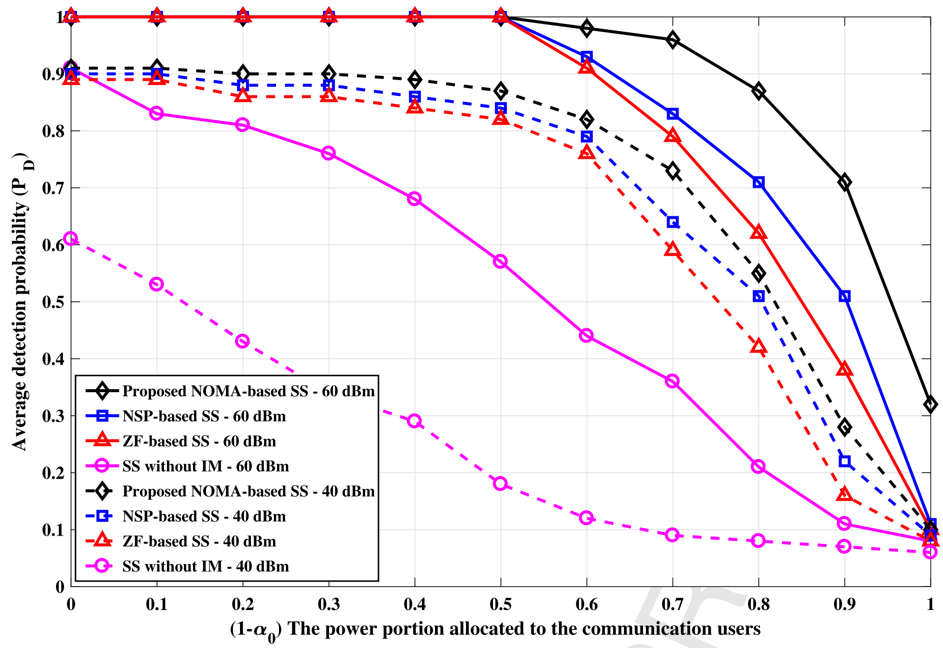

Fig. 3. Average detection probability of the MIMO radar Vs. the power portion allocated to the signals of the communication users for different spectrum sharing approaches, $P_{BS} = \{40 \text{ dB}, 60 \text{ dB}\}$, $P_{FA} = 10^{-5}$, $R_i = 2.5$ bps/Hz, $M = 4$, $K = 5$.

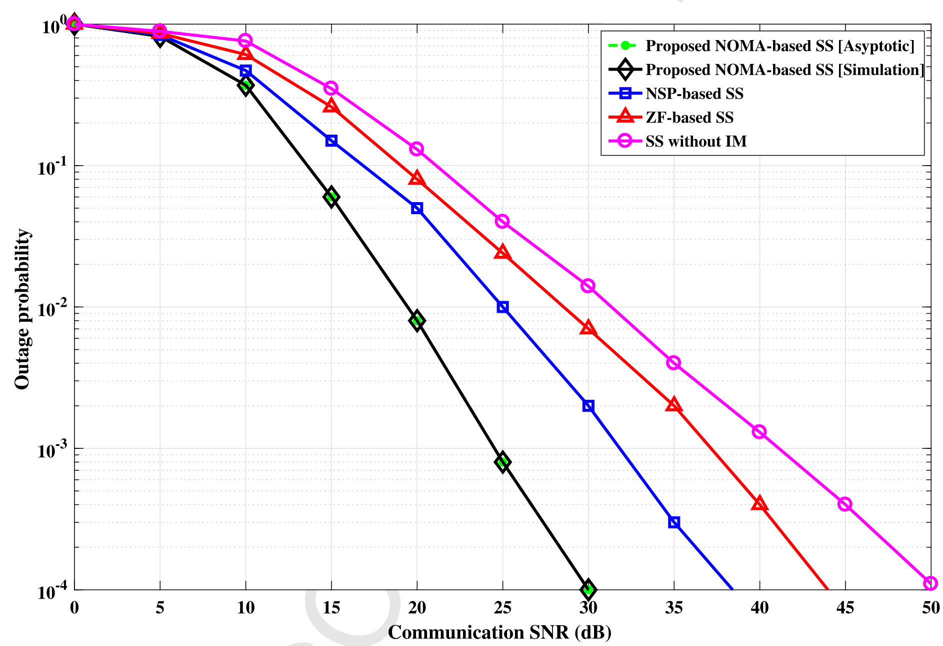

Fig. 4. Outage probability of the communication network Vs. the communication SNR for different spectrum sharing approaches. Additionally a perfect match between the numerical results gained from the closed-form expression and the simulation results can be noticed, $P_{BS} = 45$ dB, $R_i = 2.5$ bps/Hz, $M = 4$, $K = 5$.

sum-rate throughput. In Sub-section 4.2, a closed-form expression for the outage probability of the comm system that implements the proposed spectrum sharing strategy. In this part, the outage performance is numerically evaluated using both the derived analytic expression and Monte-Carlo simulations. Fig. 4 declares a perfect matching between the simulated results and derived closed-form expression. Additionally, the proposed strategy outperforms all the state-of-the-art techniques by achieving the lowest outage probability at all SNR levels. For instance, as SNR = 25 dB, the outage probability achieved by the proposed strategy equals 8×10^{-4} whereas the NSP-based approach can only provide an outage probability of 10^{-2}, and the ZF-SS only yields the outage probability of 1.5×10^{-2}. The outage probability increases semi-exponentially with the amount of power allocated for the MIMO radar signal from the BS power budget. This is logically acceptable, as the increase in the portion of power allocated to the MIMO radar signal implicitly means the decrease of the portion allocated for the comm signals, thereby leading to lower outage probability.

Another perspective for examining the proposed spectrum-sharing strategy is based on the outage performance versus the power allocation factor corresponding to the MIMO radar power, namely α_0. It is clear from Fig. 5 that α_0 has a great impact on the outage probability of the comm system.

Fig. 6 displays the impact of the throughput threshold for the comm users on the outage performance of the whole comm network. This threshold determines the number of users who will

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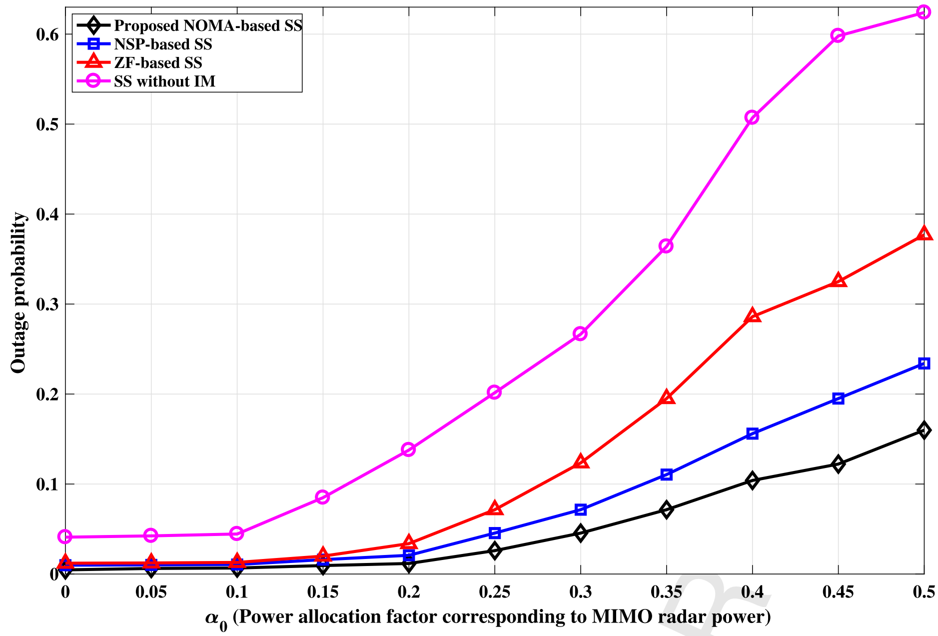

Fig. 5. Outage probability of the communication network Vs. the power allocation factor corresponding to MIMO radar power, for different spectrum sharing approaches, $P_{BS} = 45$ dB, $R_i = 2.5$ bps/Hz, $M = 4$, $K = 5$.

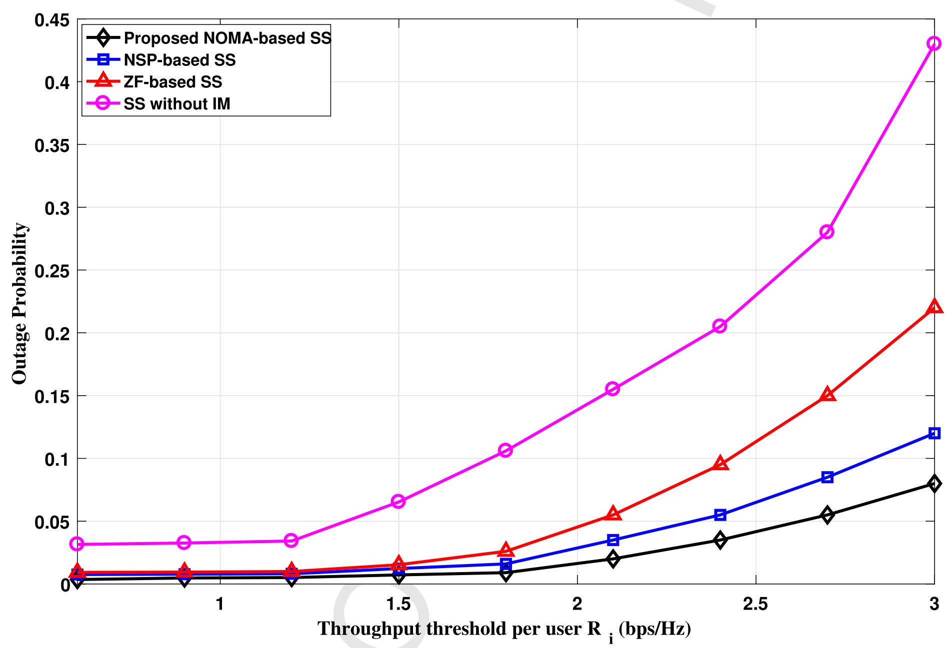

Fig. 6. Outage probability of the communication network Vs. the throughput threshold per user R_i, for different spectrum sharing approaches, $P_{BS} = 45$ dB, $M = 4$, $K = 5$.

contribute in the outage performance through their interference signals, and eventually affects the outage probability. It can be seen from Fig. 6, the total system outage probability increases as the throughput threshold level becomes larger. Also, it is clear that, at the same threshold value, the proposed strategy achieves the minimum outage probability.

One of the most important performance metrics for any comm system is the sum rate throughput in bps/Hz, which is always measured as the aggregate throughput achieved by all the active users, mathematically expressed as $\sum_{i=1}^{K} \log_2(1 + \text{SINR}_i)$, with SINR_i being the signal-to-interference-plus-noise ratio of user i. Fig. 7 plots the variation of the sum-rate throughput versus the SNR. It is obvious from the results that the sum-rate throughput achieved using the proposed strategy outperforms its counterparts achieved by the state-of-the-art approaches. Additionally, the sum-rate throughput increases with the increasing of the SNR. Specifically, it is very clear that the proposed strategy achieves approximately double the sum-rate throughput of that achieved when the two systems obliviously work together in close proximity to one-another.

Fig. 8 plots sum-rate throughput versus the power allocation factor corresponding to the MIMO radar power, namely α_0. As we mentioned previously, the BS budget is divided between the radar and comm. As a consequence, as the portion of power allocated to radar increases, the portion assigned to the comm decreases. The sum-rate throughput is related to both the portion assigned to the comm and interference introduced by the radar to the comm users. As the proposed strategy causes no interference from the MIMO radar to the comm users at the third phase, the sum-rate

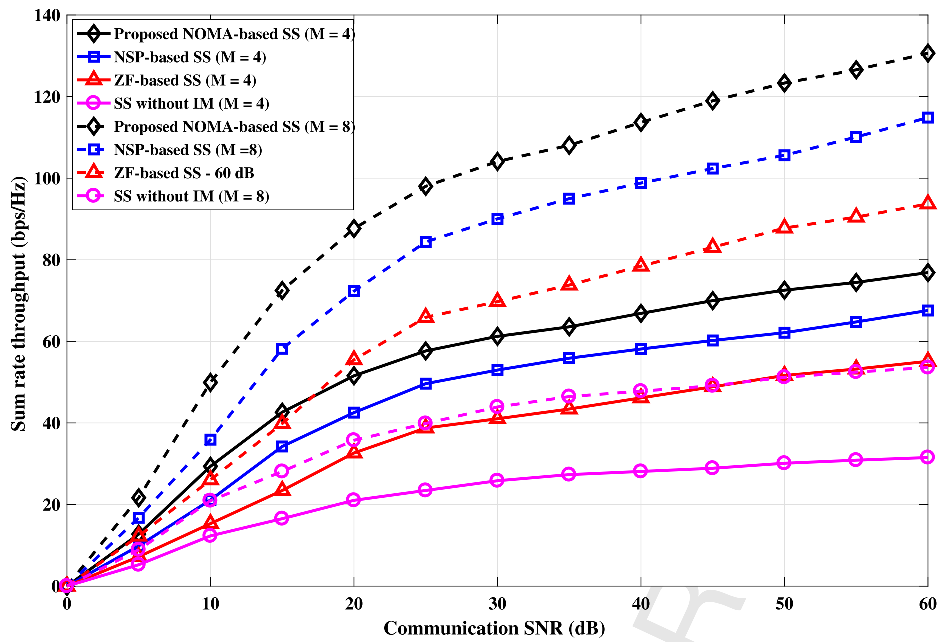

Fig. 7. Sum-rate throughput of the NOMA-based communication network Vs. SNR for different spectrum sharing strategies with different values of M, $P_{BS} = 45$ dB, $R_i = 2$ bps/Hz, $K = 5$.

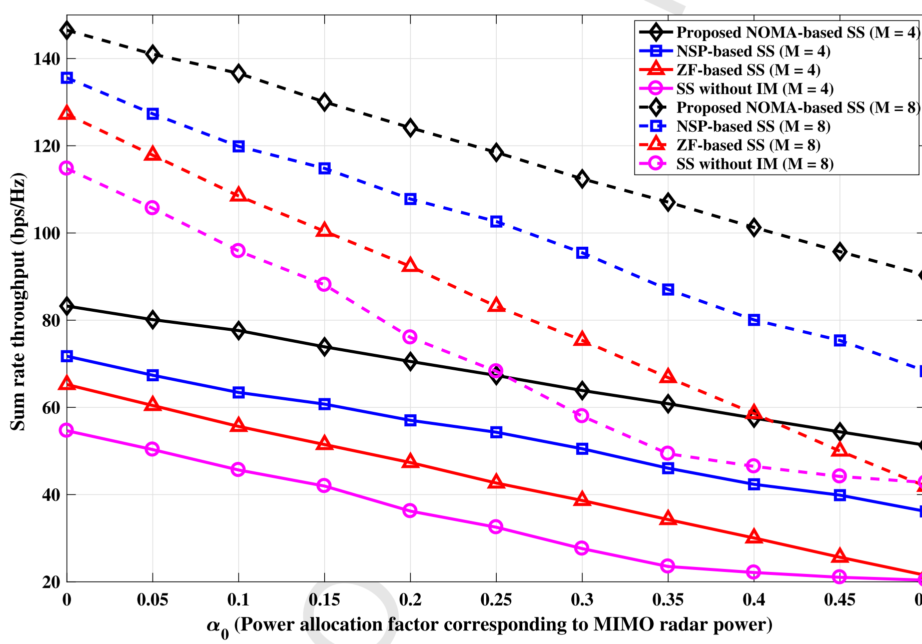

Fig. 8. Sum-rate throughput of the NOMA-based communication network Vs. the power allocation factor corresponding to MIMO radar power, for different spectrum sharing strategies with different values of M, $P_{BS} = 45$ dB, $R_i = 2$ bps/Hz, $K = 5$.

throughput depends mainly on the amount of power assigned for the communication signals from the BS power budget. It is clear that the sum-rate throughput decreases with the increasing of α_0. This is achieved for both cases of $M = 4$ and $M = 8$.

Finally, the relationship between the sum-rate throughput and the throughput threshold value for users is studied in Fig. 9. Similar to the statements above, larger throughput threshold can lead to smaller number of users serviced correctly by the BS and accordingly lower aggregate sum-rate throughput achieved by the system as a whole. In terms of the sum-rate throughput, the proposed scheme provides the best performance, followed by the NSP-based approach. The ZF-SS approach is superior to the NSP-SS approach but slightly inferior to the SS without IM scheme.

6. Conclusion

In this paper, a novel cooperative NOMA-based spectrum sharing strategy between the MIMO comm and MIMO radar has been addressed. Using the large coverage of the comm system, the task of early-warning from the perspective of radar target detection can be accomplished through building a win–win relationship between the two systems. The devised strategy uses the principles of the NOMA transmission and radio access technology to cooperatively transmit both the radar and the comm signals using one of the comm BSs. The performance of the proposed strategy has been studied in terms of the sum-rate throughput and outage probability of the comm side. On the other hand, the probability of detection at the radar side is examined. The theoretical results

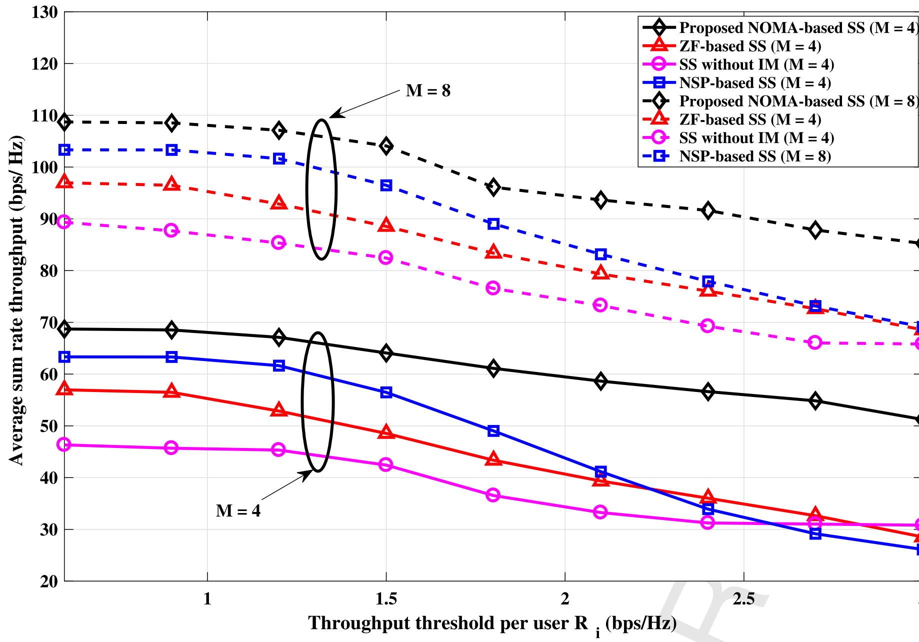

Fig. 9. Sum-rate throughput of the NOMA-based communication network Vs. the throughput threshold per user R_i, for different spectrum sharing strategies with different values of M, $P_{BS} = 45$ dB, $K = 5$.

agree well with the numerical results, thereby confirming that the proposed strategy is able to provide superior performance for both the MIMO radar and MIMO comm systems.

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Mohamed Rihan received his B.Sc. in electronics and communication engineering, with honors from Menoufia University, Egypt. He received his M.Sc. and PhD in electronics and communication engineering from Egypt–Japan University of Science and Technology in 2012 and 2015 respectively. From 2014 to 2015, he was a researcher at the Department of Advanced Information Technology, Graduate School of ISEE, Kyushu University, Japan. From 2016 to 2017, he was an adjunct professor at the center of photonics and smart materials, Zewail City of Science and Technology, Egypt. Currently, he is a postdoctoral research fellow with College of Information Engineering, Shenzhen University, China. He is also serving as an assistant professor at the Faculty of Electronic Engineering, Menoufia University, Egypt. His research interests include massive MIMO and mmWave communications, interference alignment, resource allocation, cognitive heterogeneous networks and applications of signal processing in wireless communications.

Lei Huang (M'07–SM'14) received the B.Sc., M.Sc., and Ph.D. degrees in electronic engineering from Xidian University, Xi'an, China, in 2000, 2003, and 2005, respectively. From 2005 to 2006, he was a Research Associate with the Department of Electrical and Computer Engineering, Duke University, Durham, NC. From 2009 to 2010, he was a Research Fellow with the Department of Electronic Engineering, City University of Hong Kong and a Research Associate with the Department of Electronic Engineering, The Chinese University of Hong Kong. From 2011 to 2014, he was a Professor with the Department of Electronic and Information Engineering, Harbin Institute of Technology Shenzhen Graduate School. Since November 2014, he has joined the College of Information Engineering, Shenzhen University, where he is currently a Distinguished Professor and the director of Shenzhen Key Lab of Advanced Navigation Technology. His research interests include array signal processing, statistical signal processing, sparse signal processing and their applications in radar, navigation and wireless communications. He is currently on the editorial boards of IEEE Transactions on Signal Processing, Digital Signal Processing, and IET Signal Processing. He is also an elected member of Sensor Array and Multichannel (SAM) Technical Committee (TC) of the IEEE Signal Processing Society. Additionally, he was elected an IET fellow in 2018.

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