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Hybrid AF/DF Cooperative Relaying Technique with Phase Steering for Industrial IoT Networks

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Abstract: For the next generation of manufacturing, the industrial internet of things (IoT) has been considered as a key technology that enables smart factories, in which sensors transfer measured data, actuators are controlled, and systems are connected wirelessly. In particular, the wireless sensor network (WSN) needs to operate with low cost, low power (energy), and narrow spectrum, which are the most technical challenges for industrial IoT networks. In general, a relay-assisted communication network has been known to overcome scarce energy problems, and a spectrum-sharing technique has been considered as a promising technique for the radio spectrum shortage problem. In this paper, we propose a phase steering based hybrid cooperative relaying (PSHCR) technique for the generic relay-assisted spectrum-shared WSN, which consists of a secondary transmitter, multiple secondary relays (SRs), a secondary access point, and multiple primary access points. Basically, SRs in the proposed PSHCR technique operate with decode-and-forward (DF) relaying protocol, but it does not abandon the SRs that failed in decoding at the first hop. Instead, the SRs operate with amplify-and-forward (AF) protocol when they failed in decoding at the first hop. Furthermore, the SRs (regardless of operating with AF or DF protocol) that satisfy interference constraints to the primary network are allowed to transmit a signal to the secondary access point at the second hop. Note that phase distortion is compensated through phase steering operation at each relay node before second-hop transmission, and thus all relay nodes can operate in a fully distributed manner. Finally, we validate that the proposed PSHCR technique significantly outperforms the existing best single relay selection (BSR) technique and cooperative phase steering (CPS) technique in terms of outage performance via extensive computer simulations.

Keywords: Industrial IoT; wireless sensor networks; 5G; cooperative communications; spectrum sharing; outage probability; cooperative phase steering

1. Introduction

The fourth industrial revolution (Industry 4.0) is a new generation of technology that allows collecting and processing data across machines, enabling monitoring, decision-making and automation to improve productivity, product quality, and services at low costs. Especially for the massive connectivity in the future wireless communication networks in the industry, the Internet of Things (IoT) has been considered as a key technology to provide wireless control of the systems in Industry 4.0 [1]. Especially in the industrial field, industrial IoT is considered that connects manufacturing robots, sensors, and control systems with the internet, such as smart factory. All sensors and actuators are wirelessly connected with the internet and their data are usually critical for operating factory so that highly reliable wireless communication is needed for wireless sensor networks (WSNs) in industrial IoT [2]. However, sensors usually are powered by internal batteries, thus they cannot utilize high power for reliable data transmission. To solve this problem, the relaying technique can be a reasonable solution to help communication between power limited nodes and access points (AP). On the other hand, in industrial IoT, there is another problem involving the coexistence

of heterogeneous networks with the same spectrum bands, such as unlicensed spectrum bands [3]. Because of the coexistence of networks using the same spectrum bands, there is interference among the different networks, which might cause performance degradation. To deal with the interference among the different networks, the cognitive radio technique has been considered in recent research. Consequently, to reflect these problems, relay assisted WSNs for the cognitive radio environment need to be considered.

Meanwhile, for the relay-assisted wireless communication network, a cooperative communication networks has been considered as the technology that can support multiple distributed relays. In the cooperative network, the multiple relay nodes deliver the received signal from a transmitter to a receiver, so that the transmitter can communicate with the receiver even if the transmitter cannot directly communicate with the receiver. Moreover, by multiple relays, spatial diversity can be achieved by the same signal traveling along different paths or selecting the best relay [4]. Typically, two relaying protocols are commonly used, the amplify-and-forward (AF) and the decode-and-forward (DF). In the AF relaying protocol, all relays only amplify the received signal and forward it from a transmitter to a receiver without decoding and encoding. Since relays operate only as an amplifier, the AF relaying protocol has an advantage in that it has simple computational complexity for relays. By contrast, in DF relaying protocol, relays firstly decode the received signal from a transmitter and deliver decoded signal to a receiver. As a result, the performance of DF relaying protocol is commonly better than AF relaying protocol because the noise at relays is amplified, and it acts as additional interference and degrades signal-to-noise ratio (SNR) at the receiver. Therefore, even DF relaying protocol has higher complexity than AF protocol, DF protocol is firstly considered since it can achieve better performance than AF relaying protocol by re-transmitting the original signal without any noise amplification [5]. However, for the environment in which relays are difficult to decode the original signal, DF relaying protocol experiences significant performance degradation due to a lack of available relay nodes.

To overcome both problems of AF and DF relaying protocol, another protocol called the hybrid amplify-or-decode and forward (HADF) technique has been proposed in [6,7]. The HADF relaying protocol is a new relaying protocol that combines the AF and DF relay protocols to take advantage of both relay technologies. The principle of the HADF relaying protocol is that the relay nodes can automatically select the most suitable cooperative diversity protocol (AF or DF) to process the received signal according to the channel state information (CSI) between users [8].

Meanwhile, for the cooperative communications in spectrum sharing-based cognitive radio networks, many techniques for different system environments have been proposed. Typically, the best single relay (BSR) technique is mostly considered for the multiple-relay cognitive radio networks to improve the outage performance of the secondary network communications, while both the secondary transmitter (ST) and secondary relays (SRs) should control their transmit powers such that the interference at primary networks is always below an allowable level [9–13]. In addition, several techniques are proposed for cooperative cognitive radio networks, such as for two-way relays [14], for full-duplex relays [15,16], turbo-coded cooperation of relays [17], and buffer-aided cooperation [18]. Note that, even though various cooperative relaying techniques have been proposed for various system environments, they are based on single relay selection techniques with different relay selection metrics that suit for considered system environments [19]. However, the selection based technique has a basic problem that it requires the relay state notification process and feedback process to select the best relay. Briefly, to decide which relay is the best one, another node has to gather the state of each relay, where the state notification process is needed. Then, to notify the chosen relay that another node has to transmit a signal to the chosen relay, the feedback process is needed.

To manage the signaling overhead problem of selection-based cooperative technique for cognitive radio networks, we propose another spectrum sharing-based relaying technique that is a cooperative phase steering (CPS) technique for spectrum sharing-based

WSNs [20]. In the CPS technique, relays compensate the phase distortion of transmit signal, which will be caused by the channel between themselves and the receiver. As a result, the phase of all received signals at the receiver are aligned, and are added at the same phase. Most importantly, local channel state information (CSI) is enough for the relays to operate the CPS technique, which means that feedback operation, which is needed in the selection technique, is not required [21].

Meanwhile, to the best of the authors' knowledge, the HADF protocol has not been applied to the CPS technique for the spectrum sharing-based wireless networks. Therefore, as the main contributions, we propose the phase steering based hybrid cooperative relaying (PSHCR) technique for the spectrum sharing-based networks in this paper. Most importantly, only SRs that cause less amount of interference than predefined interference constraints to primary access points (PAPs) can relay the signal to the secondary access point (SAP) with the PSHCR technique. Note that, if the secondary relay exceeds the interference constraint, it terminates transmission and saves energy since power management is a complicated process for IoT devices. Due to this transmission control of relays, the interference to the primary network is always maintained at less than the allowable interference level. Furthermore, the simulation results show that the PSHCR technique outperforms the conventional CPS technique and BSR technique in terms of outage probability.

The rest of this paper is organized as follows. A brief description of the considered system model and about the overall procedure of the proposed PSHCR technique is written in Section 2. In Section 3, simulation results about the outage probability of the proposed PSHCR are shown and compared with the conventional CPS technique and BSR technique. Finally, conclusions are written in Section 4.

2. Phase Steering Based Hybrid Cooperative Relaying Technique for Spectrum Sharing Relay Networks

In this section, we explain our considered system model and overall procedure of the proposed PSHCR technique. The conventional CPS technique only operates with DF relaying protocol, in which only SRs that succeeded in decoding can relay the original signal from ST. However, if many SRs fail in decoding, the DF relaying protocol can not perform well by a lack of available SRs. Therefore, in the PSHCR technique, AF relaying protocol is applied for the SRs that failed in decoding for additional diversity. Briefly, for the SRs that operate with AF relaying protocol, they compensate for both phase distortion of first-hop and second-hop channels.

2.1. System Model

As shown in Figure 1, we consider spectrum sharing wireless networks with multiple HADF relay nodes. The system consists of a secondary transmitter (ST), a secondary access point (SAP) node, K secondary relays (SRs), and J primary access points (PAPs). The channel between the ST and the k-th SR, between the k-th SR and j-th PAP, and between the k-th SR and the SAP are defined by $h_{\mathsf{S},k}$, $h_{k,j}$, and $h_{k,\mathsf{D}}$, respectively. Moreover, it is assumed that all the channel coefficients follow the complex Gaussian distribution, but a variance of them is different from each other for general system environments, i.e., $h_{\mathsf{S},k} \sim \mathcal{CN}\left(0, \sigma^2_{\mathsf{S},k}\right)$, $h_{k,j} \sim \mathcal{CN}\left(0, \sigma^2_{k,j}\right)$, and $h_{k,\mathsf{D}} \sim \mathcal{CN}\left(0, \sigma^2_{k,\mathsf{D}}\right)$. All channel coefficients are assumed to be static for each overall transmission (i.e., one two-hop transmission) and independently change after the overall transmission is over.

Due to the severe fading by relatively far distance and small transmit power of source node, we assume that ST does not impact any interference to PAPs, and source of the primary network does not impact interference to SAP either. As ST cannot interfere with PAPs, ST also cannot communicate with SAP directly. Consequently, ST communicates with SAP only through relaying operation of the SRs.

For the phase steering technique, which will be described later, each k-th SR is assumed to know the CSI that is associated with itself (e.g., $h_{\mathsf{S},k}$, $h_{k,j}$, and $h_{k,\mathsf{D}}$), which is called the *local channel state information (CSI)* assumption. If each SR requires only local CSI, then the overall

signaling overhead can be significantly decreased since only reference signal transmission from ST and SAP is enough to acquire all necessary CSIs. Consequently, the local CSI assumption is more practical for the multiple relaying systems than the full CSI assumption.
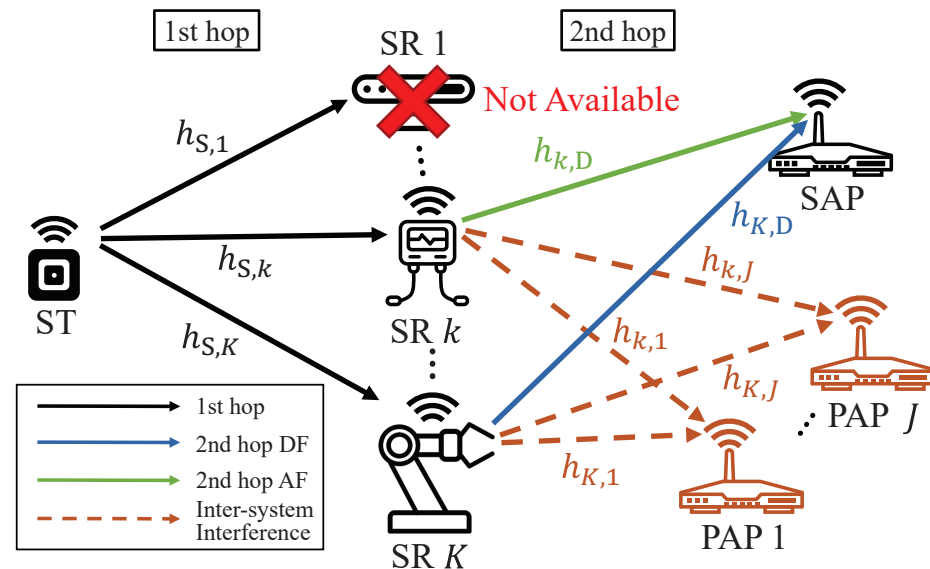

Figure 1. Considered system model of the PSHCR technique for spectrum sharing cognitive radio networks.

2.2. Overall Procedure

We explain the overall procedure of the PSHCR technique in this subsection.

2.2.1. First Hop

In the first-hop, if ST needs to transmit data, ST transmits a request-to-send (RTS) packet to SAP to acknowledge the signal transmission. Meanwhile, SRs can overhear the RTS packet from ST, in order to acquire the local CSI between ST and themselves. After SAP received the RTS packet, SAP broadcasts a clear-to-send (CTS) packet to all nodes in the network (i.e., ST and SRs). The same as RTS transmission, SRs can overhear the CTS packet from SAP and acquire the local CSI between themselves and SAP. After ST receives CTS packet, the ST transmits a signal to all SRs in the first-hop, and the received signal at each k-th SR is given by:

$$y_k = \sqrt{P_S} h_{S,k} x_S + n_k, \tag{1}$$

where P_S and x_S respectively represent the transmit power of ST and the transmit signal of the ST. Moreover, n_k denotes additive noise at the k-th SR, which is assumed to follow complex Gaussian distribution, i.e., $\mathcal{CN}(0,1)$ without loss of generality.

After receiving the signal from ST, all SRs try to decode the received signal, then there will be a set of SRs that succeeded in decoding, or failed in decoding. Thus, the set of SRs that succeeded in decoding is defined as follows by outage criterion:

$$\mathcal{D} \triangleq \left\{ k \in \mathcal{K} \mid \log_2(1 + P_S |h_{S,k}|^2) \geq 2R \right\} = \left\{ k \mid P_S |h_{S,k}|^2 \geq \rho_{th} \right\}, \tag{2}$$

where R represents a required spectral efficiency from ST to SAP and $\rho_{th} = \sqrt{2^{2R} - 1}$. Moreover, $\mathcal{K} = \{1, 2, \cdots, K\}$ represents the entire set of SRs. Note that, since the proposed HADF technique is a half-duplex relaying system, the required spectral efficiency of each

hop (i.e., first-hop or second-hop) needs to be twice that of R. On the other hand, the opposite set of $\mathcal{D}$, which is the set of SRs that failed in decoding, can be defined as

$$\bar{\mathcal{D}} \triangleq \left\{ k \in \mathcal{K} \mid P_{\mathsf{S}} |h_{\mathsf{S},k}|^2 < \rho_{th} \right\}. \tag{3}$$

Here, we assumed that each SR knows local CSI between ST and itself by receiving RTS packet from ST, and between itself and SAP by receiving CTS packet from SAP. Therefore, all SRs know the amount of phase distortion caused by their local channels and they compensate for phase distortion at the second hop.

2.2.2. Second Hop

In the second-hop, we distinguish the operation of $\mathcal{D}$ and $\bar{\mathcal{D}}$ as aforementioned, which are DF protocol for $\mathcal{D}$, and AF protocol for $\bar{\mathcal{D}}$. In addition, first of all, there is one more condition to decide whether each SR transmits a signal in the second-hop, the interference power of SRs to the PAPs in the primary network. To set the criterion for the interference power, we define the interference power limit at each PAP as Q, also known as *interference constraint*. Specifically, to determine each SR can transmit a signal or not, we define distributed interference constraint (DIC) as Q/K. Then, if the maximum interference from each SR to all PAPs exceeds DIC, this SR is terminated and cannot transmit a signal. Note that the DIC is calculated by normalizing an interference constraint with the number of entire SRs' K, not the number of relays that are finally allowed to transmit signals at the second-hop. This is because additional signaling overhead might be required to measure the number of possible SRs. Moreover, if DIC is satisfied for each SR, the total interference constraint at each PAP is automatically satisfied, since the number of available SRs is always less than K, (i.e., $\frac{Q}{K} |\mathcal{A}_{\mathsf{AF}} + \mathcal{A}_{\mathsf{DF}}| < Q$, where $|\cdot|$ represents cardinality of a set). Note that $\mathcal{A}_{\mathsf{AF}}$ and $\mathcal{A}_{\mathsf{DF}}$ denote that available SRs operate with AF protocol and with DF protocol, respectively, which are defined in (5).

Now, the set of SRs that does not exceed DIC to the PAPs is defined as

$$\mathcal{V} \triangleq \left\{ k \in \mathcal{K} \mid \max_{j \in \mathcal{J}} P_k |h_{k,j}|^2 < \frac{Q}{K} \right\}, \tag{4}$$

where $\mathcal{J} = \{1, 2, \cdots, J\}$ and P_k denotes the transmit power of the k-th SR. Please note that the partial interference CSI (e.g., channel gain value) from each SR to the PAP can be acquired at each SR by overhearing the sounding signal of the PAPs, which is broadcasted periodically. Consequently, the available SR set that respectively operates with DF protocol and AF protocol, and does not exceed DIC can be derived by finding SRs that belongs to both $\mathcal{D}$ and $\mathcal{V}$, and belongs to both $\bar{\mathcal{D}}$ and $\mathcal{V}$ as:

$$\mathcal{A}_{\mathsf{DF}} \triangleq \mathcal{D} \cap \mathcal{V}, \quad \mathcal{A}_{\mathsf{AF}} \triangleq \bar{\mathcal{D}} \cap \mathcal{V}. \tag{5}$$

Again, the SRs that belong to the $\mathcal{A}_{\mathsf{DF}}$ will operate with DF protocol; on the contrary, the SRs that belong to the $\mathcal{A}_{\mathsf{AF}}$ will operate with AF protocol.

For the SRs in $\mathcal{A}_{\mathsf{DF}}$, they only adjust the phase distortion which will be caused by the local channels between themselves and SAP, hence the phase distortion of all signals that is received at the SAP is zero. Then, the transmit signal of the l-th SR is given by

$$x_l = \exp(-i\angle h_{l,\mathsf{D}}) x_S, \tag{6}$$

where $l \in \mathcal{A}_{\mathsf{DF}}$ and $\angle a$ represent the phase of a, hence $\angle h_{l,\mathsf{D}}$ is a phase of channel between l-th SR and SAP.

On the other hand, the SRs that belong to $\mathcal{A}_{\mathsf{AF}}$ failed to acquire the original signal of ST, hence they cannot transmit a clear signal without noise. Therefore, they simply amplify the received signal from ST and adjust both phase distortions, one is caused by the local

first-hop channel and another one will be caused by the local second-hop channel at m-th SR, where $m \in \mathcal{A}_{\mathsf{AF}}$. The transmit signal of m-th SR is defined as

$$x_m = \frac{1}{\sqrt{P_S}|h_{S,m}| + 1} \exp(-i(\angle h_{S,m} + \angle h_{m,D}))y_m \tag{7}$$

where $\angle h_{S,m}$ represents the phase distortion that is caused by the local first-hop channel of m-th SR.

Then, the received signal of the SAP in the second-hop is given by

$$
\begin{aligned}
y_D &= \sum_{l \in \mathcal{A}_{\mathsf{DF}}} \sqrt{P_l} h_{l,D} x_l + \sum_{m \in \mathcal{A}_{\mathsf{AF}}} \sqrt{P_m} h_{m,D} x_m + n_D \\
&= \sum_{l \in \mathcal{A}_{\mathsf{DF}}} \sqrt{P_l}|h_{l,D}|x_S + \sum_{m \in \mathcal{A}_{\mathsf{AF}}} \left(\frac{\sqrt{P_m}|h_{S,m}||h_{m,D}|}{\sqrt{P_S}|h_{S,m}| + 1} x_S + \frac{\sqrt{P_m}|h_{m,D}| \exp(-i\angle h_{S,m})}{\sqrt{P_S}|h_{S,m}| + 1} n_m \right) + n_D,
\end{aligned}
\tag{8}
$$

where n_D represents additive noise at the SAP, which follows complex Gaussian distribution, i.e., $\mathcal{CN}(0,1)$. For a fair comparison, the total consumed power in the second-hop (i.e., $\sum_{k \in (\mathcal{A}_{\mathsf{DF}} \cup \mathcal{A}_{\mathsf{AF}})} P_k$) needs to be similar to the conventional techniques. Therefore, we set the P_k as P_R/K to normalize total consumed power, where P_R is the maximum total power budget of all SRs. Note that, since the actual number of available SRs (i.e., SRs in the $\mathcal{A}_{\mathsf{DF}} \cup \mathcal{A}_{\mathsf{AF}}$) is always less than, or the same as K, the total consumed power in the second hop is always less than P_R. However, as will be described in Section 3, it achieves better performance even though it uses less power. Finally, the outage probability of the proposed PSHCR technique can be calculated by

$$P_{out} = \mathrm{Pr}\left\{ \frac{\left(\sum_{l \in \mathcal{A}_{\mathsf{DF}}} \sqrt{\frac{P_R}{K}}|h_{l,D}| + \sum_{m \in \mathcal{A}_{\mathsf{AF}}} \frac{\sqrt{P_R}|h_{S,m}||h_{m,D}|}{\sqrt{K}(\sqrt{P_S}|h_{S,m}|+1)} \right)^2}{1 + \left(\sum_{m \in \mathcal{A}_{\mathsf{AF}}} \frac{\sqrt{P_R}|h_{m,D}|}{K(\sqrt{P_S}|h_{S,m}|+1)} \right)^2} < \rho_{th} \right\}. \tag{9}$$

3. Simulation Results

In this section, we compare the performance of the PSHCR technique with the conventional BSR technique and the CPS technique in terms of outage probability by computer simulations. For the simulation, we used MatLab 2019a software, and an internal function that generates the value that follows normal distribution is used for channel generation (i.e., *randn*). The variance of $h_{S,k}$, $h_{k,D}$, and $h_{k,j}$ is set to be $\sigma_{S,k}^2 = 0$ dB, $\sigma_{k,D}^2 = \sigma_{k,j}^2 = -10$ dB, respectively. Moreover, $P_S = P_R = $ Transmit SNR required spectral efficiency between ST and SAP is $R = 1$ bit/s/Hz in all simulations and other parameters are mentioned in each figure.

In Figure 2, the outage probability performance of the PSHCR technique is compared with that of the BSR technique and CPS technique for varying transmit SNR, where the number of SRs is $K = 7, 10, 13$. It is shown that the proposed PSHCR technique achieves higher performance than the BSR technique, which requires more signaling overhead by feedback for the SR selection. In addition, the proposed PSHCR technique outperforms the original CPS technique, in which only the SRs operate with DF protocol. The result that PSHCR is better than original CPS is because additional channel gain from SRs that operates with AF relaying protocol is much larger than the effect of amplified noise of AF relaying protocol. It is also observed that the proposed PSHCR technique achieves the same performance as the original CPS technique with high transmit SNR because all available SRs succeeded in decoding and operating with DF protocol, which is the same operation as the original CPS technique.

Figure 3 shows the performance of the PSHCR technique according to the number of SRs, where SNR $= 10, 12$, and 14 dB. It is worth noting that the PSHCR technique achieves significantly higher performance than other conventional techniques as the number of SRs increase since the PSHCR technique acquires more benefits from the spatial diversity gain.

More specifically, the PSHCR technique significantly outperforms the BSR technique with a large number of SRs. Moreover, it is shown that the PSHCR technique is always better than the original CPS thanks to the additional channel gain of SRs that operates with AF relaying protocol. On the other hand, the BSR technique requires more signaling process as the number of SRs increases, which might be critical for the IoT network that consists of many devices. Therefore, the selection-based technique is inappropriate for the relaying system for which the number of SRs is large and the PSHCR technique is better than the BSR technique since it operates in a distributed manner.
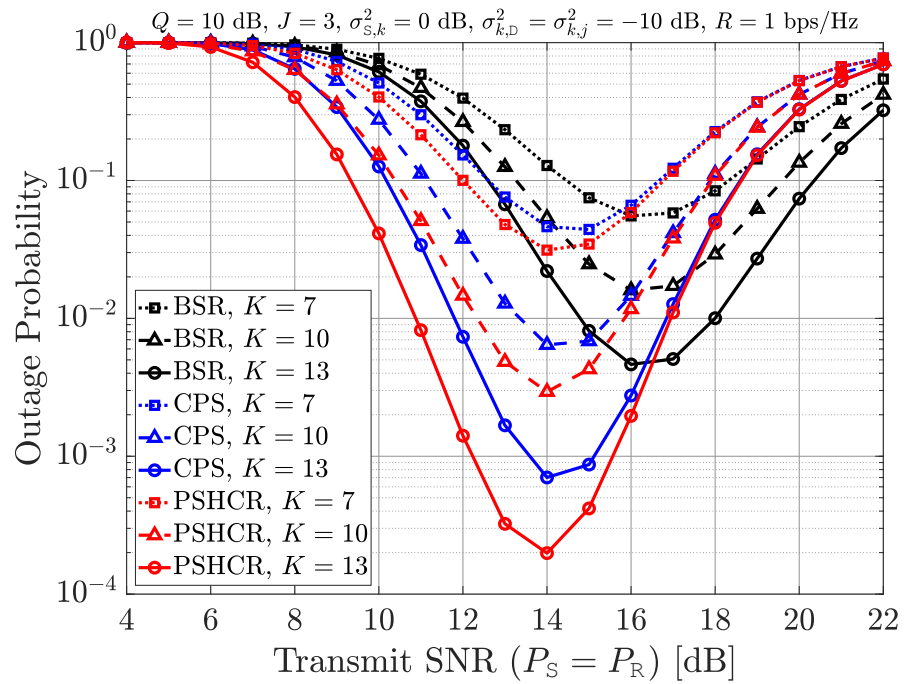

Figure 2. Outage probability performance of the PSHCR technique for varying transmit SNR.
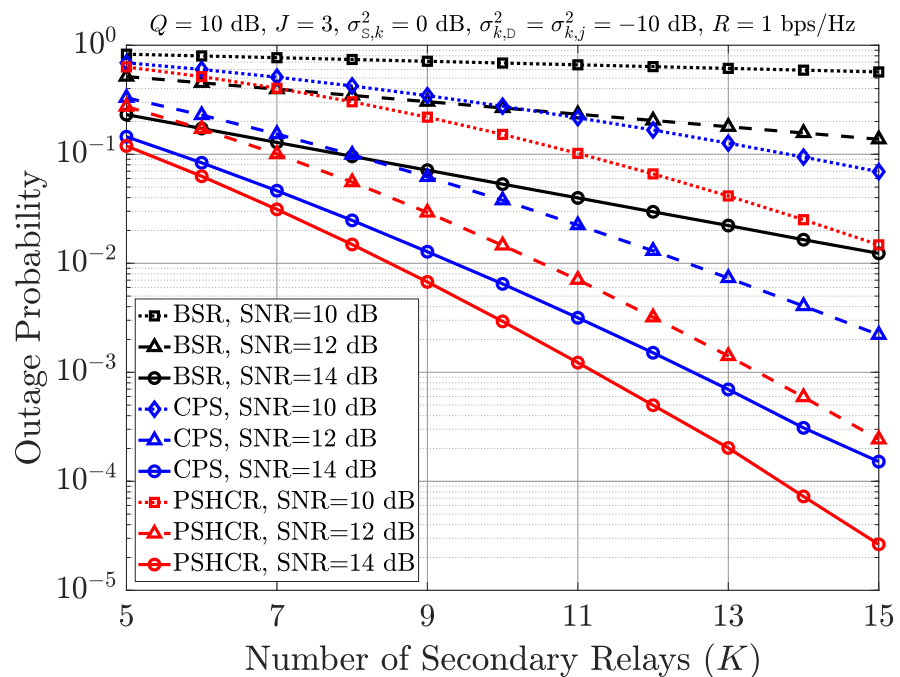

Figure 3. Outage probability performance of the PSHCR technique for varying number of SRs.

Figure 4 represents the performance of the PSHCR technique with the varying interference constraint of PAPs, where the SNR = 15 dB with a different number of SRs. It is shown that the outage probability performance of the PSHCR technique outperforms the BSR technique and the original CPS technique with a large amount of interference constraint. Moreover, the performance of the PSHCR technique improves significantly as the number of SRs increases, such as we described in Figure 3. The reason that the enhancement of the PSHCR technique is more significant than the BSR technique as the number of SRs increases is that interference power does not linearly increase. More specifically, transmit power of the BSR technique linearly increases as the number of SRs increases in our simulation since we normalized the power that is consumed in all SRs, so that a single SR utilizes all transmit power in BSR. Thus, interference power towards the primary network also linearly increases in the BSR technique. However, by contrast, all of the SRs in PSHCR operate anyway, and transmit power is distributed. Since the interference channels of each SR are not identical, the summation of the interference signal at PAP is not linearly added. As a result, the PSHCR technique can effectively utilize higher total transmit power at SRs than the BSR technique while interference power to PAP does not increase severely.
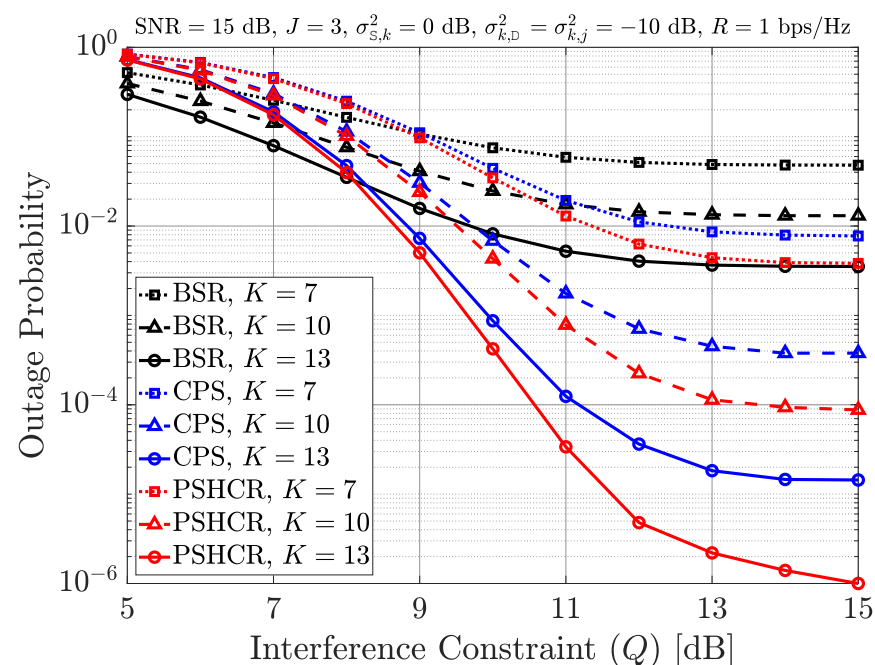

Figure 4. Outage probability performance of the PSHCR technique for varying interference constraint.

In Figure 5, the outage probability performance of the PSHCR technique for the varying amount of variance of the channel between SRs and SAP is shown in Figure 5. As the variance of the channel is smaller, the channel usually has more poor channel gain because of the severe path loss, long communication distance, deep fading, etc. As shown in Figure 5, the PSHCR technique and the original CPS technique outperform the BSR technique when the second-hop channel is poor in the spectrum sharing wireless networks. From this result, it is observed that, when the second-hop channel is poor, the spatial diversity with many SRs can achieve better performance than the selection, even though total transmit power is distributed to all SRs.

Finally, in Figure 6, the outage probability performance of the PSHCR technique is validated according to the required spectral efficiency. Note that there is an optimal transmit SNR for the minimum outage probability for a given condition as shown in Figure 2 because outage occurs often if the transmit SNR is low, and the interference constraint might not be satisfied if the transmit SNR is high. Hence, before verifying the outage probability performance according to the required spectral efficiency, we have derived the best transmit

SNR value for each required spectral efficiency by computer simulation as following Table 1. Please note that the best transmit SNR value of the CPS and the PSHCR technique for 0.5 bps/Hz is out of scope when we tried 10^7 realizations, hence we blanked it. First of all, as shown in Table 1, usually conventional techniques require a higher transmit SNR for the best outage probability, especially the BSR technique. Moreover, even though the BSR technique requires a higher transmit SNR value to achieve the best outage probability performance, the outage probability performance of the BSR technique is always poorer than the proposed PSHCR technique as shown in Figure 6. Consequently, we can understand that the PSHCR technique can achieve better performance than the conventional selection technique with small total consumed power.
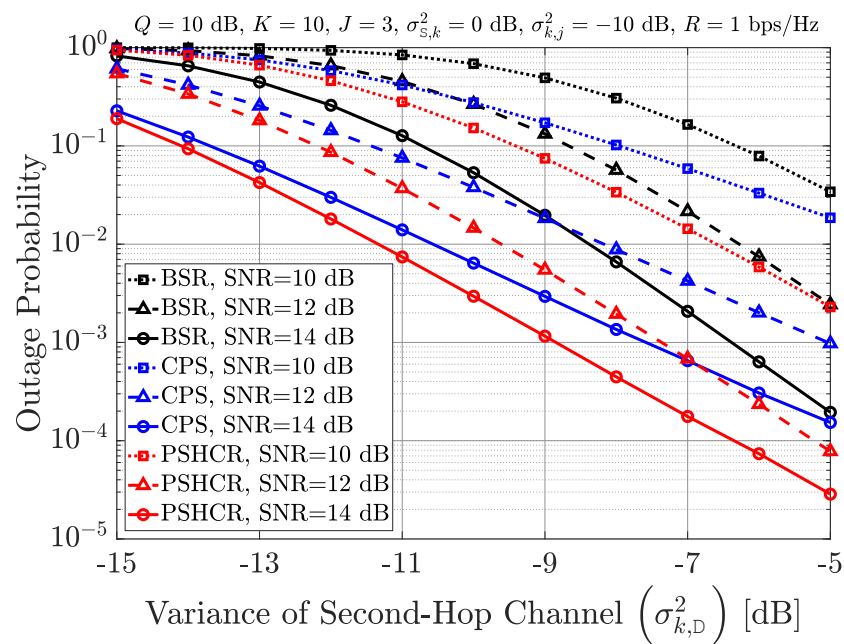

Figure 5. Outage probability performance of the PSHCR technique for a varying amount of second-hop channel variance.
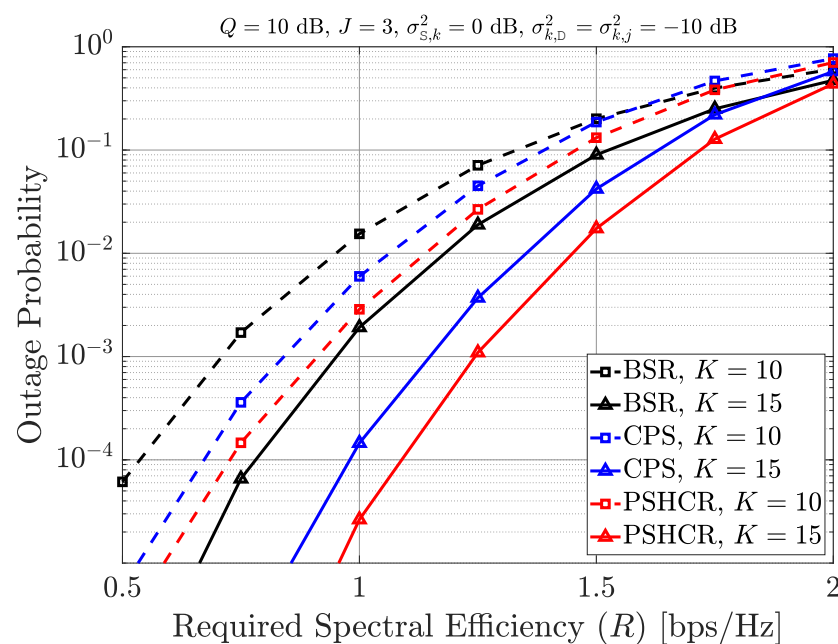

Figure 6. Outage probability performance of the PSHCR technique for varying required spectral efficiency.

Table 1. Best transmit SNR value of all techniques for given required spectral efficiency.

Required Spectral Efficiency (bps/Hz)	0.5	0.75	1	1.25	1.5	1.75	2
$K = 10$							
BSR (dB)	14.7	15.6	16.3	17.2	18	18.9	19.9
CPS (dB)	13.3	13.8	14.4	15	15.6	16.2	16.9
PSHCR (dB)	13	13.4	14.1	14.5	15.2	15.8	16.5
$K = 15$							
BSR (dB)	14.5	15.5	16.4	17.3	18	18.9	19.8
CPS (dB)	-	13.9	14.4	14.8	15.4	15.9	16.6
PSHCR (dB)	-	13	13.7	14.4	14.8	15.4	16.1

4. Conclusions

In this paper, we proposed the phase steering based hybrid cooperative relaying (PSHCR) technique for the spectrum sharing-based wireless sensor networks (WSNs) of industrial IoT. The considered system consists of a single secondary transmitter (ST), a single secondary access point, multiple secondary relays (SRs), and multiple primary access points (PAPs). Most importantly, in the proposed PSHCR technique, SRs that failed in decoding operate with amplify-and-forward (AF) relaying protocol, and SRs that succeeded in decoding operate with decode-and-forward (DF) relaying protocol. Moreover, for the protection of the spectrum sharing primary network, the interference power to the PAPs has to be less than the allowable interference constraint. Therefore, the SRs that exceed the interference constraint to the PAPs are terminated and cannot relay the signal from ST to the SAP. By computer simulations, we validated that the PSHCR technique significantly outperforms the best single relay technique with outage probability, especially when the number of SRs is large. Furthermore, it is also shown that the PSHCR technique outperforms the cooperative phase steering technique by the additional gain of the SRs that operates with AF relaying protocol. For the future work, the proposed PSHCR technique with multiple transmitters for more practical IoT systems can be considered as an interesting topic.

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Abbreviations

The following abbreviations are used in this manuscript:

IoT	Internet of things
WSN	Wireless sensor network
PSHCR	Phase steering based hybrid cooperative relaying
ST	Secondary transmitter
SR	Secondary relay
SAP	Secondary access point
PAP	Primary access point
AF	Amplify-and-forward
DF	Decode-and-forward
BSR	Best single relay

CPS	Cooperative phase steering
HADF	Hybrid amplify-or-decode and forward
SNR	Signal-to-noise ratio
CSI	Channel state information
RTS	Request to send
CTS	Clear to send

References

1. Giordani, M.; Polese, M.; Mezzavilla, M. Toward 6G networks: Use cases and technologies. *IEEE Commun. Mag.* **2020**, *58*, 55–61. [CrossRef]
2. Varga, P.; Peto, J.; Franko, A.; Balla, D.; Haja, D.; Janky, F.; Soos, G.; Ficzere, D.; Maliosz, M.; Toka, L. 5G support for industrial IoT applications–Challenges, solutions, and research gaps. *Sensors* **2020**, *20*, 828. [CrossRef] [PubMed]
3. Franham, T. Proactive wireless sensor network for industrial IoT. In Proceedings of the 2017 IEEE International Conference on Communications (ICC), Paris, France, 21–25 May 2017.
4. Peng, L.; Song, G. *Cooperative Device-to-Device Communication in Cognitive Radio Cellular Networks*; Springer: Berlin/Heidelberg, Germany, 2014.
5. Liu, X.; Du, W. BER-based comparison between AF and DF in three-terminal relay cooperative communication with BPSK modulation. In Proceedings of the 2016 12th International Conference on Mobile Ad-Hoc and Sensor Networks (MSN), Hefei, China, 16–18 December 2016.
6. Liu, C.; Zhou, C.; Hu, Q.; Zhao, H. A novel efficient cooperative diversity protocol for wireless networks. In Proceedings of the 2009 International Conference on Communications, Circuits and Systems, Milpitas, CA, USA, 23–25 July 2009.
7. Zhang, J.; Jiang, J.; Bao, J.; Jiang, B.; Liu, C. Improved relay selection strategy for hybrid decode-amplify forward protocol. *J. Commun.* **2016**, *11*, 297–304. [CrossRef]
8. Setiawan, D.; Zhao, H. Performance analysis of hybrid AF and DF protocol for relay networks. In Proceedings of the 2017 International Conference on Control, Electronics, Renewable Energy and Communications (ICCREC), Yogyakarta, Indonesia, 26–28 September 2017.
9. Zou, A.; Zhu, J.; Zheng, B.; Yao, Y. An adaptive cooperation diversity scheme With best-relay selection in cognitive radio networks. *IEEE Trans. Signal Process.* **2010**, *58*, 5438–5445. [CrossRef]
10. Luo, L.; Zhang, P.; Zhang, G.; Qin, J. Outage performance for cognitive relay networks with underlay spectrum sharing. *IEEE Commun. Lett.* **2011**, *15*, 710–712. [CrossRef]
11. Ding, H.; Ge, J.; da Costa, D.B.; Jiang, Z. Asymptotic analysis of cooperative diversity systems with relay selection in a spectrum-sharing scenario. *IEEE Trans. Veh. Technol.* **2011**, *60*, 457–472. [CrossRef]
12. Hong, J.; Hong, B.; Ban, T. W.; Choi, W. On the cooperative diversity gain in underlay cognitive radio systems. *IEEE Trans. Commun.* **2012**, *60*, 209–219. [CrossRef]
13. Sultan, K. Best relay selection schemes for NOMA based cognitive relay networks in underlay spectrum sharing. *IEEE Access* **2020**, *8*, 190160–190172. [CrossRef]
14. Zhang, X.; Zhang, Z.; Xing, J. Exact outage analysis in cognitive two-way relay networks with opportunistic relay selection under primary user's interference. *IEEE Trans. Veh. Technol.* **2015**, *64*, 2502–2511. [CrossRef]
15. Deng, Y.; Kim, K.J.; Duong, T.Q.; Elkashlan, M.; Karagiannidis, G.K.; Nallanathan, A. Full-duplex spectrum sharing in cooperative single carrier systems. In Proceedings of the 2015 IEEE Wireless Communications and Networking Conference (WCNC), New Orleans, LA, USA, 9–12 March 2015.
16. Zhang, R.; Chen, H.; Yeoh, P.L.; Li, Y.; Vucetic, B. Full-duplex cooperative cognitive radio networks with wireless energy harvesting. In Proceedings of the 2017 IEEE International Conference on Communications (ICC), Paris, France, 21–25 May 2017.
17. Moualeu, J.M.; Hamouda, W.; Takawira, F. Cognitive coded cooperation in underlay spectrum-sharing networks under interference power constraints. *IEEE Trans. Veh. Technol.* **2017**, *66*, 2099–2113. [CrossRef]
18. Zhang, R.; Nakai, R.; Sezaki, K.; Sugiura, S. Generalized buffer-state-based relay selection in cooperative cognitive radio networks. *IEEE Access* **2020**, *8*, 11644–11657. [CrossRef]
19. Bletsas, A.; Khisti, A.; Reed, D.; Lippman, A. A simple cooperative diversity method based on network path selection. *IEEE J. Sel. Areas Commun.* **2006**, *24*, 659–672. [CrossRef]
20. Lee, S.; Yoon, J.; Jung, B.C. A cooperative phase-steering technique with on-off power control for spectrum sharing-based wireless sensor networks. *Sensors* **2020**, *20*, 1942. [CrossRef] [PubMed]
21. Ban, T.W.; Choi, W.; Jung, B.C.; Sung, D.K. A cooperative phase steering scheme in multi-relay node environments. *IEEE Trans. Wirel. Commun.* **2009**, *8*, 72–77. [CrossRef]