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A cooperative phase-steering technique in spectrum sharing-based military mobile ad hoc networks

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Abstract

In military applications, mobile ad hoc networks are commonly used due to the autonomy, self-configuration, and flexibility. In addition, spectrum sharing-based communication protocols are being actively considered due to spectrum shortage. We propose a *cooperative phase-steering (CPS)* technique for a spectrum sharing-based military mobile ad hoc network which consists of a single secondary source (SS) node, multiple secondary relay (SR) nodes, a single secondary destination (SD) node, and multiple primary destination (PD) nodes. In the proposed technique, the SR nodes that succeeded the packet decoding cooperatively adjust the phase of their transmit signals such that the received signals at the SD node from the SR nodes are aligned to a certain angle, while the SR nodes control the transmit power such that the received power at all PD nodes is lower than a certain threshold. Through extensive computer simulations, it is shown that the proposed technique outperforms the conventional cooperative relaying scheme in terms of outage probability.

Keywords: Cognitive radio networks; Spectrum sharing; Military mobile ad hoc networks; Cooperative communications; Outage probability; Phase steering

1. Introduction

The demand of mobile data traffic has been explosively increased and the corresponding new spectrum resources are needed to support such a demand [1]. However, to discover and supply new spectrum bands is very challenging for most countries. Since they increase the utilization of existing unused spectrum bands without changing the spectrum allocation policy, spectrum sharing techniques have been investigated academically [2–4]. Recently, the spectrum sharing techniques have been received much attention from industry. For example, CBRS (Citizens Broadband Radio Service) alliance listed over 60 commercial companies have cooperated to promote and implement the spectrum sharing technology for the sharing of wireless spectrum in the 3.5 GHz band [5,6]. In particular, it was shown the spectrum bands for cellular networks are overloaded, while the bands for military applications like radars are insufficiently utilized [7]. Hence, spectrum-sharing opportunities exist especially in the spectrum bands for military applications, and the spectrum sharing-based military wireless networks have been actively investigated for network-centric warfare and radar applications [8].

On the other hand, mobile ad hoc networks (MANETs) have been long considered as the promising communication architectures in military applications due to the autonomy, self-configuration, and adaptability [9]. A cooperative communication is one of the most important techniques to improve physical-layer performances of the MANET by providing addition spatial diversity with multiple relay nodes [10]. The cooperative relaying techniques are expected to play an important role in future mobile MANETs called internet of battlefield things (IoBT) [11,12]. Among various cooperative relaying techniques, a selective decode-and-forward (SDF) protocol, as known as opportunistic relay selection (ORS), has been considered one of the most practical and excellent strategies in the spectrum sharing-based cooperative network [13,14]. However, the ORS scheme requires all the secondary relay (SR) nodes to feed decoding information back to the secondary source (SS) node for the best SR node selection, which induces additional signal overhead to the network. Another cooperative relaying technique called cooperative phase steering (CPS) was proposed for cooperative relay networks, which does not require the feedback information from the

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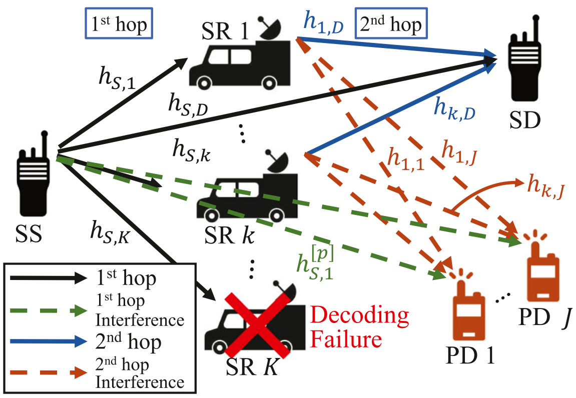

Fig. 1. System model of a spectrum sharing-based mobile MANET.

SR nodes and operates with a fully-distributed manner [15]. However the conventional CPS was not proposed for the spectrum-sharing environments.

In this paper, we modify the conventional CPS scheme for the spectrum sharing-based military MANETs, in which the relay nodes that successfully decoded the source message from the SS node send signals to the secondary destination (SD) node using cooperative phase steering while each SR node adjusts its transmit power so that all received interference power at all primary destination (PD) nodes are lower than a certain threshold. In addition, the SS node control its transmit power for satisfying the interference temperature condition at all PD nodes as well.

The rest of this paper is organized as follows. In Section 2, we describe the system model considered in this paper. An overall procedure of the proposed CPS technique for spectrum sharing-based military MANETs is explained in Section 3. In Section 4, we explain how to adjust the transmit power of relay nodes to satisfy the interference temperature condition at PD nodes in detail. Computer simulation results on outage probability of the proposed technique are shown in Section 5. Finally, conclusions are drawn in Section 6.

2. System model

We consider a spectrum sharing-based military MANET with multiple decode-and-forward (DF) relay nodes as shown in Fig. 1. There exist a single secondary source (SS) node, a single secondary destination (SD) node, J primary destination (PD) nodes, and K secondary relay (SR) nodes. In Fig. 1, $h_{S,k}$, $h_{k,D}$ and $h_{k,j}$ represent the wireless channel from the SS node to the kth SR node, from the kth SR node to the SD node, and from kth SR node to the jth PD node, respectively. Moreover, the wireless channel of the direct link from the SS node to the SD node and the wireless channel from the SS node to the jth PD node are denoted by $h_{S,D}$ and $h^{[p]}_{S,j}$, respectively. We assume that $h_{S,k}$, $h_{k,j}$, $h_{S,D}$, $h^{[p]}_{S,j}$, and $h_{k,D}$ follow independent and identically distributed (i.i.d.) complex Gaussian distribution with zero mean and different variances, i.e., $h_{S,k} \sim \mathcal{CN}\left(0, \sigma^2_{S,k}\right)$, $h_{k,j} \sim \mathcal{CN}\left(0, \sigma^2_{k,j}\right)$, $h_{S,D} \sim \mathcal{CN}\left(0, \sigma^2_{S,D}\right)$, $h^{[p]}_{S,j} \sim \mathcal{CN}\left(0, \sigma^2_{S,j}\right)$, and $h_{k,D} \sim \mathcal{CN}\left(0, \sigma^2_{k,D}\right)$. The variance of the wireless channels changes according to relative distance among communication nodes in the system model.

We assume that primary source (PS) nodes are located far from the secondary network enough and they do not cause interference to the secondary network at all as other studies on spectrum sharing techniques in the literature [3,14,16].[1] It is assumed that distance between the SS node and the SD node is larger than other distances among communication nodes, i.e., the average channel gain of the direct link from the SS node to the SD node $\sigma^2_{S,D}$ is significantly small. In addition, we assume that SS and each SR node know the channel state information (CSI) from itself to the PD nodes and SD node respectively, which is called *local CSI* assumption in the literature [15,17] and is widely known to be practical in wireless communication systems. Quasi-static frequency-flat fading is assumed, i.e., the wireless channel coefficients are constant during two-hop transmission time and change independently for every two-hop transmission time.

3. Cooperative phase steering technique

We describe the overall procedure of the proposed CPS technique in this section. In the first hop, the SS node sends the signal to all SR nodes and the SD node and the received signals at the kth SR node and the SD node are given by

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

$$y_D = \sqrt{P_S} h_{S,D} x_S + n_{D,1}, \tag{2}$$

where P_S ($\leq P_{\max}$) and x_S denote the transmit power under the maximum power constraint and the transmitted signal of the SS node, respectively. The terms n_k and $n_{D,1}$ represent additive complex Gaussian noises at the kth SR node and the SD node, respectively, they are assumed to follow $\mathcal{CN}(0, 1)$ without loss of generality. The SS node adjusts its transmit power so that the interference power from the SS node is kept lower than a certain threshold at all the PD nodes at the first hop, which will be explained in the next section.

Each SR node tries to decode the received packet from the SS node at the first hop and the packet decoding is assumed to be successful if the received signal-to-noise ratio (SNR) is larger than a certain threshold. Then, the index set of the SR nodes that succeed the packet decoding at the first hop is defined as

$$\mathcal{D} \triangleq \left\{ k \in \mathcal{K} : \rho_{S,k} \triangleq P_S \left| h_{S,k} \right|^2 \geq \rho_{th} \right\}, \tag{3}$$

where $\rho_{th} = 2^{2R} - 1$ and R indicates the data rate assuming the direct communication from the SS node to the SD node. Note that we assume two-hop communication from the SS node to the SD node and the required data rate for each hop is equal to $2R$. The set $\mathcal{K}$ is defined as $\{1, 2, \ldots, K\}$ and thus $\mathcal{D} \subset \mathcal{K}$.

At the second hop, the SR nodes that belong to $\mathcal{D}$ steer the phase of transmit signal so that the phase of all received

[1] We assume the interference from PS is negligible since the military communication systems normally are widely deployed in the battlefield and military MANETs is a type of ad hoc network that can change locations from the PS such as radars to support deployed troops.

signals at the SD node is aligned. The transmit signal of kth SR node is given by

$$x_k = \exp\left(-i\angle h_{k,D}\right) x_S, \tag{4}$$

where $\angle h_{k,D}$ denotes the phase of $h_{k,D}$. Then, at the second hop, the received signal of the SD node is given by

$$y_D = \sum_{k\in\mathcal{D}} \sqrt{P_k} h_{k,D} x_k + n_{D,2} = \sum_{k\in\mathcal{D}} \sqrt{P_k} \left|h_{k,D}\right| x_S + n_{D,2}, \tag{5}$$

where P_k ($\leq P_{\max}$) is the transmit power of the kth SR node under maximum power constraint. The transmit power of kth SR node needs to be also controlled for the interference temperature constraint of the spectrum sharing-based system [3,13,14], which will be explained in the next section.

Finally, the outage probability of the proposed CPS technique is given by

$$P_{out} = \Pr\left[P_S\left|h_{S,D}\right|^2 + \left(\sum_{k\in\mathcal{D}} \sqrt{P_k}\left|h_{k,d}\right|\right)^2 < \rho_{th}\right]. \tag{6}$$

4. Power control of CPS for spectrum sharing

We first define the interference power constraint, also known as *interference temperature*, at each PD node as Q. The interference constraint at the jth PD node at each hop is given by

$$P_S\left|h_{S,j}^{[p]}\right|^2 \leq Q, \qquad (1^{\text{st}} \text{ hop})$$
$$\left|\sum_{k\in\mathcal{D}} \sqrt{P_k} h_{k,j} e^{-j\angle h_{k,d}}\right|^2 \leq Q. \qquad (2^{\text{nd}} \text{ hop}) \tag{7}$$

In order to satisfy the above interference constraint for all $j \in \{1, 2, \ldots, J\}$, the transmit power of the SS node at the first hop P_S is given by

$$P_S = \begin{cases} P_{\max}, & P_{\max}\alpha_S \leq Q \\ Q/\alpha_S, & P_{\max}\alpha_S > Q \end{cases}, \quad \alpha_S \triangleq \max_j \left|h_{S,j}^{[p]}\right|^2. \tag{8}$$

It is difficult to jointly adjust transmit power of multiple SR nodes to satisfy the second hop interference condition of (7) and we separate the interference constraint for each SR node as follows:

$$P_k\left|h_{k,j}\right|^2 \leq \frac{Q}{K}, \quad j \in \{1, 2, \ldots, J\}. \tag{9}$$

Then, the transmit power of each SR node can be computed with a distributed manner and the transmit power of the kth SR node is given by

$$P_k = \begin{cases} P_{\max}, & P_{\max}\alpha_k \leq NQ/K \\ Q/K\alpha_k, & P_{\max}\alpha_k > NQ/K \end{cases}, \quad \alpha_k \triangleq \max_j \left|h_{k,j}\right|^2. \tag{10}$$

where N, the power normalization factor, is defined as [15]

$$N \triangleq \mathbb{E}\left[|\mathcal{D}|\right] \simeq K\exp\left(-\frac{\rho_{th}}{\sigma_s^2 P_s}\right). \tag{11}$$

where $|\mathcal{D}|$ is the cardinality of a decode set $\mathcal{D}$. Note that even though N is not actual average number of SR nodes that succeeded decoding because transmit power of SS node could be changed by interference constraint, it can be referred as normalization factor due to assumption of poor channel condition between SS node and PD nodes.

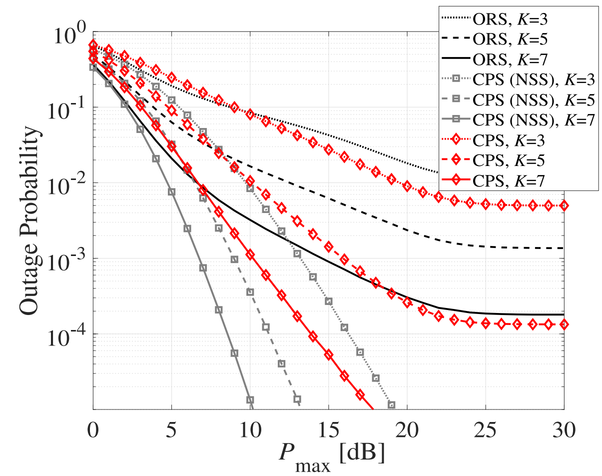

Fig. 2. Outage probability of the proposed CPS for varying maximum transmit power (or equivalently SNR).

By determining P_k as (10), the second hop interference condition of (7) is sufficiently satisfied.

5. Simulation results

In this section, we compare the performance of the proposed CPS technique with the conventional opportunistic relay selection (ORS) [13,14] scheme and conventional CPS in non-spectrum sharing environment (CPS (NSS)) [15] in terms of outage probability. The ORS scheme chooses the best SR node with the highest channel gain in the second hop among the SR nodes belongs to $\mathcal{D}$. In all simulations, $\sigma_{S,D}^2 = \sigma_{S,j}^2 = -20$ dB, $\sigma_{S,k}^2 = \sigma_{k,j}^2 = 0$ dB, $R = 0.5$ bit/s/Hz, and $Q = 5$ dB. Fig. 2 shows outage performance for varying maximum transmit power (or equivalently SNR) when $K = 3, 5, 7$ and $\sigma_{k,D}^2 = 0$ dB. It is worth noting that the performance improvement of the proposed CPS technique becomes significant as the number of SR nodes increases. Moreover, it is shown that performance of each scheme is saturated even though $P_{\max}$ increases, since transmit power of SS node and SR nodes are subordinate to statistical distribution of channel from itself to PD nodes. Fig. 3 shows outage performance the proposed CPS technique according to $\sigma_{k,D}^2$ when $K = 3, 5, 7$ and $P_{\max} = 10$ dB. It is observed that the outage probability of the proposed CPS technique outperforms the ORS scheme when $\sigma_{k,D}$ is poor. In this figure, the performance improvement of the proposed CPS becomes significant as the number of SR nodes increases as well.

6. Conclusions

In this paper, the cooperative phase steering (CPS) technique was proposed for a spectrum sharing-based military mobile ad hoc network (MANET) which consists of a single secondary source node, a single secondary destination node, multiple secondary relay nodes, and multiple primary destination nodes. In the proposed CPS technique, the transmit

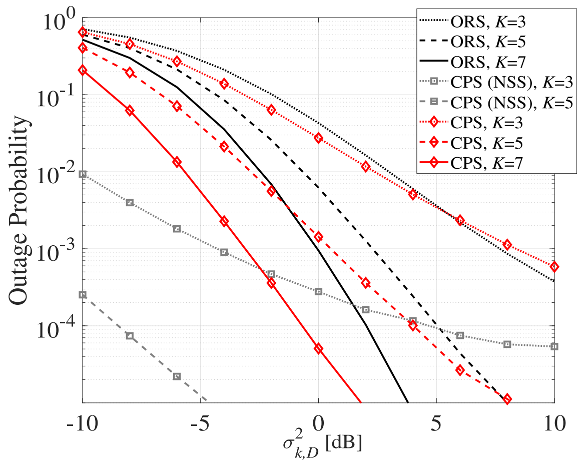

Fig. 3. Outage probability of the proposed CPS for varying $\sigma^2_{k,D}$.

power of the secondary source node and the secondary relay nodes are carefully adjusted so that their interference to the primary destination nodes is maintained lower than a certain threshold called interference temperature. Through computer simulations, we validated that the proposed CPS technique outperforms the conventional opportunistic relay selection scheme in terms of outage probability especially when the number of secondary relay nodes is large.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Sangku Lee: Writing - original draft, Validation, Methodology, Formal analysis. **Janghyuk Youn:** Software, Validation, Investigation, Formal analysis. **Bang Chul Jung:** Conceptualization, Writing - review & editing, Supervision, Resources.

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