Buffer-Aided Cooperative Phase Steering Technique for Delay-Tolerant Networks

Sangku Lee, Janghyuk Youn†, Yongjae Kim‡, Bang Chul Jung††
Deptartment of Electronic Telecommunication Engineering, Republic of Korea Air Force Academy, Cheongju, South Korea
†Satellite Anti-Jammming Group, Duksan Navcours Co., Ltd., Daejeon, South Korea
‡Maritime ICT R&D Center, Korea Institute of Ocean Science and Technology, Busan, South Korea
††Deptartment of Electronics Engineering, Chungnam National University, Daejeon, South Korea
Email: sklee@afa.ac.kr, jhyoun@oneduksan.com, yongjaekim@kiost.ac.kr, bcjung@cnu.ac.kr

***Abstract*—In this paper, we propose a novel buffer-aided cooperative phase steering (B-CPS) technique for delay-tolerant wireless networks (DTNs). In the proposed B-CPS technique, all relay nodes (RNs) that succeed in data decoding from a source node (SN) deliver the original signal of SN to a destination node (DN) with a decode-and-forward (DF) manner. With the property of DTNs, the signal from the SN is allowed to be delayed at RNs, and thus all the RNs that succeeded in decoding wait until a certain condition is satisfied, which the minimum channel gain from the RNs to the DN exceeds a threshold. When the condition is satisfied, all the RNs send the received signal to the DN with the CPS technique. Simulation results show that the proposed B-CPS significantly outperforms the conventional CPS technique in terms of outage probability.**

***Index Terms*—Buffer-aided relaying, cooperative phase steering, decode–forward, delay-tolerant networks.**

I. INTRODUCTION

The 6th generation (6G) wireless communications system aims to realize global networks capable of supporting massive and unlimited wireless connections [1]. Recently, communication with low earth orbit satellites is being considered as a new technology on the way to 6G because it can provide truly ubiquitous connectivity in remote areas by dealing with satellites as relays [2]. With this concept, delay tolerant networks (DTNs) have been proposed to provide reliable end-to-end transmission of space communications, where the communication links may be frequently disrupted. To cope with link interruption, a store-and-forward protocol is used in DTNs, which intermediate nodes can store data packets in their buffer when the communication link is temporarily broken, and then forward its data packets to the destination node when they are reconnected [3]. Additionally, the concept of DTNs can be a good solution in Internet-of-Things (IoT) networks where IoT devices are powered by batteries, since they deliver data only when communication links are established. Moreover, extended fields of DTNs applications have been considered in Vehicle-to-Vehicle (V2V) communications and IoT applications [4], [5].

In addition, for the reliable communication in relaying network, cooperative communications with multiple relays can be another good option to increase throughput and extend network coverage with limited power through spatial diversity. Furthermore, cooperative communications have been incorporated into relays with buffers to improve various performance metrics such as outage probability, throughput, and power efficiency, where buffer makes the similar concept of DTN. Among the various buffer-aided cooperative communication schemes, the relay selection based communication technique, which stores packets and relays them under favorable channel conditions through optimal relay selection, is mainly considered as one of the most practical and superior strategies [6]. However, the relay selection based schemes need another node to do that acquires channel information with relay nodes every moment, determines the best relay node and informs the best one to all relay nodes. Obviously, this process induces additional signaling overhead to the network. Moreover, due to the intermittent connectivity between the relay nodes and the destination node in DTN, the communication to select the best relay is not guaranteed. To overcome these weaknesses of relay selection schemes, another cooperative relaying technique called cooperative phase steering (CPS) was proposed for cooperative relay networks [7]. In CPS, each relay node only needs to receive reference signals from the destination node to acquire their own local channel state information (CSI) to align the phase of received signals at the destination, which can be performed in full-distributed manner. In addition, CPS techniques in various network environments have been proposed and showed better performance than ORS schemes [8], [9].

In this paper, we consider a buffer-aided CPS (B-CPS) technique that relays await to deliver the packet until channel gain condition is satisfied. Owing to the store-and-forward protocol of the buffer-aided relays in DTN, the B-CPS technique has sufficient transmission time waiting for the condition satisfaction. By the channel gain condition of B-CPS technique, the diversity gain can be maximized, therefore energy efficiency and communication performance are expected to be improved.

The rest of this paper is composed as follows. In section. II, we describe the system model considered in this paper and the overall procedure of the proposed B-CPS technique for DTN with two subsections, respectively. Computer simulation results of the proposed technique are shown in terms of outage probability in section III. Finally, the conclusion of this paper will be described in section IV.

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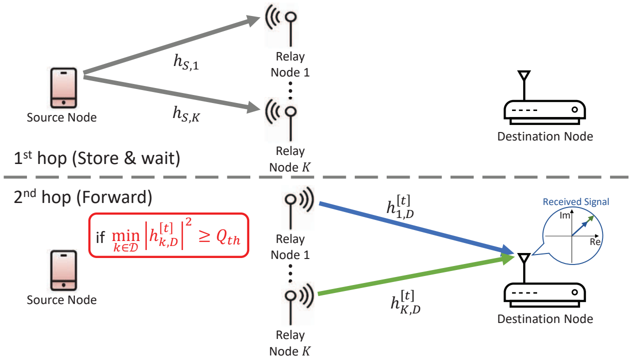

Fig. 1: Considered system model.

II. BUFFER-AIDED CPS TECHNIQUE FOR DTN

In this section, we describe our considered system model and the overall procedure of the proposed B-CPS technique for DTN in this section.

A. System Model

We consider a DTN with multiple decode-and-forward (DF) relay nodes (RNs) as shown in Fig. 1. There exist a single source node (SN), a single destination node (DN), and K RNs. $h_{S,k}$ and $h_{k,D}^{[t]}$ represent the wireless channel from the SN to the k-th RN, and from the k-th RN to the DN at t-th time slot, respectively. We assume that $h_{S,k}$, and $h_{k,D}^{[t]}$ follow an independent and identically distributed (i.i.d.) complex Gaussian distribution with zero mean and different variances, i.e. $h_{S,k} \sim \mathcal{CN}\left(0,\sigma_{SR}^2\right)$ and $h_{k,D}^{[t]} \sim \mathcal{CN}\left(0,\sigma_{RD}^2\right)$. Here, Quasi-static frequency-flat fading is assumed, i.e. the channel coefficients are constant during each time slot and change independently at the next time slot. In addition, we assume that each relay node knows the channel state information (CSI) from itself to the DN by receiving reference signals from DN, which is called *local CSI* assumption that is widely known to be practical in wireless relay communication systems.

B. Overall Procedure

In the first hop, the SN sends a signal to all RNs and the received signal at the k-th RN is given by

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

where x_S denotes the transmitted signal of the SN. The term n_k represents additive complex Gaussian noise at the k-th RN, which is assumed to follow $\mathcal{CN}(0,1)$ without loss of generality. Note that, it is necessary for RNs to know the original signal of SN without noise, to relay the original signal to the DN. Therefore, each RN tries to decode the received signal from the SN 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 RNs that succeeded in decoding is defined as

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

where $\rho_{th} = \sqrt{2^R - 1}$, and R indicates the required data rate when the same packet is delivered through the direct communication from the SN to the DN. Consequently, only second hop channels of relays belonging to $\mathcal{D}$ can store the original signal of SN, and are available. In the second hop, briefly, the RNs belonging to $\mathcal{D}$ will relay the original signal of SN when the minimum channel gain of the available second hop channel is greater than a predefined threshold within $T_{\max}$ time slots, as shown in Table. 1.

1. All RNs acquires second hop channel gain of their own by receiving reference signals from DN.
2. Each k-th RN broadcasts a pilot signal to all other RNs after certain delay time which is defined as $t_k = \left(T_{\mathsf{D}}\left|h_{k,D}^{[t]}\right|^2\right) \Big/ \left(1+\left|h_{k,D}^{[t]}\right|^2\right)$
3. Now all RNs can acquire minimum channel gain by a reverse calculating delay time of each RN, and minimum channel gain is $h_{\min} = \min_{k\in\mathcal{D}} \left|h_{k,D}^{[t]}\right|^2$
4. If $h_{\min} \geq Q_{th}$ or $t = T_{\max}$, $t^* = t$ and end the loop
5. $t = t+1$ and repeat 1-4

Table 1. Time slot selection algorithm

Here, $T_{\max}$ and Q_{th} represent the maximum delay time and gain threshold for the selection criterion, respectively. In addition, we define Q_{th} as

$$Q_{th} = \frac{\rho_{th}\left|\mathcal{D}\right|}{\rho_T} \times \frac{\sigma_{RD}\sqrt{\pi}}{2\sqrt{\mathcal{D}}} \times \frac{2}{\left|\mathcal{D}\right|\sigma_{RD}\sqrt{\pi}} = \frac{\rho_{th}}{\rho_T\sqrt{\mathcal{D}}}, \tag{3}$$

where $|\mathcal{D}|$ represents cardinality of $\mathcal{D}$ and the first of the three fraction means the threshold for when all RNs have equal channel gain, but here, each RN suffers different channel gains. Therefore, we need a threshold adapted for minimum channel gain and second and third fractions are for that. The second fraction means an average of minimum channel gain, and the third fraction means the reciprocal of the average of $|\mathcal{D}|$ summed channel gain. As a result, Q_{th} represents the threshold that is adapted for minimum channel gain by the ratio of average minimum gain to average summed channel gain.

After the time slot is selected, all RNs belonging to $\mathcal{D}$ steer the phase of transmit signal so that the phase of all received signals at the DN is aligned. Then, the transmit signal of the k-th relay node is given by

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

where $\angle h_{k,D}^{[t^*]}$ denotes the phase of $h_{k,D}^{[t^*]}$. Then, at the second hop, the received signal of the DN is given by

$$y_d = \sum_{k\in\mathcal{D}} \sqrt{\frac{\rho_T}{|\mathcal{D}|}} h_{k,D}^{[t^*]} x_k + n_D, \tag{5}$$

where n_D denotes the additive Gaussian noise at DN, which follows $\mathcal{CN}(0,1)$. Note that the square root term of (5) is transmitted SNR of each RN, which is normalized by dividing the total consumed power of all RNs by the number of RNs

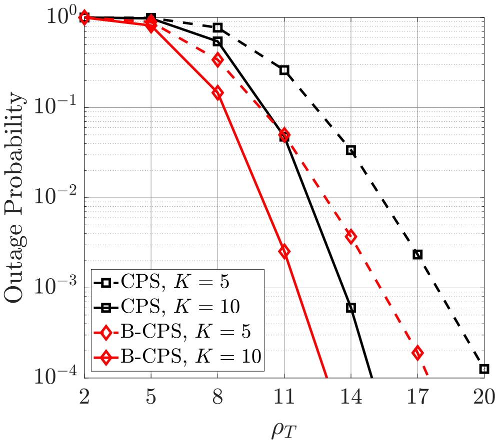

Fig. 2: Outage probability performance according to ρ_T

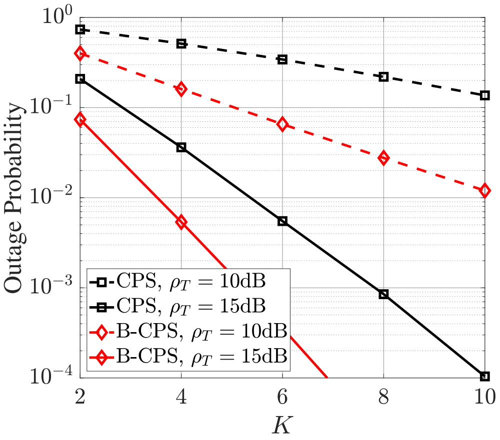

Fig. 3: Outage probability performance according to K

that succeeded in decoding. This is for comparison to other conventional techniques by regulating the total consumed power of all RNs to ρ_T.

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

$$P_{out} = \Pr\left[\frac{\rho_T}{|\mathcal{D}|}\left(\sum_{k\in\mathcal{D}}\left|h_{k,d}^{[t^*]}\right|\right)^2 < \rho_{th}\right]. \tag{6}$$

III. NUMERICAL RESULTS

In this section, we show the outage probability performance of the proposed B-CPS technique by comparing it with conventional CPS technique. In common, for all numerical results, $\sigma_{SR}^2 = \sigma_{RD}^2 = -10$ dB, $R = 1$ bps/Hz, $T_{\mathsf{max}} = 20$. Moreover, K and ρ_T is set to be as described in each simulation result.

Fig. 2 shows the outage probability performance of the proposed B-CPS technique according to ρ_T (i.e. transmit SNR), where $K = 5$ or 10. Since the B-CPS technique can simply achieve a lower outage probability at second-hop communication by guaranteeing high diversity gain, it is obvious that the B-CPS technique always outperforms the conventional CPS technique.

In Fig. 3, outage probability performance of the B-CPS technique is shown according to K (i.e. number of relays), where $\rho_T = 10$ or 15 dB. As shown in Fig. 2, Fig. 3 shows that the proposed B-CPS technique always outperforms the conventional CPS technique. Rather than only showing that the B-CPS technique always outperforms the CPS technique, it is shown that the performance gap between the B-CPS technique and CPS technique widens as the number of relays increases.

Following the numerical results above, the B-CPS technique is a promising technique for the delay-tolerant environment, since it can achieve higher performance than the conventional CPS technique while could operate in distributed manner.

IV. CONCLUSION

In this paper, we proposed a novel buffer-aided cooperative phase steering (B-CPS) technique for delay tolerant networks (DTNs). Basically, in the B-CPS technique, relay nodes (RNs) send the original signal from the source node (SN) to the destination node (DN) in a decode-and-forward (DF) manner. Moreover, the RNs wait until the minimum channel gain from the RNs to the DN exceeds a certain threshold and they simultaneously send the signal with the CPS technique when the condition is satisfied. It is worth noting that all the RNs operate in a distributed manner without feedback from DN in the proposed B-CPS technique. Through extensive simulations, it is shown that the proposed B-CPS technique significantly outperforms the conventional CPS technique in terms of outage probability.

V. ACKNOWLEDGEMENTS

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