Buffer-State-and-Thresholding-Based Amplify-and-Forward Cooperative Networks

Miharu Oiwa, *Student Member, IEEE*, Ryota Nakai, *Student Member, IEEE*, and Shinya Sugiura, *Senior Member, IEEE*

***Abstract*—In this letter, we propose a novel buffer-state-based amplify-and-forward relaying protocol for dual-hop cooperative networks. The proposed protocol is designed to amalgamate the following three concepts: 1) the exploitation of multiple source-to-relay broadcast channels; 2) the introduction of thresholding at relay and destination nodes; and 3) buffer-state-based relay selection. Our numerical results demonstrate that the proposed protocol is capable of attaining a lower end-to-end delay and a lower outage probability than previous amplify-and-forward relay selection schemes while simultaneously imposing no additional costs.**

***Index Terms*—Amplify-and-forward, buffer, broadcast channel, cooperative communications, delay, diversity, relay selection.**

I. INTRODUCTION

EXPLOITING data buffers at relay nodes in cooperative networks [1]–[3] is beneficial because it allows flexible link selection compared to the conventional relaying schemes that do not rely on buffers at relay nodes. For example, in the buffer-aided max-max relaying selection (MMRS) protocol [4], link selection is pre-scheduled into two stages: source-to-relay (SR) and relay-to-destination (RD). As a result, the MMRS protocol achieves a higher performance gain than can be achieved with a non-buffered relaying protocol. Additionally, the max-link protocol [5], [6] eliminates the pre-scheduled link selection limitation imposed by the MMRS scheme. More specifically, since the strongest available link is selected at each time slot in the max-link protocol, a maximum achievable diversity gain that is twice as high as the non-buffered and max-max relaying protocols is ensured. The buffer-state-based (BSB) relaying protocol was proposed in [7]–[11]. Here, the relay selection is carried out in a manner that prevents either full- or empty buffer states from occurring.

Most previous studies involving buffer-aided cooperative protocols focused on the decode-and-forward (DF) strategies, the only exceptions to which are the buffer-aided amplify-and-forward (AF) relaying protocols of [12] and [13]. In the AF protocol of [12], a single relay node is activated for either packet reception or transmission at each time slot, similar to the DF max-link protocol [5], while the packet received at the AF relay node is stored after the quantization of its DF counterpart.[1] In [13], the recent spatial modulation technique is applied to a single-relay buffer-aided AF cooperative network. This strategy allows us to maintain a higher security level, since the relay nodes do not decode the received packets. However, due to the broadcast nature of wireless channels, it may be possible to simultaneously exploit multiple SR links in a manner similar to the buffer-aided DF relaying protocol of [2], which would allow us to increase additional design degrees of freedom. Another potential drawback imposed on the AF max-link scheme is that, since the relay node is not allowed to check the reliability of a stored packet, error propagation from the relay node to the destination node cannot be detected. Furthermore, the above-mentioned BSB relay selection [7], [10] has not been used in the AF context.

Motivated by the recent generalized buffer-aided DF relying protocol of [2], we propose a novel buffer-aided AF relaying protocol that outperforms the conventional scheme [12]. In our proposed AF scheme, a single RD link is activated for packet transmission from the relay node, while for packet reception at the relay nodes, multiple SR links are simultaneously exploited due to the broadcast nature of wireless channels. Furthermore, the BSB relay selection concept, where the buffer states are taken into account for relay node packet transmission/reception, is introduced in our proposed protocol. This allows us to avoid full- and empty-buffer states, thereby enabling us to achieve full attainable diversity order. Additionally, in order to reduce noise-propagation effects, we introduce a thresholding technique for packet reception of relay and destination nodes. This is especially beneficial for our generalized AF scheme, which utilizes the broadcast SR links, since the broadcast links may include an unreliable links that could reduce the end-to-end signal-to-noise ratio (SNR). Because the previous buffer-aided AF protocol [12] did not rely on these three concepts, which are specific to the proposed AF scheme, the proposed protocol exhibits an improved end-to-end packet delay and a lower outage probability, which are achieved with the explicit benefits of the increased design degree of freedom provided by our system.

II. SYSTEM MODEL

Consider a two-hop relaying network, consisting of a single source node $\mathcal{S}$, K relay nodes $\mathcal{R}_k \in \{R_1, \ldots, R_K\}$, and a single

Manuscript received June 21, 2017; accepted July 17, 2017. Date of publication July 20, 2017; date of current version October 11, 2017. This work was supported in part by the Japan Society for the Promotion of Science (JSPS) KAKENHI under Grant 26709028 and Grant 17H03259, and in part by the Japan–Korea Basic Scientific Cooperation Program conducted by the JSPS and National Research Foundation of Korea. The associate editor coordinating the review of this paper and approving it for publication was I. Krikidis. *(Corresponding author: Shinya Sugiura.)*

The authors are with the Department of Computer and Information Sciences, Tokyo University of Agriculture and Technology, Tokyo 184-8588, Japan (e-mail: sugiura@ieee.org).

Digital Object Identifier 10.1109/LWC.2017.2729547

---

[1] In this letter, the buffer-aided AF scheme of [12] is referred to as the AF max-link scheme.

destination node $\mathcal{D}$, where each relay node is equipped with a buffer of a finite size L. Here, the number of packets stored at the kth relay node is represented by Ψ_k $(0 \leq \Psi_k \leq L)$. It is assumed that no direct link exists between the source and destination nodes due to obstacle blockage and that all of the relay nodes operate in a half-duplex mode under the AF principle. The transmission rate for each node is maintained at $2r_0$ bps/Hz in order to impose an upper bound to the end-to-end transmission rate of r_0 bps/Hz. Additionally, we assume that the destination node sends an acknowledge (ACK) packet to the relay nodes via stable low-rate feedback channels, while simultaneously assuming that the destination node acts as a central coordinator similar to [2], [4], [5], [12], [14]. This ACK packet is transmitted in a piggyback manner with other control packets. Hence, no substantial overhead is imposed by these actions. Note that each activated relay node transmits the queued packets in a first-come, first-served manner.

Note that, in this letter, independent and identically distributed (IID) Rayleigh fading channels are considered for all the SR and RD links, having the average SNR values of γ_{SR} and γ_{RD}, respectively. It should also be noted that while this simplified assumption of symmetric channels has been typically employed in previous studies, it can readily be extended to asymmetric counterparts. Here, the frequency-flat channel coefficient of the kth SR channel is given by h_{SR_k}, and that of the kth RD channel is given by h_{RD_k}.

A. Conventional Buffer-Aided AF Max-Link Protocol [12]

In the conventional AF max-link protocol, the single best available link is selected each time slot. More specifically, the SR links associated with the full-buffer relays and the RD links associated with empty-buffer relays are excluded as candidates, and the protocol simply selects the link associated with the highest channel coefficient.When assuming that the kth relay node is selected as a receiving node at the time instance t, the associated received packet may be written by

$$y_{\mathrm{SR}_k}(t) = \sqrt{E_s}h_{\mathrm{SR}_k}(t)s(t) + n_{\mathrm{R}_k}(t), \tag{1}$$

where E_s is the transmit power, and $s(t)$ is a source packet, while $n_{\mathrm{R}_k}(t)$ is the additive white Gaussian noise (AWGN) component. The received packet is stored in the buffer of the kth relay node after quantization.

Now, let us assume that after τ packet duration, the packet of (1) is relayed to the destination node. The corresponding packet $y_{\mathrm{RD}_k}(t+\tau)$ received at the destination node is expressed as

$$y_{\mathrm{RD}_k}(t+\tau) = \sqrt{P_k(t+\tau)}h_{\mathrm{RD}_k}(t+\tau)y_{\mathrm{SR}_k}(t) + n_{\mathrm{D}}(t+\tau), \tag{2}$$

where $P_k(t+\tau)$ is the scaling factor that normalizes the transmission power of the relay node to E_s, which is represented by $P_k(t+\tau) = E_s/(E_s|h_{\mathrm{SR}_k}(t)|^2 + N_0)$, where N_0 is the noise variance and $n_{\mathrm{D}}(t+\tau)$ is the AWGN component at the destination node.

TABLE I

PRIORITY CLASSIFICATIONS OF AVAILABLE SR LINKS

Priority	Low	High	Highest
SR links	$\Psi_k = L-1$	$1 < \Psi_k < L-1$	$\Psi_k = 0, 1$

TABLE II

PRIORITY CLASSIFICATIONS OF AVAILABLE RD LINKS

Priority	Low	High
RD links	$\Psi_k = 1$	$\Psi_k \geq 2$

Finally, based on (1) and (2), the equivalent end-to-end system model is expressed as

$$\begin{aligned} y_{\mathrm{RD}_k}(t+\tau) &= \sqrt{E_s}\sqrt{P_k(t+\tau)}h_{\mathrm{RD}_k}(t+\tau)h_{\mathrm{SR}_k}(t)s(t) \\ &\quad + n_{\mathrm{D}}(t+\tau) + \sqrt{P_k(t+\tau)}h_{\mathrm{RD}_k}(t+\tau)n_{\mathrm{R}_k}(t). \end{aligned} \tag{3}$$

B. Proposed Generalized BSB AF Protocol

The goal of our proposed scheme is to minimize a packet delay, while attaining a good reliability performance, which is comparable to those attainable by the existing schemes, in a similar manner to the DF BSB scheme [7]. As mentioned above, the conventional AF max-link scheme [12] does not allows the simultaneous activation of multiple SR links. By contrast, in our proposed scheme, the source node is allowed to broadcast a packet to the maximum K relay nodes. For the sake of simplicity, the assumption of $L \geq 3$ is made throughout in this letter. In our proposed scheme, we employ BSB relay selections that are similar to the protocol of [7] and [10], while the activations of the multiple SR links are introduced simultaneously. The buffer and link states for the relay nodes are periodically collected at the destination node (central coordinator).[2] The number of available SR and RD links that are not in outage is defined by N_{SR} and N_{RD} $(0 \leq N_{\mathrm{SR}}, N_{\mathrm{RD}} \leq K)$, respectively. After collecting the relay node buffer states Ψ_k $(k = 1, \ldots, K)$, the central coordinator activates either a single SR link, multiple SR links, or a single RD link, based on the proposed criterion, which will be explained below. First, depending on the buffer states, the central coordinator evaluates the priority of SR and RD links according to Tables I and II, respectively. More specifically, the N_{SR} available SR links are classified into three categories: low-, high-, and highest-priority SR links. The number of SR links having the low, high, and highest priorities is given by $N_{\mathrm{SR}}^{\mathrm{low}}$, $N_{\mathrm{SR}}^{\mathrm{high}}$, and $N_{\mathrm{SR}}^{\mathrm{highest}}$, respectively. Hence, we have the relationship of $N_{\mathrm{SR}} = N_{\mathrm{SR}}^{\mathrm{low}} + N_{\mathrm{SR}}^{\mathrm{high}} + N_{\mathrm{SR}}^{\mathrm{highest}}$. Here, the kth SR link priority is low when the number of packets stored at the associated relay buffer is $\Psi_k = L-1$, while the priority is high for $1 < \Psi_k < L-1$. Furthermore, the priority of the

---

[2] In the conventional buffer-aided relaying schemes, it is typically assumed that a central coordinator periodically collects channel state information and buffer states, similar to the proposed scheme. More specifically, most of the conventional buffer-aided relaying schemes [5]–[7], [10], [12] are imposed by the overhead, which is comparable to that of the proposed scheme. By contrast, the DF MMRS [4] and the DF G-MMRS schemes [2] tend to exhibit a lower overhead than the proposed scheme, which is achieved at the expense of a reduced diversity gain. The further detailed discussion may be found in [2].

TABLE III

DECISION ALGORITHMS FOR LINK ACTIVATION

	$N_{\mathrm{SR}}^{\mathrm{low}}$	$N_{\mathrm{SR}}^{\mathrm{high}}$	$N_{\mathrm{SR}}^{\mathrm{highest}}$	$N_{\mathrm{RD}}^{\mathrm{low}}$	$N_{\mathrm{RD}}^{\mathrm{high}}$	Decision
Case 1	—	—	≥ 1	—	—	Activate $N_{\mathrm{SR}}^{\mathrm{highest}} + N_{\mathrm{SR}}^{\mathrm{high}}$ highest- and high-priority SR links
Case 2	—	—	0	—	≥ 1	Activate a single high-priority RD link
Case 3	—	≥ 1	0	—	0	Activate $N_{\mathrm{SR}}^{\mathrm{high}}$ high-priority SR links
Case 4	≥ 1	0	0	≥ 1	0	Activate a single low-priority SR link or a single low-priority RD link
Case 5	≥ 1	0	0	0	0	Activate a single low-priority SR link
Case 6	0	0	0	≥ 1	0	Activate a single low-priority RD link
Case 7	0	0	0	0	0	No link activated (outage event)

SR links is the highest when the number of stored packets is $\Psi_k = 0$ or 1. Note that when the priority of an SR link is low, the buffer state of the associated relay node is close to full, which is undesirable in terms of maximizing the number of available links.

As listed in Table II, the available N_{RD} RD links that are not in outage are categorized into low- and high-priority RD links based on the buffer states for the relay nodes, where the number of links of each category is denoted by $N_{\mathrm{RD}}^{\mathrm{low}}$ and $N_{\mathrm{RD}}^{\mathrm{high}}$, respectively. When the buffer for a relay node is $\Psi_k = 1$, the priority of the associated RD link is determined to be low. Also, the priority is high for $\Psi_k \geq 2$.

Having attained the priorities of the available SR and RD links, the link activation process is carried out according to the decision classification algorithms listed in Table III. The decisions are categorized into Cases 1–7. When there is at least one highest-priority SR link, which corresponds to Case 1, all of the $N_{\mathrm{SR}}^{\mathrm{highest}} + N_{\mathrm{SR}}^{\mathrm{high}}$ highest- and high-priority SR links are activated and a source packet is copied at the buffers of all associated relay nodes. In Case 2, where there is no highest-priority SR link, but at least one high-priority RD link exists, a single high-priority RD link is activated. After the destination node successfully decodes the packet relayed from the selected relay node, the destination node transmits an ACK packet to all of the relay nodes via the stable feedback channels, after which the corresponding packet that was copied at the relay nodes is deleted from the buffers. As for Case 3, where there are neither any highest-priority SR nor high-priority RD links, but there are $N_{\mathrm{SR}}^{\mathrm{high}}$ high-priority SR links, all of the $N_{\mathrm{SR}}^{\mathrm{high}}$ high-priority SR links are activated. In Cases 4–6, we have only low-priority SR and RD links. When there are both low-priority SR and RD links, which corresponds to Case 4, the link having the highest channel coefficient is selected. Note that when the selected link is an SR link, the single strongest one out of the $N_{\mathrm{SR}}^{\mathrm{low}}$ low-priority SR links is activated. Case 5 corresponds to the scenario, where there are only $N_{\mathrm{SR}}^{\mathrm{low}}$ low-priority SR links. In this case, the one strongest low-priority SR link is activated. Case 6 corresponds to a scenario where there are only low-priority RD links, in which a single strongest low-priority RD link is activated. Finally, Case 7 corresponds to an outage event, since there are no available links.

Moreover, we introduce our relay node thresholding technique, which allows us to avoid the noise-enhancement effects of relaying. First, let us assume that a source packet $s(t)$ is transmitted to the destination node through the kth relay node at the time instance $(t+\tau)$, where the buffer states of the SR- and RD-link selections are s_i and s_j, respectively. Then, from (3), the instantaneous end-to-end SNR of both the conventional and proposed buffer-aided AF schemes are given by [12]

$$\gamma_{\mathrm{SD}}^{(s_i,s_j)}(t+\tau) = \frac{\gamma_{\mathrm{SR}_k}(t)\gamma_{\mathrm{RD}_k}(t+\tau)}{\gamma_{\mathrm{SR}_k}(t) + \gamma_{\mathrm{RD}_k}(t+\tau) + 1}, \tag{4}$$

where we have $\gamma_{\mathrm{SR}_k}(t) = E_s|h_{\mathrm{SR}_k}(t)|^2/N_0$ and $\gamma_{\mathrm{RD}_k}(t+\tau) = E_s|h_{\mathrm{RD}_k}(t+\tau)|^2/N_0$. Furthermore, by making simplified assumptions of $\gamma_{\mathrm{SR}_k}(t) = \gamma_{\mathrm{RD}_k}(t+\tau) = \bar{\gamma}$ and $\gamma_{\mathrm{SD}}^{(s_i,s_j)}(t+\tau) = 2^{2r_0} - 1$, we may have the thresholding SNR of $\bar{\gamma} = 2^{2r_0} - 1 + \sqrt{2^{2r_0}(2^{2r_0} - 1)}$, where r_0 is the target transmission rate. Hence, in the proposed scheme, when the SNR for a specific instantaneous SR link is below this thresholding SNR $\bar{\gamma}$, the associated relay node does not store the received packet. Similarly, we introduce the same thresholding technique to the packet reception process at the destination node.[3]

III. PERFORMANCE RESULTS

In this section, we provide our simulation results, in order to characterize the proposed scheme. The conventional AF max-link protocol [12] was considered as the benchmark scheme. In our simulations, we assumed an independently identical distributed (IID) Rayleigh fading scenario, where the channel coefficients were randomly generated in each time slot. For each scheme, the transmission rate at each node was $2r_0 = 2$ bps/Hz, while targeting the end-to-end rate of $r_0 = 1$ bps/Hz.

Fig. 1 show a comparison between the outage performance of the conventional AF max-link scheme and the proposed generalized AF scheme, where the system parameters were given by $(K, L) = (3, 3)$ and $(4, 3)$. In Fig. 1, it can be seen that the proposed scheme outperformed the conventional scheme in each scenario, and that the proposed scheme achieved the maximum attainable diversity gain because of the explicit benefits provided by the BSB relay selection and thresholding.[4]

Furthermore, Fig. 2 shows the delay profiles for the conventional and proposed buffer-aided AF schemes, where the

---

[3] While in this letter we focused our attention on the single-source and single-destination scenario, the extension of our protocol to the multi-flow scenario [15] is left for the future study.

[4] We note, for example, that in Fig. 1 the diversity order of the proposed scheme of $(K, L) = (3, 3)$ was approximately five, which is lower than the number of available links, i.e., six. This performance gap was mainly due to the noise-propagation effects, which are specific to AF protocols, although our thresholding technique achieved the explicit performance improvement over the existing AF scheme [12].

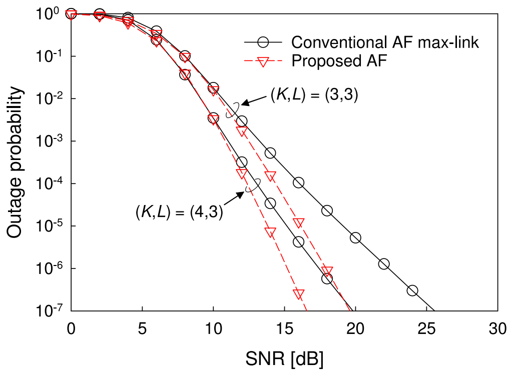
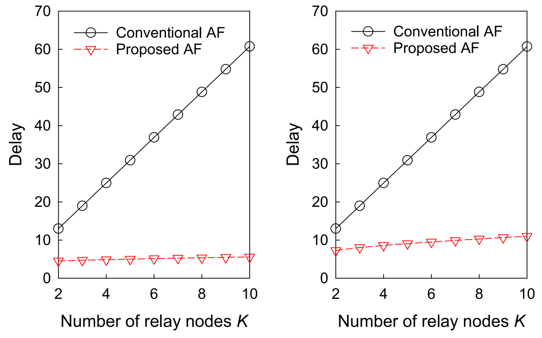
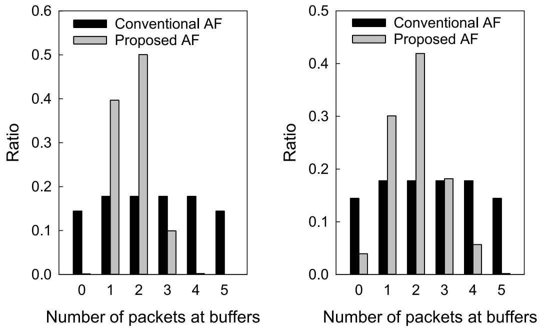


Fig. 1. Comparison of outage performance between the conventional AF max-link scheme and the proposed generalized AF scheme where the system parameters were given by $(K, L) = (3, 3)$ and $(4, 3)$.



(a) SNR = 20 dB (b) SNR = 10 dB

Fig. 2. Delay comparisons between the conventional and proposed buffer-aided AF schemes, where the number of relay nodes was varied from $K = 2$ to 10, while maintaining a buffer of $L = 6$. The SNR was (a) 20 dB and (b) 10 dB.



(a) SNR = 20 dB (b) SNR = 10 dB

Fig. 3. Distributions of packets stored at each relay node buffer, where the number of relay nodes was $K = 3$, each having a buffer size of $L = 5$. The SNR was (a) 20 dB and (b) 10 dB.

number of relay nodes was varied from $K = 2$ to 10, while maintaining a buffer of $L = 6$. The average SNR was 20 dB and 10 dB in Figs. 2(a) and 2(b), respectively. Regardless of the average SNR, it can be seen that the packet delay for the proposed scheme remained low, while that for the conventional AF scheme increased linearly with the number of relay nodes.

In Fig. 3, we plotted the distributions of packets stored at each relay node buffer, where the number of relay nodes was $K = 3$, each having a buffer size of $L = 5$. The SNR was 20 dB and 10 dB in Figs. 3(a) and 3(b), respectively. As can be seen in both Figs. 3(a) and 3(b), the proposed scheme successfully avoided the full- and empty-buffer states, while the conventional AF scheme relay buffers were uniformly distributed. This allowed the proposed scheme to achieve the maximum attainable diversity gain, as demonstrated by the results of Fig. 1. More specifically, in the proposed scheme, the amount of packets stored at the relay nodes is kept as low as possible, while avoiding empty buffers. Since the number of packets stored at relay nodes is directly related to the delay profile, as demonstrated in [2], this also contributes to the proposed scheme's delay reductions over the conventional protocol, as clarified by the results of Fig. 2.

IV. CONCLUSION

In this letter, we proposed a novel generalized AF BSB relaying protocol that simultaneously exploits multiple SR links while introducing buffer-state-and-thresholding-based relay selection. Due to the increased number of simultaneously activated links, the proposed scheme outperforms the conventional buffer-aided amplify-and-forward protocol. Our simulation results demonstrated that the proposed protocol achieves significantly lower packet delay, while maintaining a lower outage probability than that of the existing AF buffer-aided scheme.

REFERENCES

[1] N. Zlatanov, A. Ikhlef, T. Islam, and R. Schober, "Buffer-aided cooperative communications: Opportunities and challenges," *IEEE Commun. Mag.*, vol. 52, no. 4, pp. 146–153, Apr. 2014.
[2] M. Oiwa and S. Sugiura, "Reduced-packet-delay generalized buffer-aided relaying protocol: Simultaneous activation of multiple source-to-relay links," *IEEE Access*, vol. 4, pp. 3632–3646, 2016.
[3] N. Nomikos *et al.*, "A survey on buffer-aided relay selection," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 1073–1097, 2nd Quart., 2016.
[4] A. Ikhlef, D. S. Michalopoulos, and R. Schober, "Max-max relay selection for relays with buffers," *IEEE Trans. Wireless Commun.*, vol. 11, no. 3, pp. 1124–1135, Mar. 2012.
[5] I. Krikidis, T. Charalambous, and J. S. Thompson, "Buffer-aided relay selection for cooperative diversity systems without delay constraints," *IEEE Trans. Wireless Commun.*, vol. 11, no. 5, pp. 1957–1967, May 2012.
[6] C. Dong, L.-L. Yang, and L. Hanzo, "Performance analysis of multihop-diversity-aided multihop links," *IEEE Trans. Veh. Technol.*, vol. 61, no. 6, pp. 2504–2516, Jul. 2012.
[7] S. Luo and K. C. Teh, "Buffer state based relay selection for buffer-aided cooperative relaying systems," *IEEE Trans. Wireless Commun.*, vol. 14, no. 10, pp. 5430–5439, Oct. 2015.
[8] D. Poulimeneas *et al.*, "Delay- and diversity-aware buffer-aided relay selection policies in cooperative networks," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Doha, Qatar, Apr. 2016, pp. 1–6.
[9] S.-L. Lin and K.-H. Liu, "Relay selection for cooperative relaying networks with small buffers," *IEEE Trans. Veh. Technol.*, vol. 65, no. 8, pp. 6562–6572, Aug. 2016.
[10] R. Nakai, M. Oiwa, and S. Sugiura, "Generalized buffer-state-based relay selection for fixed-rate buffer-aided cooperative systems," in *Proc. IEEE Veh. Technol. Conf.*, Sydney, NSW, Australia, Jun. 2017, pp. 1–5.
[11] A. Siddig and M. F. M. Salleh, "Balancing buffer-aided relay selection for cooperative relaying systems," *IEEE Trans. Veh. Technol.*, to be published.
[12] Z. Tian, G. Chen, Y. Gong, Z. Chen, and J. A. Chambers, "Buffer-aided max-link relay selection in amplify-and-forward cooperative networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 2, pp. 553–565, Feb. 2015.
[13] K. C. Teh and S. Luo, "Performance of space-shift keying with buffer-aided amplify-and-forward relaying," *IEEE Trans. Veh. Technol.*, to be published.
[14] M. Oiwa, C. Tosa, and S. Sugiura, "Theoretical analysis of hybrid buffer–aided cooperative protocol based on max–max and max–link relay selections," *IEEE Trans. Veh. Technol.*, vol. 65, no. 11, pp. 9236–9246, Nov. 2016.
[15] B. B. Bai, W. Chen, K. B. Letaief, and Z. Cao, "A unified matching framework for multi-flow decode-and-forward cooperative networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 2, pp. 397–406, Feb. 2012.