Received December 22, 2019, accepted January 9, 2020, date of publication January 21, 2020, date of current version January 30, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2968368

Buffer-Aided Relaying Network With Hybrid BNC for the Internet of Things: Protocol and Performance Analysis

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This work was supported in part by the China Postdoctoral Science Foundation under Grant 2017M622372, in part by the Science and Technology Planning Project of Henan Province under Grant 192102210091, in part by the Key Scientific Research Fund of Henan Provincial Education Department for higher school under Grant 18A510016, and in part by the National Natural Science Foundation of China (NSFC) under Grant 61801433.

ABSTRACT In fifth generation and beyond Internet of things (5G-IoT), the buffer-aided relaying network provide an efficient way to maintain the coverage area and enhance the edge user's transmission experience. However, the effect of non-ideal factor to the buffer-aided relaying network, such as the signaling overhead, have not been investigated. In this paper, we propose a practical hybrid bit-level network coding (BNC) for the buffer-aided relaying network while taking the unreliable transmission, limited relay-buffer size and signaling overhead into consideration. Afterward, we derive its concise closed-form expressions and the associated upper bound expressions for the throughput, queuing delay and overflow probability. Monte-Carlo simulation proves the validness of our analysis. Simulation results also demonstrate that compared to existing studies, our proposal can enhance the system energy efficiency (EE) performance, and buffer size has a positive effect on the EE performance.

INDEX TERMS Internet of things, green communication, signaling overhead, unreliable transmission, bidirectional relay, finite buffer.

I. INTRODUCTION

It is well known that in the forthcoming fifth generation and beyond (5GB) era, Internet of things (IoT) aims to connect everything from everywhere at any time with a big picture of ubiquitous network [1]–[4]. In literature, 5GB-IoT has classified the potential applications into three typical scenarios, i.e., enhanced mobile broadband (emBB), massive machine-type communications (mMTC) [5], and ultra-reliable low latency communications (URLLC) [6]. Higher carrier frequency resource allocation and more transmission antennas are inevitable solutions to the requirements of higher transmission speed and more connected devices. In this regard, millimeter wave (mmWave), massive multi-input multi-output (MIMO) and non-orthogonal multiple access (NOMA) [3] have been widely agreed as the fundamental technologies of 5GB-IoT [7]. However, these existing 5GB technologies, especially the massive MIMO and mmWave, will result in cell densification and coverage area maintenance, which present a barrier to their adoption in 5GB IoT.

Relay-assisted transmission is a practical way to solve the cell densification problem. It can maintain the coverage area without extra base station (BS) implementation, which yields reduced implementation cost to the vendor [7]. Moreover, relay-assisted transmission has been proved to be an efficient way to enhance the link quality, reduce the system energy consumption and extend the battery life of mobile phone terminals, which can enhance the system energy efficiency (EE) performance [8]. Gu *et al.* [9] studied the system overall energy consumption from the point view of resource scheduling, and proposed an auction-based relay selection mechanism to improve system capacity and to prolong the lifetime of mobile terminals for green communications with relay-assisted transmission. Similarly, Singh and Ku [10] presented a relay-assisted approach to enhance the system EE performance. Wu and Wang [11] proposed a power-efficient

The associate editor coordinating the review of this manuscript and approving it for publication was Zhenyu Zhou.

amplification factor to reduce the power consumption and outage probability. Studies from [12], [13] revealed that two-way relay outperforms one-way relay system model on the spectrum utilization. In addition, with the help of network coding (NC), two-way relay can use the broadcast property of wireless channels to combine two packet's information at the relay node. In this case, each receiver can acquire its desired data by treating the other user's information as interference and cancel it, which yields reduced spectrum usage and energy consumption. However, in the literature, study on relay-assisted system with NC is relatively scarce.

In the literature, relay-assisted systems with NC can be divided into two categories: the physical layer network coding (PNC) [14]–[17] and the bit-level network coding (BNC) [18], [19]. Generally, PNC needs two phases for each transmission cycle, and the time and phase synchronization are precisely required. Additionally, transmit power also needs to be well controlled. Otherwise PNC performance will be dramatically degraded. In the study of PNC, Zhang *et al.* [14] proved that with poor time and phase synchronization, power penalty of PNC is 1.57dB and 3.4dB, respectively. The instantaneous channel state information (CSI) is also needed in PNC, which consumes considerable signaling overhead. These disadvantages restrict the employment of PNC. Compared to PNC, BNC is a simple and efficient method. It was initially proposed in the butterfly network, and the main purpose is on data compression. Prior work found that BNC can efficiently reduce the transmission time and enhance the system throughput performance [20]. In the study of [21], [22], BNC was applied to exploit the broadcast nature of the wireless channel and reduce the energy consumption. By following a similar analytical procedure, we focus on the EE performance of BNC protocol in this paper.

Besides, buffer-aided relaying systems have been intensively studied as an efficient method to improve the system performance, see, e.g., [23]–[26]. Specifically, [23] proposed a QoS-aware buffer-aided relaying for the wireless body area network (WBAN). It was found that this framework can bring some dramatic benefits to the IoT communications such as throughput, delay and energy consumption. Based on the full duplex (FD) buffer-aided relaying systems, [24] presented two optimal multiuser scheduling method to maximize the throughput under the fixed and adaptive transmission power constraints. In [25], a novel relay selection scheme based on the prioritization-based buffer-aided relay systems was proposed for the cooperative NOMA, which can seamlessly combine the NOMA and orthogonal multiple access (OMA) transmission. Based on the buffer-aided relaying systems, [26] proposed a link selection scheme to enhance the physical layer security. It was found that the $2K$ (K is the relay number) of the secrecy diversity gain can be achieved when buffer size is unlimited. Actually, all existing work on the buffer-aided relay network can be summarized into three categories, i.e., the optimization relay selection method (including the link selection), the power allocation strategy and the NC in different relay scenarios.

In the literature, Markov chain model provide an efficient way for the performance analysis of buffer queuing protocol problem in BNC. For instance, [19], [27], [28], proposed the Markov chain models to capture the processes of the BNC protocol with finite relay buffer. Specifically, [27] analyzed the throughput of the NC scheme in ALOHA network, and derived the optimal switching strategy between PNC, HNC and NNC under unbalanced traffic load. [19] proposed a low-complexity coded transmission scheme (batch code) for lossy relay links with finite buffer which considered the decoding cost at the receiver. Jamali defined different channel access modes in bidirectional relay network [28], and designed a strategy to dynamically select an optimal transmission mode according to the instantaneous link capability for higher sum rate. However, these papers only considered the error-free link in their analytic modeling, and the practical signaling overheads, such as the preambles and the ACK/NACK messages, were ignored for simplicity. In fact, the packet transmission failure caused by the lossy link, which is particularly severe in the 5G-IoT environment. In fact, the packet transmission failure caused by lossy link is particularly severe in the 5G-IoT environment. Therefore, it is of significant importance to develop a different Markov chain model by taking the effect of lossy link into consideration. To the authors' best knowledge, the performance (e.g., throughput, EE and et al.) of the buffer-aided hybrid one-way and two-way relay network considering the signaling overhead and unreliable link has not been analyzed, which motives us to form this work.

In order to solve the aforementioned problems, we consider a practical buffer-aided green relaying network with the joint consideration of unreliable transmission, signaling overhead and finite relay buffer, where the relay node employs BNC with the best effort. Detailed relaying processes are well designed to save the signaling overhead. Moreover, an analytic model is proposed to evaluate the practical bidirectional relay network with the above-mentioned joint consideration, and the concise closed-form expressions of the throughput, overflow probability and queuing delay are presented. The practical upper bound is also derived. The simulation results justify the accuracy and feasibility of the proposed analytical model. The throughput performance of our proposed buffer-aided relaying network with hybrid BNC could be better than that of the existing optimal bidirectional relaying network [28] when the unreliable channel and signaling overhead are taken into account. Moreover, Our developed relaying strategy also outperforms the transmission model [28] in terms of the EE performance. Our analysis shows that the EE performance can be further improved by increasing the buffer size.

The remainder of the paper is organized as follows: Section II presents the system model, Section III presents the proposed hybrid two-way relay protocol. In Section IV, by focusing on the transition process of relay buffer states, a Markov chain model is developed, based on which the closed-form of the throughput, queueing delay and the

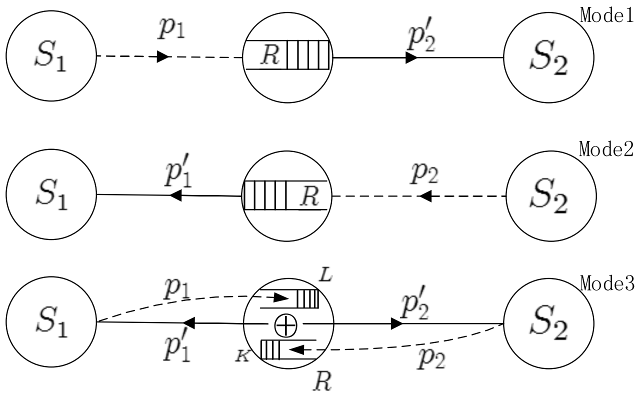


FIGURE 1. **Network model, where p_1 is the packet success probability from user S_1 to R; p_2 is the packet success probability from S_2 to R; P'_1 is the packet success probability from R to user S_1; p'_2 is the packet success probability from R to user S_2. There are three working modes to satisfy any traffic flows: $S_1 \rightarrow S_2$, $S_1 \leftarrow S_2$ and $S_1 \leftrightarrow S_2$, which include two kinds of relaying method: one-way relay and two-way relay. The dashed lines denote the transmission of data sources and the solid lines denote the relaying operation.**

over-flow probability are derived in Section V. Numerical and simulation results are presented in Section VI and some conclusions are drawn in VII.

II. SYSTEM MODEL

We consider a simple network in which user 1, denoted by S_1, and user 2, denoted by S_2, intend to exchange data with each other with the help of a relay node, as shown in Fig.1. S_1 and S_2 can communicate with each other only through the relay R, i.e., there is no direct link between S_1 and S_2. The source nodes first send packets to the relay and possibly stores all the correct packets in its buffer, and eventually forwards them to S_1 and S_2 respectively at the same timeslot or at the different timeslot. We also assume that the transmission duration is divided into equal length slots. The physical relay buffer is logically divided into two queues with the size of L and K. They are used to store the packets received from S_1 and S_2, respectively. Throughout this paper, we assume the source node S_1 and S_2 always have packets to transmit.

Network model, where p_1 is the packet success probability from user S_1 to R; p_2 is the packet success probability from S_2 to R; P'_1 is the packet success probability from R to user S_1; p'_2 is the packet success probability from R to user S_2. There are three working modes to satisfy any traffic flows: $S_1 \rightarrow S_2$, $S_1 \leftarrow S_2$ and $S_1 \leftrightarrow S_2$, which include two kinds of relaying method: one-way relay and two-way relay.

In this paper, we only consider the link layer operation, and denote the probability of successful packet transmission from S_1 to R as p_1 ($p_1 : S_1 \rightarrow R$) which is caused by the unreliable link. Similarly, the probability of successful packet transmission of $S_2 \rightarrow R$, $R \rightarrow S_1$ and $R \rightarrow S_2$ are denoted as p_2, p'_1 and p'_2, respectively. This channel is practical in the IoT scenario, e.g., all the sensor nodes/Data gateways located in a fixed place and communicate with each other. The consideration of p_i is different from most of the existing studies, where they assume all the nodes can transmit packets ideally. This means that, the transmitter and receiver have to acquire the real-time channel state information (CSI) to adjust its transmitting data rate. In addition, the saved signalling overhead will degrade the throughput performance, this degradation is even worse as the node number increasing.

In this paper, we mainly analysis the relationship between relay buffer size, partition size of the two logical queues, and the throughput performance under the practical consideration. Thus, we assume a saturation traffic and the buffer resource at S_1 and S_2 are always enough. We also assume Inter Frame Space (IFS), preamble of frame, scheduling messages, and all duration without payload transmission as overhead in this paper.

III. DEVELOPED PRACTICAL HYBRID TWO-WAY RELAY PROTOCOL

In order to study the influence of the inevitable non-ideal factors, we develop a practical transmission process of hybrid one-way relay and two-way relay protocol without scheduling operation in this section. The signaling overhead, practical unreliable link and finite relay buffer are jointly taken into account. Compared with existing studies, here we consider the signalling overhead and unreliable transmission.

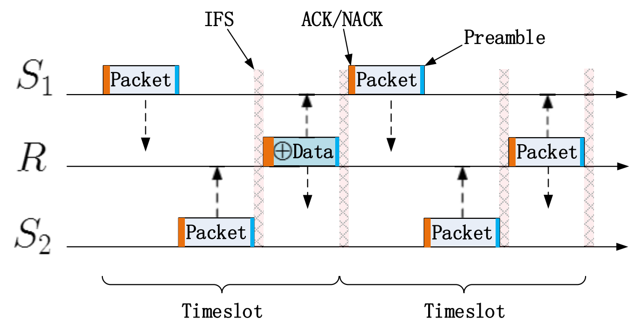


FIGURE 2. **Transmission process of the buffer-aided Hybrid BNC protocol, IFS is the inter frame spacing which is used for transmission switching between different node.**

Fig. 2 shows the practical protocol where data source nodes and relay node transmit data in a Box and Cox arrangement, and each node transmits data in the unit of packet or frame. Without loss of generality, the duration of each packet is set equal. In order to reduce the signaling overhead and the scheduling complicity, the data nodes and the relay node transmit packets in a pre-allocated style. We call the timeslots where S_1 and S_2 transmit packets to relay node as ‘‘access stage’’, and the timeslots where the relay node has the opportunity to transmit as ‘‘broadcast stage’’. The two stages take place alternately, and the duration of the ‘‘access stage’’ is twice of the ‘‘broadcast stage’’.

In the ‘‘access stage’’, each source node picks a packet from the FIFO (First Input First Output) transmitting queue, and sends it to the relay node successively. R puts all the correctly decoded packets delivered by S_1 and S_2 in the logical queues L and K, respectively.

After the "access stage", R obtains the opportunity to transmit packets. On condition that each relay queue has packets, the earliest received packet in the queue will be selected. R then imports the two candidate packets into the network coding operator, where the two packets are compressed into a new packet with XOR operation. Importantly, the new generated packet only consumes the same amount of transmission resources as the original packet, and R then transmits this new generated packet to both S_1 and S_2 simultaneously via the broadcast channel. S_1 and S_2 then execute the receiving action, and carry out the inverse operation of network coding. This can cancel the information of itself from the received packet. It then derive its desired data from the remaining packets. This bidirectional transmission method corresponds to the mode 3 is given by Fig. 1.

Practically, physical relay buffer is finite and wireless transmission is unreliable, thus there are some empty situations of each relay queue. When one in two relay queues is empty, network coding is unused, and R just picks up one packet from the nonempty relay queue and relays it to its destination, i.e., the relay node works in the method of traditional one-way relay as the mode 1 and mode 2 presented in Fig. 1. If both relay queues are empty, R just gives up this transmission opportunity, and the three nodes keep idle at this pre-allocated "broadcast stage". We can see that, this arrangement is not suitable for severe channel, meanwhile it can reduce large amount of scheduling overheads. The advantage and disadvantage of this arrangement will be discussed detailed in the following.

With pre-allocation, scheduling message is not required to dynamically arrange the timeslots. In addition, real time ACK/NACK is also unnecessary at the transmitter due to the pre-allocated method. Thus, feedback information from the receivers can be appended to the next packet. The advantage of this method is that signaling overhead can be significantly reduced. This is because the two-hop relay system requires more radio resources to deliver the real-time relay queue state to the two users. For example, if data source nodes requires the real-time relay buffer queue status, three signaling messages are required after the transmission of R, i.e., two ACK/NACK messages from S_1 and S_2 to R, and one signaling message from R to S_1 and S_2.

Despite one-bit feedback is adopted and the associated signaling overheads are ignored in some existing studies, the inter frame space, packet head, preamble and other components are still unavoidable in some scenarios. Here, the signalling overheads caused by ACKs/NACKs are non-negligible if the payload is relatively small. In addition, we do not claim the optimization of this developed process, and only present a demonstration which outperforms the existing optimal one when signalling overhead is taken into account. The followed simulations also demonstrate that the probability of idle stage is extremely low, and this pre-allocation of the transmission stage is reasonable in some scenarios.

IV. PROPOSED MARKOV CHAIN MODEL FOR BUFFER-AIDED HYBRID BNC PROTOCOL WITH UN-RELIABLE TRANSMISSION AND FINITE BUFFER

In order to derive the average throughput and other performances, we engage in analysing the transition process of relay buffer queue states, and then a Markov chain model will be constructed in this section. Without loss of generality, finite relay buffer, unreliable transmission and signaling overhead are joint considered during the modeling. With the steady state probabilities of the relay buffer queues, the close-form expressions of average throughput, queueing delay and overflow probability can be calculated.

The working process of Mode1, Mode2 and Mode3 described in Section II actually results in a same transmission states. Thus, we only need to characterize the data flow and buffer states in our modeling process, and jointly consider the transmitting and receiving actions of all modes in a unified modeling framework. In order to capture the forwarding process of the relay, we let the tuple (l, k) observed at the ending of each transmission be the Markov chain states, where the $l(l = 0, 1, .., L)$ and $k(k = 0, 1, .., K)$ are the instantaneous size (i.e., the number of the stored packets) of the relay buffer queue L and K respectively. With the description in Section III, we can see that the transition from state (l_i, k_i) observed in the $i-$ th timeslot to the state $(l_j, k_j), j = i + 1$ observed in the next timeslot depends solely on the present state (l_i, k_i). This memoryless property indicates that future and past states are independently, which yields the Markovian transition processes.

Obviously, the simple tuple (l, k) cannot characterize the transmission processes in detail due to that the two types of events, i.e., "transmitting" and "receiving", may result in a same state. Notably, this misleading phenomenon can be avoided by adding a parameter to the tuple, whereas it will increase the dimension of the following Markov chain model. The complexity of the modeling and calculation will increase significantly. In this paper, we first classify the states into two groups: one group is observed at the beginning of the "broadcast stage", these states are assembled in the state space $\mathcal{R}$; another group is observed at the beginning of the "access stage", these states are grouped by the state space $\mathcal{U}$. The transitions from the states in $\mathcal{R}$ to the states in $\mathcal{U}$ are shown in Fig. 4, and the contrary transitions are presented in Fig. 3. As described in Section III, the states in the two groups appear alternately.

Specifically, Fig.3 depicts the state transition processes caused by the transmission of S_1 and S_2. The correctly received packets are stacked in the relay buffer queues when the transmission from S_1 or/and S_2 to R is successful, which results in the increment of l or/and k. We can see that the step length equals to the transmitted packet number, and the value is 1. If the packet cannot be correctly received at R, the state parameter(s) remain(s) unchanged. Thus the state transition can be expressed as: $(l, k) \to (l + i, k + j), i, j \in \{0, 1\}$. Particularly, if $l = L$ or/and $k = K$, the relay has

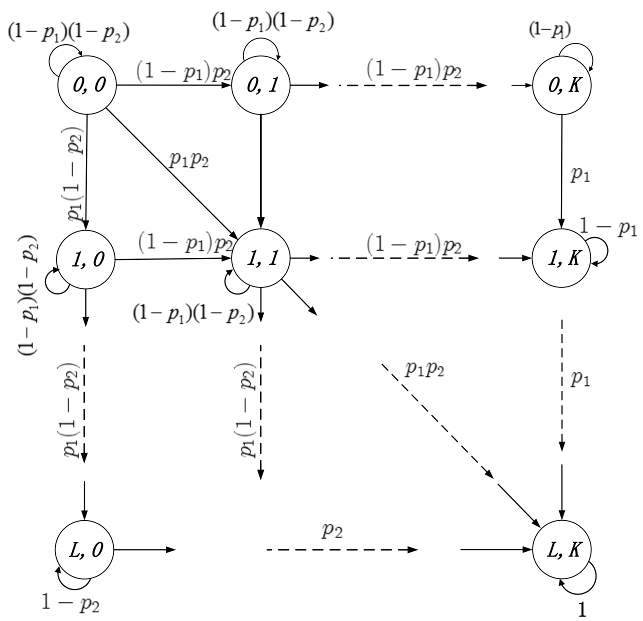


FIGURE 3. The state-transition diagram corresponding to the transmitting of S_1 and S_2, in which l and k switch to $l+i, i=\{0,1\}$ and $k+j, j=\{0,1\}$ respectively in accordance with whether the transmission is successful.

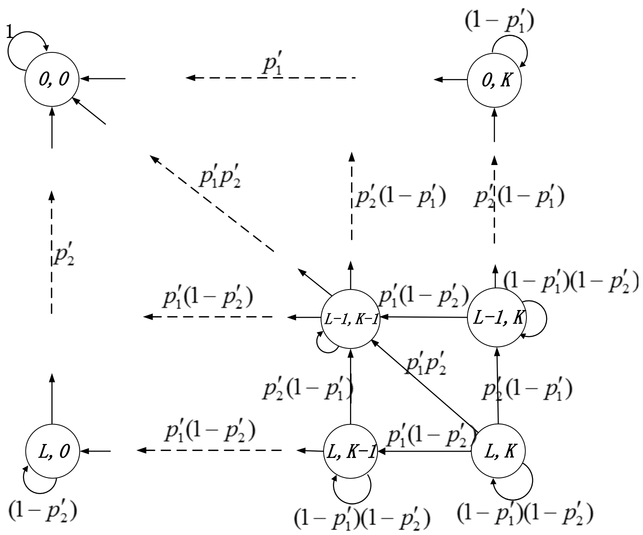


FIGURE 4. The state-transition diagram corresponding to the transmitting of relay, in which l and k switch to $l-m, m=\{0,1\}$ and $k-m, m=\{0,1\}$ respectively in accordance with whether the transmission is successful.

to discard the correctly received packet(s) from S_1 or/and S_2, and the associated queue(s) remain(s) unchanged, which is because of the finite relay buffer size. The unchanged queue thus causes overflow, and the correctly received packet is discarded.

In contrast with Fig. 3, Fig. 4 describes the events happened at the "broadcast stage" where the relay obtains the opportunity to transmit packet to the two destinations. If the network coding is employed and the transmission is successful, both of the parameters l and k decrease by 1. If the transmission of either links, i.e., $R \rightarrow S_1$ or $R \rightarrow S_2$, is failed, the associated state parameter, i.e., l or k, remains the same, and the remaining parameter reduces by 1. Thus, the state transition can be expressed as: $(l,k) \rightarrow (l-i, k-j), i,j \in \{0,1\}$. Note that, the state (0,0) can only transit to itself since there is no packet in the relay buffer.

To derive the steady state probability, we arrange the tuples (l,k) in $\mathcal{U}$ as $\mathbf{U}$, where $\mathbf{U}_i = (l,k), i = (K+1)l+k+1$. Similarly, states in $\mathcal{R}$ are arranged as $\mathbf{R}_i = (l,k), i = (K+1)l+k+1$.

Denote the (l_m, k_m) in $\mathcal{R}$ as $\mathbf{s}_m^{\mathcal{R}}$, where the subscript m is the timeslot. During the transmission "broadcast stage", we can get transition probability from state $\mathbf{s}_m^{\mathcal{R}}$ to state $\mathbf{s}_n^{\mathcal{U}}$, $n = m+1$ as

$$\Pr\{\mathbf{s}_n^{\mathcal{U}}|\mathbf{s}_m^{\mathcal{R}}\} = \begin{cases} (1-p_1')(1-p_2'), & \text{if } l_m = l_n \text{ and } k_m = k_n; \\ p_1'(1-p_2'), & \text{if } l_m = l_n \text{ and } k_m - 1 = k_n; \\ p_2'(1-p_1'), & \text{if } l_m - 1 = l_n \text{ and } k_m = k_n; \\ p_1'p_2', & \text{if } l_m - 1 = l_n \text{ and } k_m - 1 = k_n; \\ 0, & \text{otherwise,} \end{cases} \tag{1}$$

where $l_m k_m \neq 0$.

On condition that $l_m k_m = 0$, we have the transition probabilities,

$$\Pr\{\mathbf{s}_n^{\mathcal{U}}|\mathbf{s}_m^{\mathcal{R}}\} = \begin{cases} (1-p_2'), & \text{if } l_m = l_n \text{ and } k_m = 0; \\ p_2', & \text{if } l_m - 1 = l_n \text{ and } k_m = 0; \\ (1-p_1'), & \text{if } l_m = 0 \text{ and } k_m = k_n; \\ p_1', & \text{if } l_m = 0 \text{ and } k_m - 1 = k_n; \\ 1, & \text{if } l_m = 0 \text{ and } k_m = 0; \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Based on (1) and (2), we can construct the probability matrix from $\mathbf{R}$ to $\mathbf{U}$, denoted as $\Gamma \in \mathbb{R}^{(L+1)(K+1)\times(L+1)(K+1)}$. The (i,j)-th element of Γ then can be given as

$$\Gamma_{i,j} = \Pr\{s_2^{\mathcal{U}}|s_1^{\mathcal{R}}\} = \Pr\{(l_2^{\mathcal{U}}, k_2^{\mathcal{U}})|(l_1^{\mathcal{R}}, k_1^{\mathcal{R}})\}, \tag{3}$$

where $i = l_1^{\mathcal{R}}(K+1)+k_1^{\mathcal{R}}+1$ and $j = l_2^{\mathcal{U}}(K+1)+k_2^{\mathcal{U}}+1$.

After the "broadcast stage", the user S_1 and S_2 begin transmit packets to relay. It can be described by the transition process from state $s_n^{\mathcal{U}} = (l_n, k_n)$ in $\mathcal{U}$ to state $s_h^{\mathcal{R}} = (l_h, k_h), h = n+1$ in $\mathcal{R}$. The probability of state transition can be expressed as

$$\Pr\{s_h^{\mathcal{R}}|s_n^{\mathcal{U}}\} = \begin{cases} (1-p_1)(1-p_2), & \text{if } l_h = l_n \text{ and } k_h = k_n; \\ (1-p_1)p_2, & \text{if } l_h = l_n \text{ and } k_h - 1 = k_n; \\ p_1(1-p_2), & \text{if } l_h - 1 = l_n \text{ and } k_h = k_n; \\ p_1p_2, & \text{if } l_h - 1 = l_n \text{ and } k_h - 1 = k_n; \\ 0, & \text{otherwise,} \end{cases} \tag{4}$$

where $l_n \neq L$ and $k_n \neq K$. In the case $l_n = L$ or $k_n = K$, the transition probability is given by

$$\Pr\{\mathbf{s}_h^{\mathcal{R}}|\mathbf{s}_n^{\mathcal{U}}\} = \begin{cases} (1-p_2), & \text{if } l_n = L \text{ and } k_h = k_n \neq K; \\ p_2, & \text{if } l_n = L \text{ and } k_h - 1 = k_n; \\ (1-p_1), & \text{if } l_h = l_n \neq L \text{ and } k_h = k_n = K; \\ p_1, & \text{if } l_h - 1 = l_n \text{ and } k_h = k_n = K; \\ 1, & \text{if } l_h = l_n = L \text{ and } k_h = k_n = K; \\ 0, & \text{otherwise.} \end{cases} \quad (5)$$

The transition probability matrix from states in **U** to states in **R** is expressed as $\Lambda \in \mathbb{R}^{(L+1)(K+1)\times(L+1)(K+1)}$. The $(i,j)-th$ element of Λ is given by

$$\Lambda_{i,j} = \Pr\{(l_2^{\mathcal{R}}, k_2^{\mathcal{R}})|(l_1^{\mathcal{U}}, k_1^{\mathcal{U}})\}, \quad (6)$$

where $i = l_1^{\mathcal{U}}(K+1) + k_1^{\mathcal{U}}$ and $j = l_2^{\mathcal{R}}(K+1) + k_2^{\mathcal{R}}$.

In the relay buffer first-in-first-out (FIFO) queue, Little's law [29] is applicable. The average packet numbers flowing in and out the relay buffer queue are equal. Thus, we only need to derive the probabilities of the steady states observed at either the "broadcast stage" or the "access stage". Without loss of generality, we take the states in $\mathcal{R}$ as the effective Markov states, and the states in $\mathcal{U}$ are processed as the auxiliary states. Transition probability between different states of **R** can be derived by

$$\Pr\{s_j^{\mathcal{R}}|s_i^{\mathcal{R}}\} = \sum_{s_m \in \mathcal{U}} \Pr\{s_j^{\mathcal{R}}|s_m^{\mathcal{U}}\} \Pr\{s_m^{\mathcal{U}}|s_i^{\mathcal{R}}\}. \quad (7)$$

With this conjunction, the states in $\mathcal{U}$ are absorbed into the transition processes between the states of **R**. Let $\Omega_{i,j} \in \mathbb{R}^{(L+1)(K+1)\times(L+1)(K+1)}$ express the $(i,j)-$ th element of the transition probability matrix between any two states of **R**, which can be given by

$$\Omega_{i,j} = \Pr\{(l_2^{\mathcal{R}}, k_2^{\mathcal{R}})|(l_1^{\mathcal{R}}, k_1^{\mathcal{R}})\}. \quad (8)$$

With above state merging, any two states of $\mathcal{R}$ are mutually accessible since there is no isolated state, thus the Markov process presented here is irreducible. It can be seen that, each state in $\mathcal{R}$ can transit to itself immediately with a probability, thus the state transition process submits to aperiodicity character. As a result, the Markov chain process has a unique steady state distribution $\boldsymbol{\pi} \in \mathbb{R}^{(L+1)(K+1)}$. We can obtain $(L+1)(K+1)+1$ equations based on the Markov chain character, which is

$$\begin{cases} \boldsymbol{\pi}\boldsymbol{\Omega} = \boldsymbol{\pi} \\ \sum_i \sum_j \boldsymbol{\pi}_{i,j} = 1. \end{cases} \quad (9)$$

The closed-form steady state probabilities of $\mathcal{R}$ are equivalently given by (10), as shown at the bottom of this page, where $0 \leqslant l \leqslant L$ and $0 \leqslant k \leqslant K$, $[i]^+ = 0$ if $i < 0$, and $[i]^+ = i$ if $i \geq 0$, and $\binom{x}{y}$ denotes the combination function.

In the symmetric situation, i.e., $p_1 = p_2 = p_1' = p_2' = p$ and $L = K$, (10) can be simplified as,

$$\boldsymbol{\pi}_{l,k} = \frac{(1-p)^{\delta(l)+\delta(k)}}{(p-L-1)^2}, \quad (11)$$

where $\delta(l) = 1$ if $l = 0$, and $\delta(l) = 0$ otherwise.

We classify the transmission events into two types, and the steady state character of one type event is sufficient to analyze the average throughput, energy consumption and other performance. The computation complexity is thus reduced. This classification is because that, the amount data of entering and leaving a steady queue is equal. In other words, R receives (at "access stage") and transmits (at "broadcast stage") the same amount of data during sufficient long period. It means that we only need to compute the steady state probability of one type events, and we can split the entire relaying transmission as shown by Fig. 3 and Fig. 4.

V. PERFORMANCE ANALYSIS

In this section, we derive the average throughput, overflow probability, average queue length, queuing delay and other system performance, by using the derived steady state probabilities in Section IV.

As mentioned before, two types of transmission stages alternately occur, thus the time expenditure of each relaying period is fixed. Let $\rho = 3(\tau_{\text{Data}} + \tau_{\text{Pre}} + \tau_{\text{ACK}}) + 2\tau_{\text{IFS}}$ express the average relaying period. Here the τ_{Data} is the actual duration of the payload λ; τ_{Pre} denotes the preamble time duration; τ_{ACK} is the duration of the ACK/NACK bits (without preamble); τ_{IFS} denotes the duration of IFS. Specifically, every node is pre-allocated a transmission opportunity during each transmission cycle, and there are three τ_{Pre}, τ_{Data} and τ_{ACK} in each cycle. The switching between the "access stage" and the "broadcast stage" costs two τ_{IFS} in each transmission cycle.

The throughput, denoted by ϕ, can be calculated by adding up the probability of each successfully delivered packet in each transmission period, and then dividing the duration of the transmission cycle,

$$\begin{aligned} \phi &= \phi_l + \phi_k \\ &= \xi \sum\sum \Big((\varepsilon(l)p_2' + \varepsilon(k)p_1') \times \boldsymbol{\pi}_{l,k} \Big), \end{aligned} \quad (12)$$

where ϕ_l and ϕ_k are throughput of user S_1 and S_2, respectively, $\xi = \frac{\lambda}{\rho}$; $\varepsilon(x) = 1$ if $x > 0$, and $\varepsilon(x) = 0$ if $x \leq 0$. Science there is no scheduling message transmission in this relay network, users will continuous send packets to the relay

$$\boldsymbol{\pi}_{l,k} = \frac{p_1^l(1-p_2')^l {p_2'}^{L-l}(1-p_1)^{[L-l-1]^+} p_2^k (1-p_1')^k {p_1'}^{K-k}(1-p_2)^{[K-k-1]^+}}{\sum_{j=0}^{L}\left\{ {p_2'}^j p_1^{L-j}\left(\sum_{i=0}^{j}\binom{L}{i}(-p_1)^i\right)\right\} \sum_{j=0}^{K}\left\{ p_2^j {p_1'}^{K-j}\left(\sum_{i=0}^{j}\binom{K}{i}(-p_1')^i\right)\right\}}, \quad (10)$$

even if the buffers are filled, and the relay has to throw away the correctly received packet. Defining the buffer overflow probability as the average discarded packet number per unit time, we can get the overflow probability by adding up the successfully delivered packet when the queue is filled, which is given by,

$$P_{ov} = \left\{ \boldsymbol{\pi}_{L,K}(p_1 + p_2) + \sum_{l=0}^{L-1} \boldsymbol{\pi}_{l,K} p_2 + \sum_{k=0}^{K-1} \boldsymbol{\pi}_{L,k} p_1 \right\} /2. \tag{13}$$

The average queue length (average stored packet number in the two relay queues) can be derived by adding up all the queue lengths weighted by the steady state probabilities, which is given by (14)

$$\begin{aligned} \varsigma &= \varsigma_L + \varsigma_K \\ &= \frac{1}{2}\left\{ \sum_{l=0}^{L}\sum_{k=0}^{K}(l+k)\boldsymbol{\pi}_{l,k} \right\}. \end{aligned} \tag{14}$$

The queuing delay (the average queue length over the average arrival rate) can be given by

$$\begin{aligned} \upsilon &= \frac{1}{2}\left\{ \frac{\varsigma_L}{\phi_L} + \frac{\varsigma_K}{\phi_K} \right\} \\ &= \frac{1}{2}\left\{ \frac{\sum\sum l \cdot \boldsymbol{\pi}_{l,k}}{\xi \sum\sum \varepsilon(l) p_2' \boldsymbol{\pi}_{l,k}} + \frac{\sum\sum k \cdot \boldsymbol{\pi}_{l,k}}{\xi \sum\sum \varepsilon(k) p_1' \boldsymbol{\pi}_{l,k}} \right\}. \end{aligned} \tag{15}$$

In the symmetric channel situation, we have the following lemmas:

Lemma 1: In the mixed one-way and two-way relay system with the joint consideration of unreliable transmission, finite relay buffer and signaling overhead, throughput is a monotone increasing and concave function with respect to the buffer size.

Proof: Substitute (11) into (12), we can derive the expression of the throughput under the symmetric situation, which is given by,

$$\phi = \xi \frac{2pL}{(L+1-p)} \qquad 0 < p < 1 \text{ and } L \in N^*. \tag{16}$$

It is found that (16) satisfies:

$$\lim_{L\to\infty^+} \xi \frac{2pL}{(L+1-p)} = 2\xi p, \tag{17}$$

which is the throughput upper bound of this relaying network. The first and second derivative of (16) is given by

$$\frac{\mathrm{d}\phi}{\mathrm{d}L}(L) = \xi \frac{2p(1-p)}{(L+1-p)^2}, \tag{18}$$

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}L^2}(L) = \xi \frac{4p(p-1)}{(L+1-p)^3}. \tag{19}$$

Since $p < 1$, we can easily obtain the value of the first-order and second-order derivative. The former and latter are always positive and negative, respectively. Thus, the throughput is a monotone increasing function with respect to the buffer size, and is also concave. We can also see that, the derivative value decreases with the growth of the relay buffer size, and eventually approaches to zero when $L \to +\infty$. This indicates that, increasing the relay buffer size can improve the throughput, and the improvement becomes gradually weak as the relay buffer size growing large.

Lemma 2: When the relay buffer is greater than 2, the overflow probability is a monotone decreasing function with respect to the buffer size; when the relay buffer is greater than 3, the overflow probability is a convex function with respect to the buffer size.

Proof: Substitute (11) into (13), we can derive the expression of the overflow probability under the symmetric situation, which is given by

$$P_{ov} = \frac{p(2L-p-1)}{2(p-L-1)^2} \quad L = 2, 3, \ldots \tag{20}$$

The first and second derivative respect with L can be given by,

$$\frac{\mathrm{d}P_{ov}}{\mathrm{d}L} = \frac{p(2-L)}{(1+L-p)^3}, \tag{21}$$

$$\frac{\mathrm{d}^2P_{ov}}{\mathrm{d}L^2} = \frac{p(2L+p-7)}{(p-L-1)^4}. \tag{22}$$

Equations (21) and (22) show that the first-order value is negative when $L > 2$, and the second order is greater than zero when $L > 3$. Thus, the overflow probability is a convex function and monotone decrease with respect to the buffer size. This lemma indicates that increasing the buffer size can decrease the overflow probability.

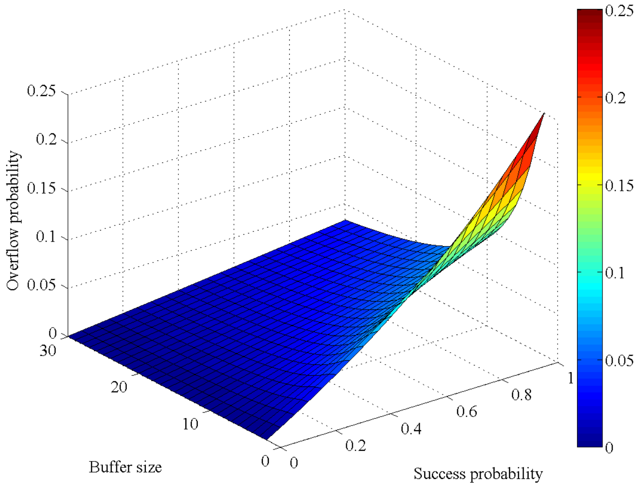
Fig. 5 plots the theoretic results of the derived buffer overflow probability respect with the buffer size and link reliability. We can see that the overflow probability can be easily cut down by increasing the buffer size, and then the adverse effect of overflow is neglectful. A small possibility of overflow is worth this best-effort style design because it can save plenty of radio resources required by the scheduling overhead. It is noticeable that in some environment [9], [24] where the traffics are severe unbalanced or the channels are severe asymmetric, appropriate message scheduling can improve the average throughput. We thus need to take the signalling overhead into consideration while designing the scheduling mechanism.

Lemma 3: The queue length and the queuing delay are approximately linear with respect to the buffer size if the buffer size is beyond a threshold.

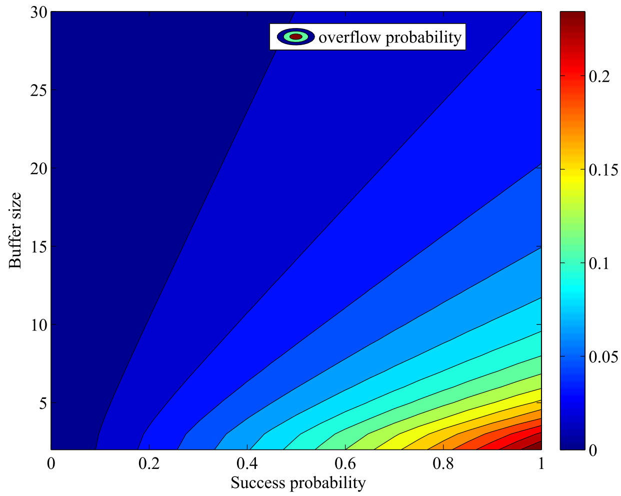
Proof: Substitute (11) into (14) and (15), we can derive the expression of the queue length and queuing delay under the symmetric situation as follows:

$$\varsigma = \frac{L(1+L)}{2(1+L-p)} \quad L \in \mathbb{N}^+, \tag{23}$$

$$\upsilon = \frac{1+L}{4\xi p}. \tag{24}$$



(a) 3D mesh plot



(b) 2D contour plot

FIGURE 5. Overflow Probability respect to the buffer size and transmission probability. The result were calculated from (20).

Equation (23) can be rewritten as

$$\varsigma = \frac{1+L}{2(1+\frac{1-p}{L})} \approx \frac{1}{2} + \frac{L}{2}, \text{ when } L \gg 1-p. \tag{25}$$

We can see that when the buffer is beyond a threshold, the average queue length is approximately linear with respect to buffer size. Actually, we can find some reasonable buffer size according to equation (12) and (15) to improve the throughput under a certain delay restriction.

VI. NUMERICAL AND SIMULATION RESULTS

For the sake of comparison, the existing optimal bidirectional relay system [28] is used as benchmark. Here, we jointly take scheduling messages, real-time global CSI and immediate ACK/NACK into consideration. We also employ the unreliable transmission and finite buffer size in [28]. All presented results have been confirmed by Monte-Carlo simulation, and not all of the simulations are shown here for clarity of this presentation.

Considering Gray mapping, and the detection errors only occur when misjudgement happens between adjacent modulation constellation points. Therefore, the packet successful probability can be calculated by

$$P = \sum_{k=0}^{K_c} \binom{\lambda}{k} p_s^k (1-p_s)^{\lambda-k}, \tag{26}$$

where p_s is the symbol error probability, and K_c is the error correction capability of channel code. Consider 4-QPSK signals, p_s can be written as

$$p_s = 2Q(\sqrt{3\gamma}), \tag{27}$$

where $Q(\cdot)$ is the Q-function, and $\gamma = \frac{P}{N_0}h$ is the instantaneous SNR, h is instant channel gain. N_0 is the average noise power at the receivers.

According to IEEE 802.11b, the parameters are set as: payload $\lambda = 2000$bits, unless specified otherwise; transmission rate $r = 11$ Mbps; preamble of each transmission $\tau_{\text{Pre}} = 96\mu s$; inter frame space $\tau_{\text{IFS}} = 10\mu s$; ACK/NACK bits duration (without preamble) $\tau_{\text{ACK}} = 11\mu s$. Additive noise power is 3.9×10^{-12} mW/H; transmission power is 320mW; the Bandwidth is set as 5MHz, and the path loss exponent is 2.

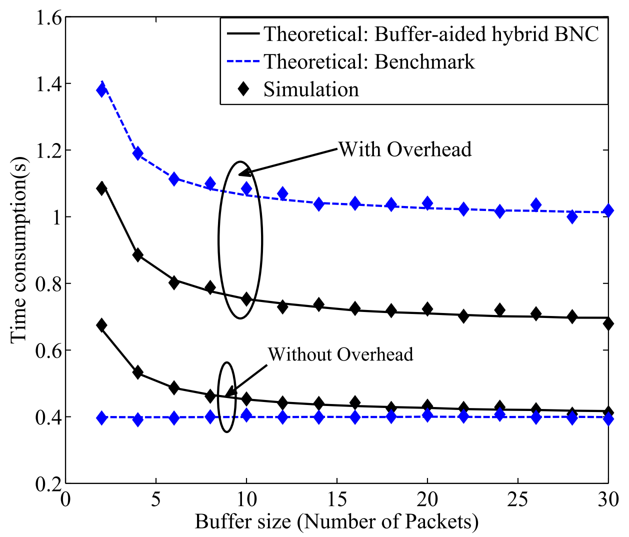


FIGURE 6. Time consumption vs the growth of relay buffer size, where the distance between the relay and users is 30m. The buffer-aided Hybrid BNC is our developed protocol in Section IV, and the benchmark is reference [28].

Fig.6 plots the Monte Carlo-based and theoretical results of the time consumption per 1 Mbits with respect to the growing relay buffer size, where the distance from the relay to each user is 30m. We can see that analytic results match Monte Carlo-based simulations closely whenever the signalling overhead is considered or not, which validates the accuracy of our model.

Fig. 6 also demonstrates relationship between the transmission duration of a fixed-size data block and the relay buffer size. The first point to note is the similar grow down trend of all the curves, which indicates that increasing the buffer size can reduce the average forwarding duration for a certain traffic. If we consider the signaling overhead, the time consumption of the two relaying strategies decrease steadily with the growth of the buffer size, and the time consumption gain brought by the buffer is $\frac{1.11-0.69}{0.69} = 60.8\%$ and $\frac{1.41-1.01}{1.01} = 39.6\%$ for our developed buffer-aided hybrid BNC and the benchmark protocol respectively. The main reason for this significant gain is that, a higher buffer size can improve the nonempty probability of the two relay queues, which results in a higher probability of network coding and higher average throughput.

If we ignore the signaling overhead, the transmission duration of the developed mixed one-way and two-way relay protocol can be saved by (0.6747-0.4118)/0.4118=63.8% as the buffer size grows from 1 (number of packets) to 30 (number of packets), whereas the duration of the benchmark protocol remains steady. It is attributable to that, the ideal transmission of the benchmark can optimally allocate the channel resources according to the global network information, e.g., the CSI and the real-time buffer queue length. This dynamical arrangement requires a heavy load of scheduling messages, and the radio resource can be utilized maximally when the signaling overhead is not taken into account, thus the growth of the buffer size has no impact on the transmission capability.

The statistics lead us to the conclusion that, the benchmark protocol can forward the packets more efficiently without the consideration of signaling overhead; On the contrary, the developed buffer-aided hybrid BNC protocol consume less time if the practical signaling overhead is considered (with a time gain of (1.019-0.6791)/0.6791=50%). This demonstrates that the developed buffer-aided hybrid BNC protocol is more suitable for the practical relay network, and the current researches on the two-way XOR relay are no more applicable if the signaling overhead is considered. Specifically, the signaling overhead has different degree of influence on the transmission efficiency according to the protocol design and the payload size.

Fig. 7 plots the throughput of the two schemes under asymmetric links, where the relay buffer size is $L = K = 5$ (number of packets). The distance between S_1 and S_2 is 50 m and the relay node moves between the two users. Due to fixed transmission power (300mW), we change the location of R, e.g., R moves from S_2 to S_1. Denote the distance between R and user S_2 as the x-axis, we can see that our analytic results precisely match the simulations, which proves that the proposed model is also suitable for the BNC system under the imbalanced links.

Fig. 7 also demonstrates that the developed buffer-aided hybrid BNC outperforms the benchmark when the signaling overhead is considered, and the gap declines if the links are more asymmetric. We can also see that, the throughput

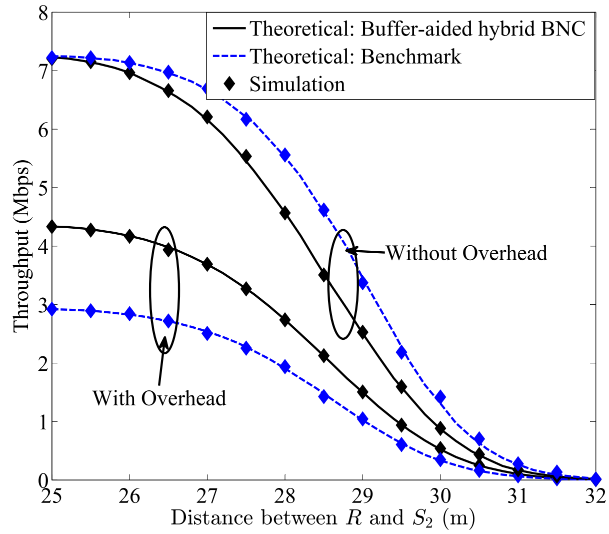


FIGURE 7. Throughput vs the growth of the distance from relay to S_2, where the distance between the two users is 50m, and relay moves from user S_2 to S_1.

of the developed buffer-aided hybrid BNC decreases even faster compared to the benchmark if signaling overhead is considered. This is because the scheduling messages enable the system to dynamically allocate the time, power and other resources, and there is no such scheduling in the developed buffer-aided hybrid BNC scheme.

The EE performance with growing relay buffer size is displayed in Fig. 8. Here we use criteria Mbit/Joule, and the payload is 2000bits, the distances from R to S_1 and S_2 are 30 m, respectively. As can be seen from this figure, theoretical results closely match the simulation results, which proves that our proposed analytical model framework can precisely predict the energy consumption of the NC relay system with and without scheduling, and the signaling overhead can also be captured accurately.

Without the calculation of signaling overhead, Fig. 8 also demonstrates that the developed buffer-aided Hybrid BNC scheme has better EE performance than the benchmark while transmitting the same amount of payload. We can also observe that increasing the buffer size can reduce the gap between two curves, and the merits of benchmark will be decreased from (8.412-4.94)/4.94 = 70.3% to (8.474-8.094)/8.094 = 4.6%). It means that, the buffer resource can cover up the energy shortage of the developed buffer-aided hybrid BNC even if the signaling overhead is not taken into account.

From the aforementioned discussions, we can see that EE performance of our developed buffer-aided hybrid BNC outperforms the benchmark. This advantage gradually increases with the increase of the buffer size. For instance, the energy gain varies from (3.073-2.368)/2.368 = 29.8% to (4.908-3.29)/3.29 = 49.2% as the buffer size increases from 2 packets to 30 packets. The advantage on the EE performance shows that the best-effort buffer-aided hybrid BNC can save 29.2%−49.2% energy compared to the benchmark.

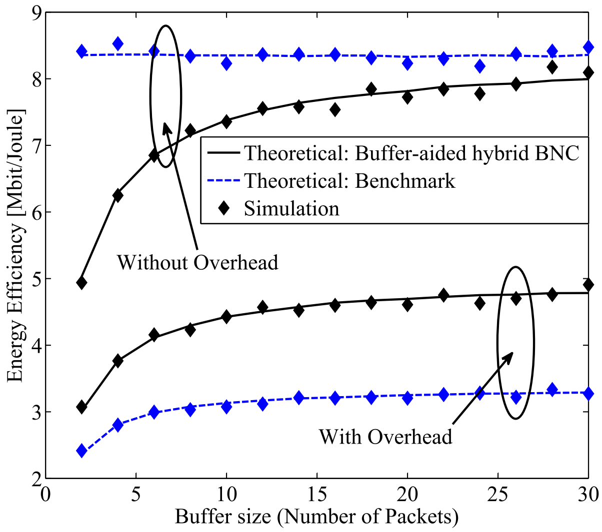


FIGURE 8. EE performance vs the growth of relay buffer size, where the relay queue size $L = K$, the distance between the relay and users is 30m, and the payload is 2000bits.

We can see that, increasing the relay buffer size can reduce the energy consumption for both transmission methods, see Fig. 8. For example, with the signaling overhead, unit energy can support 3.073 Mbits data when the buffer size is 2 (number of packets), whereas the same energy can satisfy the transmission of 4.908 Mbits when the buffer size is 30 (number of packets). It indicates that we can trade the relay buffer resource for the EE, and the effect is remarkable when the buffer size is small and then becomes ignorable when the buffer size is sufficient.

Additionally, we can also find an interesting result: the growth rate of the best-effort buffer-aided hybrid BNC is more significantly than that of the benchmark curve, which illustrates that the scheduling operation can reduce the dependence on the buffer size, i.e., the function of increasing the buffer resource can be alternately realized by proper scheduling design. The reason for this is that the scheduling controller can force the buffer queue to discharge the stored data according to the traffic load, real-time CSI and the available buffer resource, whereas the best-effort buffer-aided hybrid BNC has no such mechanism for the purpose of reducing signaling overhead.

VII. CONCLUSION

In this paper, we developed a practical buffer-aided hybrid BNC protocol for the 5GB-IoT with unreliable transmission and finite relay buffer size. Considering the signaling overhead, we propose an analytic Markov model framework to characterize the practical mixed bidirectional protocol, and the concise closed-form expressions of the throughput, overflow probability and queuing delay were derived. Monte-Carlo simulation demonstrated the validness of our analytic model, and revealed that the throughput of the developed buffer-aided hybrid BNC protocol increases by 50% if the signaling overhead was considered. Simulation results also revealed that our buffer-aided hybrid BNC outperforms the existing buffer-aided benchmark in terms of the EE performance, and the merit is even better with increased buffer size.

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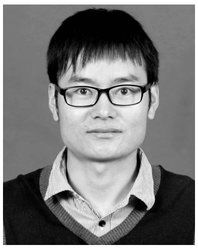

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