Almost as Good as Single-hop Full-Duplex: Bidirectional End-To-End Known Interference Cancellation

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***Abstract*—There is growing interest in new physical-layer transmission methods based on known-interference cancellation (KIC). These KIC-based methods share the common idea that the interference can be cancelled when the bit-sequence of it is known, which can improve the efficiency of wireless data communications. Existing work on KIC mainly focuses on single-hop or two-hop networks, with physical-layer network coding (PNC) and full-duplex (FD) communications as typical examples. This paper extends the idea of KIC to multi-hop networks, and proposes a bidirectional end-to-end KIC (BE2E-KIC) transmission method for the scenario where two nodes intend to exchange packets through multiple intermediate nodes. With BE2E-KIC, the involved nodes can simultaneously transmit and receive on the same channel. We first discuss the procedure of BE2E-KIC and provide a theoretical analysis on its feasibility and effectiveness. Then, we propose a medium access control (MAC) scheme that supports BE2E-KIC, which schedules packet transmissions in more realistic cases with the presence of packet-loss. Simulation results illustrate that BE2E-KIC can improve the network throughput and reduce the end-to-end delay compared with other existing transmission methods.**

***Index Terms*—Full duplex (FD), known-interference cancellation (KIC), medium access control (MAC), physical-layer network coding (PNC), wireless networks.**

I. INTRODUCTION

Known-interference cancellation (KIC) based technologies have recently attracted much attention because they can increase the throughput of wireless multi-hop networks [1]–[6]. KIC utilizes the fact that each node in the network knows the bit sequences of packets that were either sent by itself or were received from other nodes previously. The interference caused by subsequent (repetitive) transmissions of known packets can be effectively cancelled by using interference cancellation techniques [4]–[6]. As a result, more concurrent transmissions become possible, which brings benefits in terms of increasing the network throughput and reducing the packet queuing delay.

Typical examples of KIC include physical-layer network coding (PNC) and full-duplex (FD) communications, which mainly focus on limited hops (particularly, one or two hops) [4]–[6]. This paper considers KIC in *multi-hop* cases and proposes a new type of KIC-based transmission method, namely *bidirectional end-to-end KIC (BE2E-KIC)*, which combines and extends the idea of both PNC and FD.

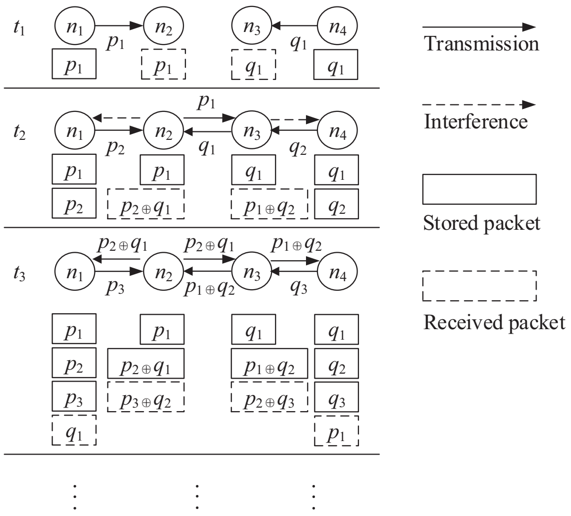

Fig. 1. Four-node chain topology with BE2E-KIC. Packets are sent from n_1 to n_4 and also from n_4 to n_1. Variables t, n, p and q respectively denote the timeslots, nodes, packets from n_1 to n_4, and packets from n_4 to n_1.

Fig. 1 shows the core idea of BE2E-KIC, where the end nodes n_1 and n_4 exchange packets through intermediate nodes n_2 and n_3. To illustrate, we consider the receptions and transmissions of node n_2 in timeslots t_2 and t_3 as an example. In timeslot t_2, node n_2 receives a superposed signal that is the sum of three independent signals respectively from n_1, n_2 (itself), and n_3. These three signals respectively carry packets p_2, p_1, and q_1. Because node n_2 knows its own transmission, it can cancel p_1 from the superposed signal by utilizing self-interference cancellation that is used in FD transceivers [6]. The remaining superposed signal contains two independent signals, which can be mapped into an encoded packet $p_2 \oplus q_1$ by using PNC techniques [7], [8]. Similarly, in timeslot t_3, node n_2 can map the superposed signal into an encoded packet $p_3 \oplus p_1 \oplus q_2$ after cancelling its own transmission. Because node n_2 also knows p_1, it can cancel p_1 from the encoded packet, so that the new encoded packet becomes $p_3 \oplus q_2$. The encoded

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packets obtained in each timeslot is sent out in the next slot. By applying the same procedure in the subsequent timeslots, we can find that the end nodes n_1 and n_4 can always decode one packet from the other end in each timeslot t_j ($j = 3, 4, ...$), by first cancelling out its own transmission and then cancelling out the known packet(s) from the encoded packet they receive. For instance, in timeslot t_3, node n_1 receives $p_2 \oplus q_1$ after cancelling its own transmission p_3. It can decode q_1 from $p_2 \oplus q_1$ because it knows p_2 which was sent in timeslot t_2.

We can infer that the throughput of BE2E-KIC can potentially be *arbitrarily close to that of single-hop full-duplex communications*, because each end node receives one packet in each timeslot t_j ($j = 3, 4, ...$). We will discuss the general case more rigorously in Section II. BE2E-KIC can be used in many practical scenarios where nodes are likely to be deployed in a line, such as multi-hop vehicle-to-vehicle communications [9].

One major issue arising with BE2E-KIC is to design a medium access control (MAC) scheme to coordinate the simultaneous transmissions of multiple nodes. Existing MAC schemes mainly focused on KIC with one or two hops [1], [10]–[12], which cannot be straightforwardly extended to support BE2E-KIC because there are more nodes participating in the packet exchange with BE2E-KIC. The main challenges in the design of the MAC scheme for BE2E-KIC are as follows:

1) Ensure that destination nodes can extract their intended packets. Because more packets are encoded together, it is more difficult for BE2E-KIC MAC to ensure decodability compared with existing KIC-supported MAC schemes.
2) Limit the number of native packets (i.e. non-encoded packets) to be encoded together. To identify the native packets, a longer header is required if more native packets are encoded into an encoded packet.
3) Limit the control overhead. To maintain the benefit of BE2E-KIC, the control overhead needs to be low.

We propose a MAC scheme to effectively support BE2E-KIC in this paper. In the proposed scheme, the involved nodes can identify the native packets contained in an encoded packet, and at the same time, limit the number of native packets that are encoded together, by using a simple and effective method. To resolve the impact of packet-losses, an acknowledgement (ACK) scheme is introduced in the proposed BE2E-KIC MAC. Multiple ACK frames are simultaneously sent if they do not interfere each other or if the interference can be cancelled through KIC. The core idea of the proposed MAC scheme is to encourage concurrent transmission.

The main contributions of this paper are summarized as follows:

1) We propose the BE2E-KIC mechanism, which supports KIC in multi-hop networks. We show that BE2E-KIC has the potential to approach the performance of single-hop full-duplex communications.
2) We propose a MAC scheme for BE2E-KIC, which can coordinate multiple nodes to access the channel with low overhead.
3) Simulations are performed to evaluate the performance of the proposed approach.

The remainder of this paper is organized as follows. Section II discusses the basic principles of BE2E-KIC. Section III introduces the BE2E-KIC MAC scheme. The simulation results are shown in Section IV. Section V draws conclusions and outlines the future work.

II. PRINCIPLES OF BE2E-KIC

In this section, we discuss the fundamental principles of BE2E-KIC. We consider N nodes that are sequentially placed on a line, where the end nodes n_1 and n_N always have packets to exchange (i.e. their transmit queues are backlogged[1]). We consider the case where only adjacent nodes are within the transmission range of each other, and assume that the two-hop interference (i.e. the interference that node n_i causes to nodes n_{i+2} and n_{i-2}) is small enough so that it can be neglected. This is valid with appropriate topology control, routing, and transmission power control mechanisms. Detailed study on the interferences from non-adjacent nodes will be left for future work. We name the network topology with the above properties as a chain topology with N nodes. Ideal communication channels without packet-loss are considered in this section, and we consider more realistic cases with the presence of packet-loss in Section III.

A. Packet Transmission Procedure

The packet transmission procedure of BE2E-KIC is as illustrated in Fig. 1. In each timeslot, the end nodes n_1 and n_N transmit a new packet, and the intermediate nodes $n_2, n_3, ..., n_{N-1}$ transmit the encoded packet obtained in the previous timeslot. After receiving a superposed signal, the end nodes decode the new packet from the superposed signal, and the intermediate nodes cancel out all the known packets from the superposed signal so that the remaining encoded packet contains a reasonably small number of native packets. The known packets at intermediate nodes can be either native or encoded.

B. Feasibility

In the following, we show that BE2E-KIC is feasible.

Proposition 1: Considering ideal communication channels without packet-loss, for a chain topology with N nodes, each end node (n_1 or n_N) can receive one new packet in each timeslot t_j ($j = N-1, N, N+1, N+2, ...$).

Proof: Due to symmetry, we only consider node n_N receiving packets from node n_1, and the reverse direction is analogous.

Suppose nodes n_1 and n_N respectively send out packets p_j and q_j in timeslot t_j, and p_1 and q_1 are the first packets being sent out. According to the packet transmission procedure of BE2E-KIC (see Section II-A), the content of p_j can only be

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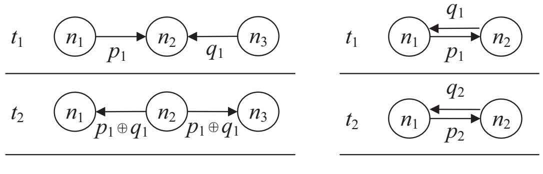
[1] Note that the analysis in this section can be easily extended to non-backlogged transmit queues, by regarding some packets as empty. We assume that the queues are backlogged only for simplicity.



(a) (b)

Fig. 2. Basic scenarios for existing KIC methods: (a) PNC, (b) FD. In both subfigures, the first node and the last node want to exchange packets. Variables t, n, p and q respectively denote timeslots, nodes, packets from the first node to the last node, and packets from the last node to the first node.

transmitted one hop towards n_N in each timeslot, and it can be carried by either a native packet or an encoded packet.

Initial packet: At timeslot t_{N-1}, node n_N receives an encoded packet which contains p_1 and a subset among packets $\{q_1, ..., q_{N-1}\}$. Because node n_N knows all the packets $q_1, ..., q_{N-1}$ which are sent by itself, it can obtain p_1 from the encoded packet it receives.

Subsequent packets: At timeslot t_{N+j-2}, where $j \in \{2, 3, ...\}$, node n_N receives an encoded packet which contains p_j and a subset among packets $\{p_1, ..., p_{j-1}\} \cup \{q_1, ..., q_{N+j-2}\}$. Because node n_N knows all the packets $q_1, ..., q_{N+j-2}$ (sent by itself) and $p_1, ..., p_{j-1}$ (received in previous timeslots), it can obtain p_j from the encoded packet it receives. ■

C. Achievable Throughput

1) BE2E-KIC: With BE2E-KIC, the two source nodes n_1 and n_N transmit the same number of packets. We need $N - 1$ timeslots to finish the end-to-end transmission of the first packets p_1 and q_1. In each subsequent timeslot, one packet is received by a destination node as discussed earlier. Therefore, the packets p_j and q_j $(j > 1)$ arrive at their destination nodes in the $(N + j - 2)$th timeslot. To transmit a total of $2M$ packets to the destination nodes n_N and n_1, BE2E-KIC needs $N + M - 2$ timeslots. Therefore, the achievable throughput of BE2E-KIC in the chain topology with N nodes is

$$R_{\text{BE2E-KIC}} = \frac{2M}{N + M - 2} \,. \tag{1}$$

2) PNC and FD: We compare the achievable throughput of BE2E-KIC with two typical existing KIC methods, namely PNC and FD. The basic scenarios of PNC and FD are shown in Fig. 2, where the first node and the last node want to exchange packets. Fig. 2(a) shows the procedure of PNC. In timeslot t_1, nodes n_1 and n_3 simultaneously transmit their signals, which results in a superposed signal at n_2. In timeslot t_2, node n_2 maps the superposed signal into an encoded packet and broadcasts the encoded packet to n_1 and n_3. By using cached packets, the destination nodes can exact their wanted packets from the encoded packet. Fig. 2(b) depicts the FD method, where nodes operate in the full-duplex mode. In each timeslot, two nodes can simultaneously exchange their packets through self-interference cancellation [6]. More existing KIC methods with one or two hops can be found in [2].

From Fig. 2, the achievable throughputs of PNC with two hops and FD with one hop can be easily derived. For PNC with two hops, two packets are received by their destinations every *two* timeslots. In other words, the achievable throughput of PNC with two hops is

$$R_{\text{PNC}}^{\text{two-hop}} = 1 \,. \tag{2}$$

Similarly, the achievable throughput of FD with one hop is

$$R_{\text{FD}}^{\text{one-hop}} = 2 \,, \tag{3}$$

because with FD, two packets are forwarded to their destinations in *each* timeslot.

It is obvious that using PNC or FD in a multi-hop scenario cannot bring higher throughput than in the two-hop scenario (for PNC) or one-hop scenario (for FD). Reference [4] discussed how to optimally schedule PNC transmissions in a relay network with more than two hops, while optimally scheduling FD transmissions in multi-hop cases has not been explicitly studied in the literature.

3) Performance Comparison: According to (1), when $M \to \infty$, we have $R_{\text{BE2E-KIC}}^{M\to\infty} \triangleq \lim_{M\to\infty} R_{\text{BE2E-KIC}} = 2$. It follows that

$$R_{\text{BE2E-KIC}}^{M\to\infty} : R_{\text{FD}}^{\text{one-hop}} : R_{\text{PNC}}^{\text{two-hop}} = 2 : 2 : 1 \,, \tag{4}$$

$$R_{\text{BE2E-KIC}}^{M\to\infty} = R_{\text{FD}}^{\text{one-hop}} \,. \tag{5}$$

From (4) and (5), we can conclude that BE2E-KIC has the potential to enable wireless multi-hop networks to approach the single-hop full-duplex throughput performance.

III. MAC SCHEME FOR BE2E-KIC

In this section, we illustrate the design of the MAC scheme for BE2E-KIC. The proposed scheme has two main stages: 1) packet exchange stage; 2) ACK stage. In the first stage, the involved nodes simultaneously transmit their packets and cancel the known interferences to receive their intended signals. In the second stage, multiple pairs of ACK frames are simultaneously transmitted to acknowledge the successful receptions of data packets. The above process is repeated as long as there are packets to send. We consider a centralized MAC scheme in this paper, and the design of a distributed MAC scheme will be left for future work. Centralized MAC schemes can be applicable for scenarios where there exists a marcocell base-station serving as a control plane for all nodes under its coverage, which is a possible scenario for future 5th-generation (5G) networks.

The standard timing of BE2E-KIC is shown in Fig. 3, where there exists a chain topology with N nodes. Data flows from n_1 to n_N and from n_N to n_1 are configured. The formats of the frames in BE2E-KIC MAC are presented in Fig. 4. We define T_{SIFS} as the short inter-frame space (SIFS) as in the IEEE 802.11 standard [13]. Let $T_{\text{PHY-Hd}}$, $T_{\text{MAC-Hd}}$, and T_{DATA} respectively denote the time-length of the physical-layer header, MAC-layer header, and data part of the data frame, and we use T_{ACK} to denote the time-length of the ACK frame. To simplify the design of the proposed scheme, we assume that data frames have the same length, which can always be satisfied by fragmenting over-sized frames and zero-padding shorter frames. Each node n_i maintains a queue $\mathbf{S}_i$ to

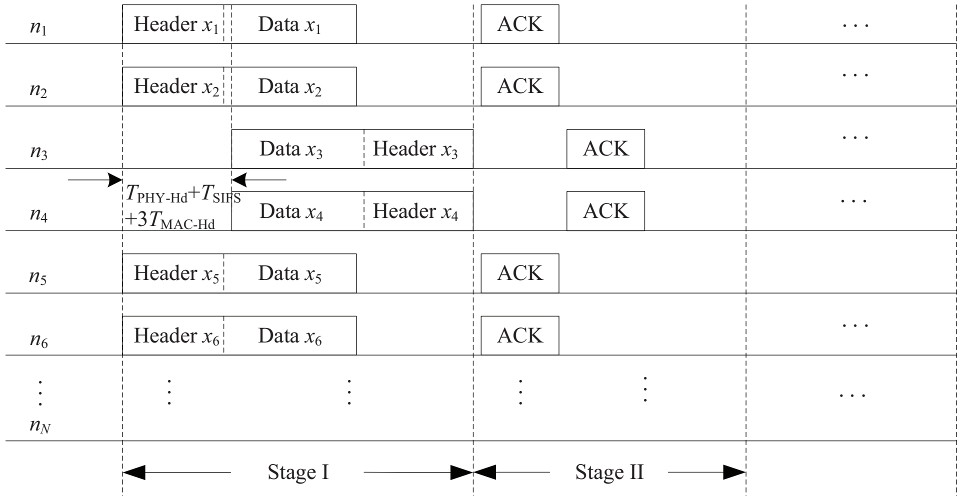


Fig. 3. Standard timing diagram of frame exchange in BE2E-KIC MAC.

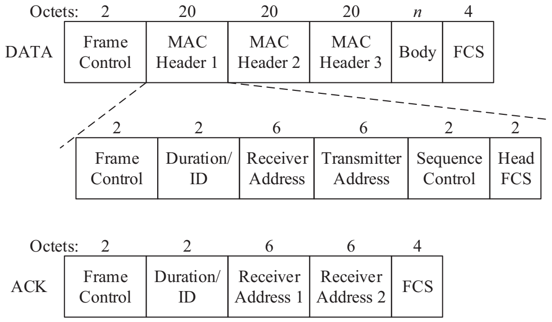


Fig. 4. Frame formats of BE2E-KIC MAC.

store the known packets that have been either sent or received previously.

A. Timing of BE2E-KIC MAC Scheme

In this subsection, the details of the two stages in the timing of BE2E-KIC MAC are described.

Stage I is the data exchange stage, which is designed to make sure that destination nodes can extract their wanted messages from encoded packets with low overhead. As shown in Fig. 3, in Stage I, the data bits are transmitted either in normal sequence or in adverse sequence (i.e. the tail of the data frame is sent first), and the sequence alternates every two nodes. The transmission sequence of node n_i can be determined by

$$\beta_i \triangleq \mathrm{mod}_2(((2i+1-\mathrm{sign}(\mathrm{mod}_2(i+1)-0.5))/4)), \quad (6)$$

where $\mathrm{mod}_2(\cdot)$ is the modulo 2 function and $\mathrm{sign}(\cdot)$ is the sign function. The value $\beta_i = 1$ means that node n_i transmits packets in normal bit sequence, and $\beta_i = 0$ indicates that the data packets sent by n_i are in adverse bit sequence and a delay of $T_{\text{PHY-Hd}} + T_{\text{SIFS}} + 3T_{\text{MAC-Hd}}$ is added at the beginning of Stage I. The delay ensures that only the data parts of the two frames from n_{i-1} and n_{i+1} are superposed at node n_i. Because the interference caused by self-transmission can be cancelled, the headers of the two partly superposed frames can be decoded, which can be used to identify the native packets contained in the superposed signal.

After receiving a superposed signal that represents an encoded packet, by using the known packets in queue $\mathbf{S}_i$, each intermediate node attempts to reduce the number of native packets in the encoded packet, and each destination node attempts to decode the wanted packet from the encoded packet. We propose a cancellation algorithm to perform the cancellation/decoding in Section III-B. Each node stores the remaining packet after cancellation (which can be either an encoded or a native packet) in its queue $\mathbf{S}_i$.

Stage II is the ACK exchange stage. Node n_i sends an ACK frame if it has successfully received an encoded or native packet. Considering that n_i may receive an encoded packet that is obtained from a superposed signal from n_{i-1} and n_{i+1}, the ACK frame can have two receiver addresses. Because nodes are in full-duplex mode, two adjacent nodes can simultaneously transmit ACK frames because interferences can be cancelled with self-interference cancellation. Furthermore, nodes that are two or more hops away can also simultaneously send their ACK frames because their interferences are weak enough to be ignored. Such a way of simultaneously exchanging ACK frames consumes less time compared with a sequential ACK scheme.

Stages I and II are repeated to transmit new native packets from source nodes and to forward the packets received in the previous round at intermediate nodes. An intermediate node does not send packets in a packet exchange round if it has not received any packet in the previous round.

B. Cancellation/Decoding Algorithm

In this subsection, we propose an algorithm to cancel the known packets from the superposed signal, so that the remaining packet is either the native packet that the node wants to receive or an encoded packet that contains a limited number of native packets.

With BE2E-KIC, it is possible for a node to receive a superposed signal that contains multiple native packets. However, the data frame (as shown in Fig. 4) only includes three MAC header fields which are used to identify the native packet(s)

Algorithm 1 Cancellation algorithm for BE2E-KIC with XOR encoding

Input: Node index i, packet x obtained directly from the received superposed signal after XOR operation

Output: New packet to store in $\mathbf{S}_i$ and to transmit in next timeslot if $1 < i < N$

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for all packets $s$ in queue $\mathbf{S}_i$ do
    if two or all native packets contained in $s$ are contained in $x$ then
        $x \leftarrow x \oplus s$
        restart loop
    end if
end for
return $x$
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that is/are contained in the data packet, where the data packet can be either a native or an encoded packet. Because the number of MAC header fields is limited, we need to limit the number of native packets in an encoded packet, so that the packet can be transmitted under the predefined frame format. In the following, we propose a cancellation algorithm which attempts to achieve this goal.

The cancellation/decoding algorithm is shown in Algorithm 1, where we consider the use of XOR encoding method. After receiving a superposed signal that contains encoded packet x, node n_i checks through all the packets stored in its queue $\mathbf{S}_i$, and a particular packet is denoted by $s \in \mathbf{S}_i$. Let $|x|$ and $|s|$ respectively denote the number of native packets contained in x and s. We always have $|s| \leq 3$, because packets containing more than three native packets will be discarded by the node (as will be discussed in Section III-C). An XOR operation $x \oplus s$ is performed if 1) $|s| = 1$ and s is also contained in x, or 2) $|s| = 2$ or $|s| = 3$ and two of the native packets in s are also contained in x. In Case 1, we have $|x \oplus s| = |x| - 1$. In Case 2, we have $|x \oplus s| \leq |x| - 1$, because two native packets are cancelled from x and at most one new native packet is introduced. It follows that Algorithm 1 attempts to reduce the number of native packets in x. Because a new packet may be introduced when performing $x \oplus s$, we restart the for-loop whenever x is changed. When each source node sends M packets in total, the complexity of the algorithm is $O(M + N)$, because $\mathbf{S}_i$ can contain at most $M + N - 2$ packets (see Section II-C1) and $|x| \leq 6$ in all cases. The fact that $|x| \leq 6$ is because an encoded packet that is being transmitted can contain at most three native packets, and at most two packets are superposed at a node (after cancelling out the self-interference).

C. Exception Handling

In this subsection, we discuss how to handle exceptional cases such as frame loss, no data to send, etc.

1) Number of native packets in an encoded packet after cancellation is bigger than 3: A node discards an encoded packet x if $|x| > 3$ after performing Algorithm 1, and it does not send any packet in the next timeslot.

2) No Data to Send: If a node has no packet to send, it keeps silent (does not transmit packets) during Stage I. However, it transmits ACK in Stage II if it has correctly received a packet.

3) Data Packet Error or Cannot Be Decoded: If a node receives an erroneous packet or a destination node cannot decode the received packet based on the packets in $\mathbf{S}_i$, it does not send ACK and waits for the end of the current packet exchange process.

4) ACK Loss: When a node does not receive the corresponding ACK frame after sending a packet, it will retransmit the data packet in the next packet exchange round unless the number of retransmission attempts exceeds its limit.

IV. SIMULATION RESULTS

The performance of BE2E-KIC is evaluated with a discrete-event network simulator developed jointly with MATLAB and C [11, Appendix A]. In the physical layer, we use the IEEE 802.11 direct-sequence spread spectrum (DSSS) with 1 MHz baseband bandwidth and differential binary phase-shift keying (DBPSK) modulation. The transmission power is set to 0 dBm (1 mW). The channel power gain is $1/D_{i,j}^4$, where $D_{i,j}$ is the distance between nodes n_i and n_j in meters. The background noise density is -174 dBm/Hz with 6 dB noise figure. The receiver's clear channel assessment (CCA) sensitivity is set to -106 dBm. With these settings, a node can *receive* a signal from the distance of approximately 200 m, and *sense* signal transmissions from approximately 450 m. User Datagram Protocol (UDP) packets with 1000 bytes packet size are sent by the end nodes in a chain topology.

The performance of BE2E-KIC is compared with PNC and FD, and also with the conventional store-and-forward routing method. The MAC protocols for PNC and FD are respectively the PNC-MAC protocol in [11] and the efficient-and-fair FD (EF-FD) MAC protocol in [12]. The store-and-forward routing uses the IEEE 802.11 MAC [13]. We also compare with the throughputs of two-hop PNC and one-hop FD, where a centralized MAC scheme with ACK exchange is used, and the links are configured with zero packet-loss. We study the performance under different number of nodes in the chain topology. The distance between two adjacent nodes is 200 m, and the first and last nodes intend to exchange packets. The packet rate is fixed at 100 packets/s. To evaluate overall performance, each simulation is run for 50 s with 10 different random seeds.

Fig. 5 shows the throughput under different number of nodes. When the number of node N is between 4 and 6, BE2E-KIC achieves 90% of the throughput provided by FD with one hop. When $N \in \{8, 9\}$, BE2E-KIC can approach 92% of the throughput provided by two-hop PNC. Even when $N = 12$, BE2E-KIC can reach 70% of the throughput provided by two-hop PNC. Compared with the existing KIC schemes and the store-and-forward scheme (IEEE 802.11), the BE2E-KIC scheme has the best performance. The average throughput gain of BE2E-KIC over EF-FD is 6.3. When the number of nodes increases, the throughput of BE2E-KIC decreases. The reason

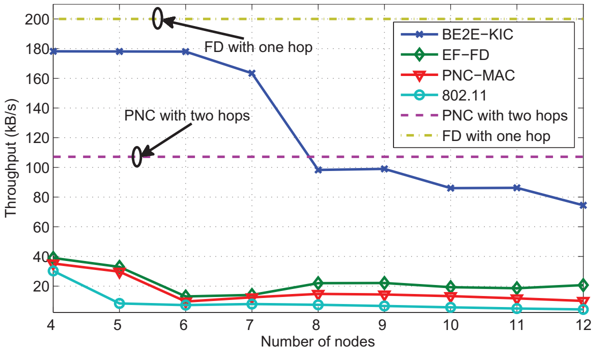

Fig. 5. Throughput under different number of nodes.

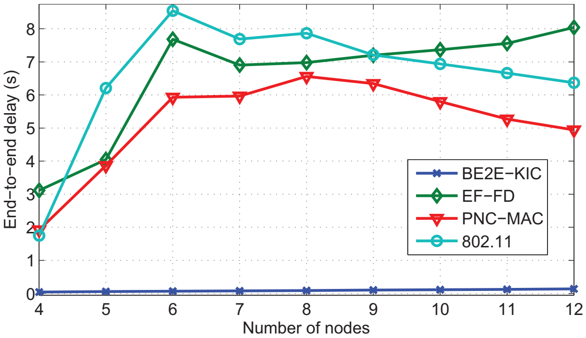

Fig. 6. End-to-end delay under different number of nodes.

is that when $N > 6$, it is more likely that an encoded packet contains more than 3 native packets, which leads to a large number of discarded packets. When $N < 6$, the throughputs of EF-FD, PNC-MAC, and IEEE 802.11 decrease with the number of nodes. After that, when further increasing the number of nodes, their throughputs may slightly increase due to more opportunities of spatial reuse in large-scale wireless networks.

Fig. 6 shows the end-to-end delays under different number of nodes, where the delays of packets that have been successfully received by the destination nodes are considered. The delay is calculated from the time when the packet leaves the source node until the time when the packet arrives at the destination node. We can observe that the delay of BE2E-KIC is lowest, because more nodes concurrently transmit and the MAC scheme reduces the ACK exchange time. It is also because nodes are coordinated to access the channel with BE2E-KIC MAC. We can also observe that the delay of EF-FD is higher than that of PNC-MAC, and it increases with the number of nodes when $N > 7$. The reason is that PNC-MAC has a mechanism to avoid unnecessary channel contention, while EF-FD does not have such mechanism. It is necessary to note that the delay of BE2E-KIC increases with the increasing of the number of nodes, instead of staying constant. It is because the main delay of BE2E-KIC is the transmission delay, which is proportional to the number of nodes.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we have proposed BE2E-KIC for a chain topology with a bidirectional data flow between end nodes. The idea is that known information can be cancelled from the superposed signal, and new packets can be decoded at the end nodes. We have also proposed a MAC scheme that supports BE2E-KIC. The proposed scheme can simultaneously exchange multiple packets belonging to a bidirectional data flow with low overhead. Besides, BE2E-KIC MAC allows simultaneous transmissions of ACK frames, so that the ACK overhead remains low. Both theoretical analysis and simulations show that BE2E-KIC (together with its MAC scheme) can improve the efficiency of wireless multi-hop networks.

This paper is an initial step toward KIC in multi-hop wireless networks. In the future, more general network structures and the applicability of KIC in those cases can be considered. More detailed signal-level analysis with the consideration of interferences from nodes that are two or more hops away can be studied. It will also be interesting to see whether there is an upper bound on the number of native packets to be contained in an encoded packet, and whether there is a provably optimal way to perform packet cancellation and decoding. The MAC scheme proposed in this paper can also be extended to a fully distributed scheme by using similar ideas as in [11].

ACKNOWLEDGMENT

This work was supported in part by the Program for the National Natural Science Foundation of China (61471109, 61302071, 61302072, 91438110), the Fundamental Research Funds for the Central Universities (N140405005, N120804002, N130817002), and the Liaoning BaiQianWan Talents Program.

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