End-to-End Known-Interference Cancellation (E2E-KIC) with Multi-Hop Interference

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Abstract—Recently, end-to-end known-interference cancellation (E2E-KIC) has been proposed as a promising technique for wireless networks. It sequentially cancels out the known interferences at each node so that wireless multi-hop transmission can achieve a similar throughput as single-hop transmission. Existing work on E2E-KIC assumed that the interference of a transmitter to those nodes outside the transmitter’s communication range is negligible. In practice, however, this assumption is not always valid. There are many cases where a transmitter causes notable interference to nodes beyond its communication distance. From a wireless networking perspective, such interference is caused by a node to other nodes that are multiple hops away, thus we call it multi-hop interference. The presence of multi-hop interference poses fundamental challenges to E2E-KIC, where known procedures cannot be directly applied. In this paper, we propose an E2E-KIC approach which allows the existence of multi-hop interference. In particular, we present a method that iteratively cancels unknown interferences transmitted across multiple hops. We analyze mathematically why and when this approach works and the performance of it. The analysis is further supported by numerical results.

Index Terms—Communications, end-to-end known-interference cancellation (E2E-KIC), multi-hop transmission, wireless ad hoc networks

I. INTRODUCTION

Wireless multi-hop networks have attracted extensive interest due to its flexibility of deployment and adaptability to changing network topologies. These features are particularly useful for many emerging applications today, such as vehicular networking. One big problem in multi-hop networks is its performance degradation compared to single-hop networks. This is illustrated in Fig. 1(a), where node 1 can only transmit one packet every three timeslots, due to the half-duplex nature of conventional radio transceivers and to avoid collision of adjacent packets. Obviously, if the transmission between the source and destination nodes are carried out in a single hop, node 1 can transmit one packet per timeslot to node 4. It turns out that in this simple example, multi-hop transmission brings only one third of the throughput of single-hop transmission. A natural question is: Can we close this gap?

Efforts have been made to improve the performance of multi-hop networks with advanced physical-layer techniques.

1In a large network, there may exist other transmitting nodes for which collision needs to be avoided, but we ignore that case here for simplicity. We also ignore packet losses, congestion, etc.

2We refer to bidirectional data flows as two separate unidirectional data flows in this paper.

![Figure 1. Procedure of conventional multi-hop communication (a) and E2E-KIC (b), where node 1 sends packets to node 4 via nodes 2 and 3.](image-url)
by equipping nodes with FD transceivers [6]; bidirectional E2E-KIC supporting two opposite flows can be achieved by leveraging both PNC and FD techniques [7]. It was shown that both unidirectional and bidirectional E2E-KIC can achieve a throughput of 1 packet/(slot · flow) when ignoring a few idle timeslots caused by propagation delay. This implies that the throughput of E2E-KIC is (almost) the same as the single-hop counterparts.

The basic concept of E2E-KIC is shown in Fig. [1b]. The source node 1 starts the transmission by sending out its first packet \( x(1) \) to node 2 in slot 1. Then, in slot 2, node 1 sends its second packet \( x(2) \) and node 2 relays the first packet \( x(1) \) to node 3. Node 2 can receive \( x(2) \) while transmitting \( x(1) \) due to its FD capability. In slot 3, node 1 sends \( x(3) \), node 2 sends \( x(2) \), and node 3 sends \( x(1) \). Now, node 2 can receive \( x(3) \) because it can cancel out \( x(2) \) transmitted by itself as well as \( x(1) \) transmitted by node 3. It can cancel out \( x(1) \) because it has received \( x(1) \) before and knows its contents. Node 3 can receive \( x(2) \) due to its FD capability. Slot 4 and all remaining slots are then analogous. With this approach, node 1 is able to transmit one packet per slot, and node 4 is able to correctly receive one packet per slot starting from slot 3.

In this example as well as existing work [6, 7], multi-hop interference has not been considered, i.e., it has been assumed that the signal transmitted by node 1 is negligible at node 3, for instance. If this is not the case, the existing E2E-KIC scheme becomes inapplicable. Consider slot 2 in Fig. [1b] as an example, if the signal transmitted by node 1 causes strong interference at node 3, node 3 may not be able to correctly receive \( x(1) \) from node 2. Unfortunately, such non-negligible multi-hop interference widely exist in practical scenarios. It is quite possible that two nodes are not close enough to correctly receive the transmitted data, but also not far away enough to ignore the transmitter’s interference signal [8]. Therefore, we need to investigate whether and how E2E-KIC works in scenarios with multi-hop interference. In this paper, we propose an E2E-KIC scheme that is feasible for such scenarios.

II. System Model

Similar to related work [5, 6, 7], we focus on a chain topology with \( N \) nodes. We note that these nodes can be part of a larger network with arbitrary topology, and the chain sub-network can be obtained via MAC protocols that support E2E-KIC [6]. Nodes in the chain topology are sequentially indexed with \( 1, 2, ..., N \), where node 1 is the source node, node \( N \) is the destination node. We use \( t \) to denote the timeslot index starting at 1, and use \( x(t) \) to denote the signal (containing data packet) that the source node (indexed 1) sends out in timeslot \( t \). Let \( h_{ji} \) denote the channel coefficient from node \( j \) to node \( i \). We consider frequency-flat, slow-varying channels in this paper, so that \( h_{ji} \) does not vary over our time of interest.

1We only focus on unidirectional E2E-KIC in this paper, and refer to it as E2E-KIC.

We use \( x(t) \) to denote both the data packet and its corresponding signal in this paper.

We also assume that \( h_{ji} \) is known a priori, while anticipating that techniques similar to blind KIC [1] or correlation-based approaches [9] may be applied for cases with unknown \( h_{ji} \).

We assume that when a node receives a superposed signal, it can successfully cancel out all its known signals. For example (see Fig. [2], when \( N = 7 \), node 4 knows the signals sent by nodes 5 and 6 because they were previously relayed by node 4. Thus, node 4 can cancel out the signals transmitted by nodes 5 and 6 as well as its own transmitted signal (due to FD capability). Node 4 intends to receive the signal sent by node 3, while nodes 1 and 2 are potential multi-hop interferers transmitting unknown signals for node 4.

For an arbitrary node \( i \) (node 4 in the above example), after cancelling out all known signals from nodes \( i \) (itself), \( i + 1, ..., N \), the remaining received signal in slot \( t \) is

\[
y_i(t) = \sum_{j=1}^{i-1} h_{ji} \cdot x(t_j) + z_i(t),
\]

where \( x(t_{i-1}) \) is the packet that node \( i \) intends to receive (which is sent by node \( i - 1 \)), \( \sum_{j=i-2}^{i-1} h_{ji} \cdot x(t_j) \) is the sum of unknown interference signals sent by nodes \( i, i-2, ..., i-1 \), and \( z_i(t) \) is the noise signal with power \( \sigma^2 \). Residual interference caused by imperfect KIC can be considered as part of the noise, and we do not specifically study it in this paper. We use \( P_T \) to denote the transmission power so that \( E[|x(t)|^2] = P_T \).

The variables \( t_j \) in (1) stand for the slot index when the packet has been sent out by node 1 for the first time (see definition of \( x(t) \) earlier). We always have \( t = t_1 > t_2 > ... > t_{i-2} > t_{i-1} \) due to the packet relaying sequence. The specific values of \( t_j \) are related to the interference strength. For single-hop interference (see Fig. [1b]), we always have \( t_j - t_{j-1} = 1 \). For multi-hop interference, it is possible that \( t_j - t_{j-1} > 1 \) (see next section), which means that we may need to wait for more than one slot before we can cancel out all interferences and successfully decode the packet. We define \( \Delta_j = t - t_j \) to denote the total delay incurred for transmitting the packet from node 1 to node \( j \).

For simplicity, we assume that packets can always be correctly received if the signal-to-interference-plus-noise ratio (SINR) is larger than a threshold \( \gamma \). In practice, this can be achieved by a properly designed error-correcting code. For the convenience of analysis later in this paper, we assume \( \gamma \geq 1 \).

III. Interference Cancellation Scheme

We focus on how to cancel\(^3\) the unknown multi-hop interferences, i.e., the \( \sum_{j=1}^{i-1} h_{ji} \cdot x(t_j) \) terms in (1). Cancellation

\(^3\)Strictly speaking, instead of cancelling, we aim to reduce the strength of unknown interferences to a satisfactory level so that the packet can be correctly decoded. For simplicity, we use the term “cancel” in this paper.
of known interferences is analogous with existing KIC work, so we do not consider it here.

A. Constructive Example

We first illustrate the interference cancellation procedure using a constructive example with $N = 5$, as shown in Fig. 3. Same as in the existing E2E-KIC approach, node 1 transmits one packet $x(t)$ in every slot $t \in \{1, 2, \ldots \}$. Because there is no unknown multi-hop interference at the receiver of node 2, according to $[1]$, the signal that node 2 receives in slot $t \geq 1$ (after cancelling any known interferences) is

$$y_2(t) = h_{12}x(t) + z_2(t),$$

from which it can successfully decode packet $x(t)$.

Node 2 sends out its received packet in the next slot, so that the received signal at node 3 in slot $t \geq 2$ is

$$y_3(t) = h_{13}x(t) + h_{23}x(t - 1) + z_3(t),$$

where $h_{23}x(t - 1)$ carries the packet that node 3 intends to receive, and $h_{13}x(t)$ is the interference signal.

Upon receiving $y_3(t)$, node 3 checks whether it can correctly decode the packet. If not, it assumes that this is due to the unknown multi-hop interference caused by node 1, in which case it waits for signals received in additional slots. In slot $t + 1$, node 3 receives

$$y_3(t + 1) = h_{13}x(t + 1) + h_{23}x(t) + z_3(t + 1),$$

which contains a strong signal $h_{23}x(t)$ and a weak signal $h_{13}x(t + 1)$.

Node 3 can use the strong signal in $y_3(t + 1)$ that contains $x(t)$ to eliminate the interference signal $h_{13}x(t)$ in $y_3(t)$.

4Obviously, if $h_{13}x(t)$ is strong enough, node 3 can receive the packet $x(t)$ sent by node 1 directly without needing node 2 as relay. However, we assume here that $h_{13}x(t)$ is not strong enough for correct reception, because otherwise the underlying routing mechanism will not choose node 2 as relay, but $h_{13}x(t)$ may cause a remarkable level of interference that affects the correct reception of $x(t - 1)$ from $h_{23}x(t - 1)$.

Explicitly, node 3 calculates the following:

$$g_{3,1}(t) = y_3(t) - \frac{h_{13}}{h_{23}}y_3(t + 1) = h_{23}x(t - 1) + z_3(t) - \frac{h_{13}}{h_{23}}(h_{13}x(t + 1) + z_3(t + 1)).$$

The resulting signal now contains the useful signal $h_{23}x(t - 1)$ and the interference-plus-noise signal $z_3(t) - \frac{h_{13}}{h_{23}}(h_{13}x(t + 1) + z_3(t + 1))$. We expect that the remaining interference-plus-noise signal in $g_{3,1}(t)$ is much smaller than $h_{13}x(t) + z_3(t)$ in $y_3(t)$, because $|h_{13}|^2 \ll |h_{23}|^2$ and the additional noise signal $z_3(t + 1)$ is usually much weaker than the data-carrying signal. A rigorous analysis on the remaining interference-plus-noise power will be given later in this paper.

If the remaining interference-plus-noise is still too strong, node 3 can wait for one more slot to receive

$$y_3(t + 2) = h_{13}x(t + 2) + h_{23}x(t + 1) + z_3(t + 2)$$

and perform another round of cancellation to cancel out the term involving $x(t + 1)$ in $y_3(t)$, yielding

$$g_{3,2}(t) = g_{3,1}(t) + \frac{h_{13}^2}{h_{23}^2}y_3(t + 2) = h_{23}x(t - 1) + z_3(t) - \frac{h_{13}}{h_{23}}z_3(t + 1) + \frac{h_{13}^2}{h_{23}^2}(h_{13}x(t + 2) + z_3(t + 2)).$$

Now, the remaining interference-plus-noise term is further smaller. Suppose node 3 can now decode $x(t - 1)$ from $g_{3,2}(t)$, it can then send out $x(t - 1)$ in the next slot $t + 3$, so that node 4 receives the following signal for $t \geq 5$:

$$y_4(t) = h_{14}x(t) + h_{24}x(t - 1) + h_{34}x(t - 4) + z_4(t).$$

Using the definition of $t_3$ and $\Delta_3$ in Section $[\ldots]$ we have $\Delta_3 = t - t_3 = 4$, because node 3 transmits packet $x(t - 4)$ in slot $t$. The operation is similar for node 4 and all remaining nodes. From $y_4(t)$, node 4 intends to receive $x(t - 4)$ transmitted by node 3, and has to cancel out the signals $h_{14}x(t)$ and $h_{24}x(t - 1)$ from nodes 1 and 2, respectively. Node 4 waits for four additional slots until it has received the following signals:

$$y_4(t + 3) = h_{14}x(t + 3) + h_{24}x(t + 2) + h_{34}x(t - 1) + z_4(t + 3)\quad y_4(t + 4) = h_{14}x(t + 4) + h_{24}x(t + 3) + h_{34}x(t) + z_4(t + 4).$$

It then computes

$$g_{4,1}(t) = y_4(t) - \frac{h_{14}}{h_{34}}y_4(t + 4) - \frac{h_{24}}{h_{34}}y_4(t + 2)$$

to cancel out $h_{14}x(t)$ and $h_{24}x(t - 1)$ from $y_4(t)$, which introduces additional interference terms (of much lower strength) involving $x(t - 2), x(t + 3)$, and $x(t + 4)$. If needed, these can be cancelled out again using $y_4(t + 6), y_4(t + 7),$ and $y_4(t + 8)$ received in subsequent slots. Assuming the SINR is then sufficiently large for decoding $x(t - 4)$, node 4 can send...
\[ g_{i,m}(t) = g_{i,m-1}(t) + \sum_{j_1=1}^{i-2} \sum_{j_2=1}^{i-2} \cdots \sum_{j_{m-1}=1}^{i-2} \sum_{j_m=1}^{i-2} \frac{h_{j_1}h_{j_2} \cdots h_{j_{m-1}}h_{j_m}}{h_{m}^{(i-1),i}} y_i(t + \delta_{j_1} + \delta_{j_2} + \ldots + \delta_{j_m}) \]

\[ = h_{(i-1),i} x(t_{i-1}) + \sum_{j_1=1}^{i-2} \sum_{j_2=1}^{i-2} \cdots \sum_{j_{m+1}=1}^{i-2} \frac{h_{j_1}h_{j_2} \cdots h_{j_{m+1}}}{h_{m}^{(i-1),i}} x(t_{i-1} + \delta_{j_1} + \delta_{j_2} + \ldots + \delta_{j_{m+1}}) \]

\[ + \sum_{j_1=1}^{i-2} \sum_{j_2=1}^{i-2} \cdots \sum_{j_{m+1}=1}^{i-2} \frac{h_{j_1}h_{j_2} \cdots h_{j_{m+1}}}{h_{m}^{(i-1),i}} z_i(t + \delta_{j_1} + \delta_{j_2} + \ldots + \delta_{j_{m+1}}) \]

where we note that \( t_{j_1} = t_{i-1} + \delta_{j_1} \). This expression shows that node \( i-1 \) transmits \( x(t_j) \) in slot \( t + \delta_j \), so we can use \( y_i(t + \delta_j) \) to cancel \( h_{j_1} x(t_j) \) in \( y_i(t) \).

After waiting for \( \max_j \delta_j = \Delta_{i-1} \) slots, node \( i \) can cancel all the interferences from \( y_j(t) \) by calculating

\[ g_{i,1}(t) = y_i(t) - \sum_{j=1}^{i-2} \frac{h_{j_1}}{h_{(i-1),i}} y_i(t + \delta_{j_1}) \]

\[ = h_{(i-1),i} x(t_{i-1}) - \sum_{j_1=1}^{i-2} \sum_{j_2=1}^{i-2} \frac{h_{j_1}h_{j_2}}{h_{m}^{(i-1),i}} x(t_{i-1} + \delta_{j_1} + \delta_{j_2}) \]

\[ - \sum_{j_1=1}^{i-2} \frac{h_{j_1}}{h_{(i-1),i}} z_i(t + \delta_{j_1}) + z_i(t). \]

If another round of cancellation is needed to further reduce the remaining interference term \( \sum_{j_1=1}^{i-2} \sum_{j_2=1}^{i-2} \frac{h_{j_1}h_{j_2}}{h_{m}^{(i-1),i}} x(t_{i-1} + \delta_{j_1} + \delta_{j_2}) \), node \( i \) waits for additional \( \Delta_{i-1} \) slots and calculates

\[ g_{i,2}(t) = g_{i,1}(t) + \sum_{j_1=1}^{i-2} \sum_{j_2=1}^{i-2} \frac{h_{j_1}h_{j_2}}{h_{m}^{(i-1),i}} y_i(t + \delta_{j_1} + \delta_{j_2}) \]

\[ = h_{(i-1),i} x(t_{i-1}) + \sum_{j_1=1}^{i-2} \sum_{j_2=1}^{i-2} \frac{h_{j_1}h_{j_2}h_{(i-1),i}}{h_{m}^{(i-1),i}} y_i(t + \delta_{j_1} + \delta_{j_2} + \delta_{j_3}) \]

\[ + \sum_{j_1=1}^{i-2} \sum_{j_2=1}^{i-2} \frac{h_{j_1}h_{j_2}}{h_{m}^{(i-1),i}} z_i(t + \delta_{j_1} + \delta_{j_2}) \]

\[ - \sum_{j_1=1}^{i-2} \frac{h_{j_1}}{h_{(i-1),i}} z_i(t + \delta_{j_1}) + z_i(t). \]

Considering the general case, the \( m \)-th round of cancellation is performed according to (4), which can be expanded as (5), where we denote \( g_{i,0}(t) = y_i(t) \) for simplicity. These expressions are obtained by iteratively applying the following cancellation principle:

- Cancel all interference terms from \( g_{i,m-1}(t) \) in the \( m \)-th cancellation round, without considering any additional interference terms that are brought in by the cancellation process (these additional interferences are cancelled in the next cancellation round if needed).
We note that the sign of interference signals inverses in every cancellation round, thus the “±” sign in (3) takes “+” when \( m \) is even and “−” when \( m \) is odd. In (2) and (3), \( \sum_{j=1}^{i-2} \sum_{j_2=1}^{i-2} \cdots \sum_{j_m=1}^{i-2} \sum_{j_{m+1}=1}^{i-2} \) stands for the concatenation of \( m \) sums with their respective iteration variables \( j_1, \ldots, j_m \). It can be verified that (5)−(8) are special cases of (2) and (3).

After \( m \) rounds of cancellation, \( m \Delta_{i-1} \) slots have elapsed since slot \( t \). If node \( i \) can successfully decode \( x(t_{i-1}) \) now, it sends out \( x(t_{i-1}) \) in slot \( t + m \Delta_{i-1} + 1 \).

**End-to-End Delay:** Assume that \( m \) is the same for different nodes \( i \), we have \( \Delta_i - \Delta_{i-1} = t_{i-1} - t_i = m \Delta_{i-1} + 1 \), yielding

\[
\Delta_i = (m + 1) \Delta_{i-1} + 1,
\]

which is a difference equation with respect to \( \Delta_i \). Noting that \( \Delta_1 = 0 \), we can solve the difference equation (9) as

\[
\Delta_i = \left\{ \begin{array}{ll}
\frac{i - 1}{m + 1 - 1}, & \text{if } m = 0 \\
\frac{i - 1}{m + 1 - 1}, & \text{if } m > 0
\end{array} \right.
\]

We note that \( \Delta_i \) is the end-to-end delay (expressed in the number of timeslots) of packet transmission from node 1 to node \( i \). Therefore, (10) is an expression for calculating the delay. The total delay from node 1 to node \( N \) is \( \Delta_N \).

**IV. WHEN DOES IT WORK?**

In the following, we discuss insights behind the aforementioned interference cancellation scheme, and derive conditions under which the proposed scheme works.

**A. Upper Bound of Interference-Plus-Noise Power**

We note that in (3), all the signal components starting from the second term (i.e., excluding \( h_{(i-1),i} x(t_{i-1}) \)) are either interference or noise. Let \( P_{T,m} \) denote the total power of these interference-plus-noise signals in \( g_{i,m}(t) \). We have an upper bound of \( P_{T,m} \).

**Proposition 1.** For \( i \geq 3 \), \( P_{T,m} \) has the following upper bound:

\[
P_{T,m} \leq \left| h_{(i-2),i} \right|^2 (i - 2) \rho^m P_T + \sigma^2 \frac{1 - \rho^{m+1}}{1 - \rho},
\]

where we recall that \( P_T \) denotes the transmission power and \( \sigma^2 \) denotes the noise power, \( \rho \) is defined as

\[
\rho = \frac{\left| h_{(i-2),i} \right|^2 (i - 2)}{\left| h_{(i-1),i} \right|^2}.
\]

**Proof:** Because \( |h_{jk}|^2 \leq |h_{(i-2),i}|^2 \) for \( j \in [1, i - 2] \), by finding the power of \( g_{i,m}(t) \) from its expression (3), replacing the coefficients \( |h_{jk}|^2 \) at the numerators with the upper bound \( |h_{(i-2),i}|^2 \), and noting that the noise-related terms constitute a geometric series, we have

\[
P_{T,m} \leq \sum_{j_1=1}^{i-2} \sum_{j_2=1}^{i-2} \cdots \sum_{j_m=1}^{i-2} \sum_{j_{m+1}=1}^{i-2} \left| h_{(i-2),i} \right|^{2(m+1)} \left| h_{(i-1),i} \right|^{2m} P_T
\]

\[
+ \sigma^2 \sum_{\theta=0}^{m} \left| h_{(i-2),i} \right|^{2\theta} \theta^m (i - 2)^\theta
\]

\[
= \left| h_{(i-2),i} \right|^2 (i - 2) \left( \frac{\left| h_{(i-2),i} \right|^2 (i - 2)}{\left| h_{(i-1),i} \right|^2} \right)^m P_T
\]

\[
+ \sigma^2 \sum_{\theta=0}^{m} \left( \frac{\left| h_{(i-2),i} \right|^2 (i - 2)}{\left| h_{(i-1),i} \right|^2} \right)^\theta
\]

\[
= \left| h_{(i-2),i} \right|^2 (i - 2) \rho^m P_T + \sigma^2 \frac{1 - \rho^{m+1}}{1 - \rho}.
\]

**B. Sufficient Condition for Successful Packet Reception**

**Proposition 2.** Node \( i \geq 3 \) can successfully decode \( x(t_{i-1}) \) from \( g_{i,m}(t) \) when the following conditions hold:

\[
i < \frac{\left| h_{(i-1),i} \right|^2}{\left| h_{(i-2),i} \right|^2} - \frac{\gamma \sigma^2}{\left| h_{(i-1),i} \right|^2} + 2
\]

\[
m \geq \log_\rho \left( \frac{P_T - \frac{\sigma^2}{\gamma} \left| h_{(i-1),i} \right|^2 - \left| h_{(i-2),i} \right|^2 (i - 2) P_T - \frac{\sigma^2}{1 - \rho} \rho^m}{\left| h_{(i-1),i} \right|^2 - \left| h_{(i-2),i} \right|^2 (i - 2)} \right) - 1.
\]

**Proof:** We note that node \( i \) can successfully decode \( x(t_{i-1}) \) when the following condition holds:

\[
\frac{\left| h_{(i-1),i} \right|^2}{\left| h_{(i-2),i} \right|^2} P_T \geq \gamma.
\]

Combining (15) with (11), we obtain a stricter condition for successful reception:

\[
\frac{\left| h_{(i-1),i} \right|^2 P_T}{\left| h_{(i-2),i} \right|^2 (i - 2) \rho^m P_T + \sigma^2 \frac{1 - \rho^{m+1}}{1 - \rho}} \geq \gamma;
\]

which is equivalent to

\[
\frac{\left| h_{(i-1),i} \right|^2 P_T}{\gamma} - \sigma^2 \frac{1 - \rho}{1 - \rho} \geq \left( \frac{\left| h_{(i-2),i} \right|^2 (i - 2) P_T - \frac{\sigma^2}{1 - \rho} \rho^m}{\gamma} \right) \rho^m.
\]

Substituting (12) into the above inequality, we know that (16) is equivalent to

\[
\frac{\left| h_{(i-1),i} \right|^2 P_T}{\gamma} - \sigma^2 \frac{1 - \rho}{1 - \rho} \geq \left( \frac{\left| h_{(i-1),i} \right|^2 P_T - \frac{\sigma^2}{1 - \rho} \rho^m}{\gamma} \right) \rho^{m+1}.
\]

Using elementary algebra, we can easily verify that when the following conditions are satisfied:

\[
\rho < 1,
\]

\[
\frac{\left| h_{(i-1),i} \right|^2 P_T}{\gamma} - \sigma^2 \frac{1 - \rho}{1 - \rho} > 0
\]

(\text{thus } \frac{\left| h_{(i-1),i} \right|^2 P_T - \frac{\sigma^2}{1 - \rho} \rho^m}{\gamma} \rho^{m+1} > 0 \text{ because } \gamma \geq 1),

\[
m \geq \log_\rho \left( \frac{\left| h_{(i-1),i} \right|^2 P_T - \frac{\sigma^2}{1 - \rho} \rho^m}{\gamma} \rho^{m+1} \right) - 1.
\]
then (17) is satisfied, thus (15) and (16) are also satisfied. Substituting (12) into (18)-(20), we can show that (18) is equivalent to $i < \frac{|h_{(i-2),i}|}{\sigma^2}$, and (19) is equivalent to (13). Hence, when (13) holds, (18) and (19) also hold. The right-hand side (RHS) of (20) is equal to the RHS of (14), thus (20) holds when (13) holds.

Proposition 2, which gives a set of sufficient conditions, provides a possibly conservative value on the number of required cancellation rounds $m$, governed by the lower bound in (14). If (13) is satisfied, packet $x(t_{(i-1)})$ can be successfully received by node $i$ when $m$ satisfies (14). We note that the minimum value of $m$ satisfying (14) is always finite if (13) (thus (18) and (19) in the proof) holds. Therefore, we can say that multi-hop interference can be effectively cancelled within a finite number of rounds when (13) holds.

C. How Many Nodes Are Allowed?

Condition (13) imposes an upper bound on $i$, implying that $i$ (thus $N$) cannot be too large. Assume that $|h_{ji}|^2 \propto \frac{1}{d_{ji}^{d}}$, where $d_{ji}$ is the geographical distance between nodes $j$ and $i$, and $\alpha$ is the path-loss exponent related to the wireless environment. Suppose we have equally spaced nodes, such that $d_{(i-2),i} = 2d_{(i-1),i}$. Define a quantity $B > 0$ such that
\[
\frac{|h_{(i-2),i}|^2 P_T}{\sigma^2} = \frac{\gamma}{B}, \tag{21}
\]
thus $\frac{|h_{(i-2),i}|^2 P_T}{\sigma^2} = B$. When $B = 2 - \epsilon$ for an arbitrarily small $\epsilon > 0$, condition (13) becomes
\[
i < 2^\alpha + \epsilon. \tag{22}
\]
In practical environments, we normally have $2 < \alpha < 6$, which means that the proposed approach always works for chain networks with $N = 4$ nodes. Whether it works with more nodes depends on the value of $\alpha$ in the environment. For example when $\alpha = 4$, we can have $N = 16$. Also note that we are using the sufficient condition given by Proposition 2 so our results here may be conservative (as we will see in the numerical results next section), and the proposed approach may work well with much larger values of $N$.

The value of $B$ in (21) is related to the placement of nodes. A smaller value of $B$ implies a larger $|h_{(i-2),i}|^2$. We should normally have $B > 1$ because otherwise nodes $i - 2$ and $i$ can communicate directly (when there is no interference) and node $i - 1$ may be ignored by common routing protocols. Aspects related to optimal node placement is open for future research. Because we fix the ratio $|h_{(i-1),i}|^2/|h_{(i-2),i}|^2 = 2^\alpha$ here, a smaller $B$ also yields a larger $|h_{(i-1),i}|^2$.

V. NUMERICAL RESULTS

We now present some numerical results of the proposed interference cancellation scheme based on the above analysis.

We first evaluate the SINR after interference cancellation, at different nodes and with different number of cancellation rounds $m$. The same static channel model as in Section IV-C is used in the evaluation. More realistic cases involving random channel coefficients is left for future work. We set the signal-to-noise (SNR) ratio of single-hop transmission (without interference) to 20 dB, based on which we can calculate the SINR of $g_{i,m}(t)$. We use two different methods to calculate the SINR. One is based on the theoretical interference-plus-
noise upper bound in (11), which gives an SINR lower bound (LB); the other is based on the actual signal expression in (3). Obviously, the second method gives the actual SINR, but it is also more complex than the first method. Fig. 4 shows the results with different path-loss exponents $\alpha$.

Note that $m = 0$ corresponds to the existing E2E-KIC approach without cancelling unknown multi-hop interferences. We can see from Fig. 4 that the proposed approach (with $m > 0$) provides a significant gain in SINR. Even when $m = 1$, the gain compared to $m = 0$ is over 4 dB (based on the actual SINR values) in all cases we evaluate here. The gain goes higher when $\alpha$ is larger because the multi-hop interference is more attenuated with a larger $\alpha$. This SINR gain is important for E2E-KIC to work in scenarios with multi-hop interference. For example, consider $\alpha = 3$ and $\gamma = 10$ dB, E2E-KIC would not work without the proposed approach (i.e., $m = 0$) when $N \geq 3$, because the SINR is below the $\gamma = 10$ dB threshold; using a single round of cancellation with the proposed approach (i.e., $m = 1$), the SINR becomes significantly above $\gamma = 10$ dB and E2E-KIC works (at least for $N \in \{3, 4, 5, 6\}$).

At node $i = 2$, the SINR is equal to the single-hop SNR (20 dB), because there is no unknown multi-hop interference at this node. For nodes $i \geq 3$, the SINR is below 20 dB and depends on the value of $m$. As expected, a larger $m$ yields a higher SINR. When $m$ is large enough, the SINR becomes very close to the single-hop SNR.

The theoretical LB is equal to the actual SINR when $i = 3$. At $i > 3$, the LB tends to significantly underestimate the SINR and thus the performance of the proposed approach. This is because the interference-plus-noise upper bound in (11) replaces all $|h_{j,i}|^2$ for $j < i - 2$ with $|h_{i(i-2),i}|^2$, which remarkably enlarges the interferences from nodes that are three or more hops away. This validates that the results presented in Section IV.C are quite conservative, and the proposed approach should actually perform much better. Since it is hard to obtain meaningful analytical results directly from (3), an interesting direction for future work is to find tighter theoretical bounds for the interference-plus-noise power.

Fig. 5 shows the end-to-end delay from node 1 to node $i$, i.e., the $\Delta_i$ values computed from (10). When $i = N$, this corresponds to the total delay from the source node (node 1) to the destination node (node $N$). We see that the delay increases with the number of cancellation rounds $m$ and the node index $i$. However, a good news is that $m$ usually does not need to be too large to obtain a reasonably high SINR gain, as seen in Fig. 4. Also note that the “packets ” in this paper do not need to be full data packets on the network layer. In fact, they can be as short as a single symbol if a proper scheduling and synchronization scheme is available.

Furthermore, the delay is due to the idling time before each node receives its first packet. Once the first packet has been received, there is no additional delay for receiving subsequent packets. A large chain network does not necessarily have all nodes waiting for the first packet to arrive (or waiting for the whole transmission to complete). It can schedule some other transmissions in those idling slots instead. With such a properly designed scheduling mechanism, the throughput benefit of E2E-KIC can still be maintained although the transmission delay may be large.

VI. CONCLUSION

In this paper, we have studied E2E-KIC with multi-hop interference. We have noted that among all multi-hop interferences, the unknown interferences from nodes preceding the current node are the most challenging, while the other known interferences can be cancelled with existing KIC approaches. We have therefore proposed an approach that iteratively reduces the strength of unknown interferences to a sufficiently low level, so that nodes can successfully receive new packets. Analytical and numerical results confirm the effectiveness and also provide insights of the proposed approach.

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