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Design and Implementation of a Full-Duplex Pipelined MAC Protocol for Multihop Wireless Networks

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ABSTRACT In multihop wireless networks, data packets are forwarded from a source node to a destination node through intermediate relay nodes. With half-duplex relay nodes, the end-to-end delay performance of a multihop network degrades as the number of hops increases, because the relay nodes cannot receive and transmit at the same time. Full-duplex relay nodes can reduce their per-hop delay by starting to forward a packet before the whole packet is received. In this paper, we propose a pipelined medium access control (PiMAC) protocol, which enables the relay nodes on a multihop path to simultaneously transmit and receive packets for full-duplex forwarding. For pipelined transmission over a multihop path, it is important to suppress both the self-interference of each relay node with the full-duplex capability and the intra-flow interference from the next relay nodes on the same path. In the PiMAC protocol, each relay node can suppress both the self- and intra-flow interference for full-duplex relaying on the multihop path by estimating the channel coefficients and delays of the interference during a multihop channel acquisition phase. To evaluate the performance of the PiMAC protocol, we carried out extensive simulations and software-defined radio-based experiments.

INDEX TERMS Full-duplex, intra-flow interference, MAC protocol, wireless relay network, multihop transmission.

I. INTRODUCTION

Recently, in-band full-duplex communication has emerged as a candidate technology for next-generation 5G wireless networks. Using in-band full-duplex wireless, nodes can simultaneously transmit and receive signals in the same frequency band. The key to full-duplex transmission is the cancellation of self-interference, which is interference caused by the signal transmitted by the node itself; see a sampling of the proposed methods in [1]–[7]. To utilize the recent advances in physical-layer technologies for full-duplex wireless communication, several medium access control (MAC) protocols have been studied [5]–[13].

With half-duplex nodes in a multihop network, the packet forwarding is limited by the achievable spatial reuse, which in turn impacts the transmission delay. With half-duplex nodes, a packet has to be forwarded before the node can begin to receive a new packet. With full-duplex capability, the nodes can potentially pipeline packets, i.e., send packets while receiving a new one. However, full-duplex transmission introduces a new type of interference, which we call *intra-flow interference*. Intra-flow interference occurs when the next relay node on the same multihop path forwards a packet at the same time. Because it occurs within the same flow path, we define this interference as intra-flow interference.

Figure 1 shows an example of a full-duplex wireless relay network. A source node (S) transmits packets to a destination node (D) through the relay nodes (R_i). If S transmits a packet to R_1, R_1 can start the transmission of the packet while it is

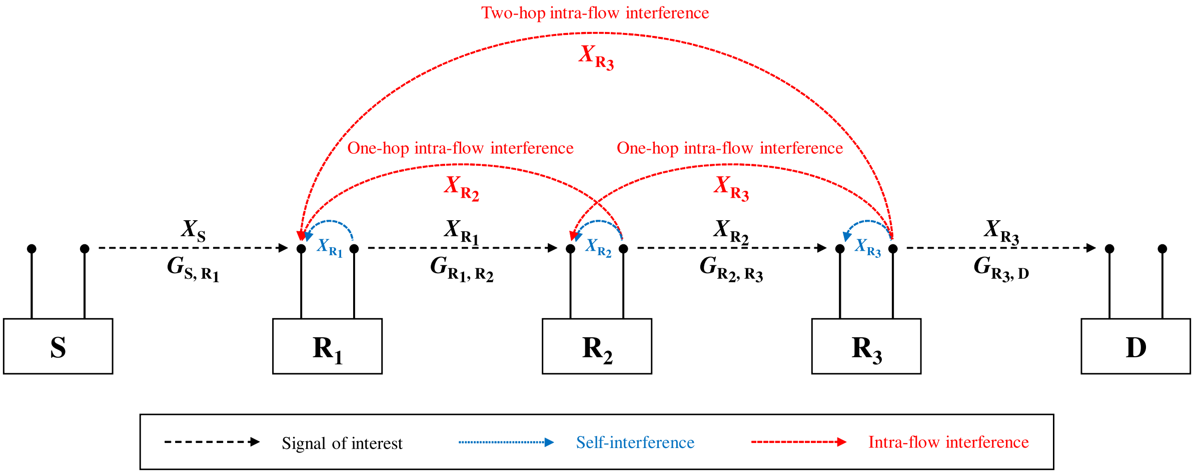


FIGURE 1. Full-duplex relaying model with self-interference and intra-flow interference in multihop wireless networks.

still being received. When R_1 forwards the received packet to R_2, R_2 performs the same operations as R_1. However, at R_2, the signal forwarding the received packet to R_3 interferes with the packet reception at R_1, i.e., intra-flow interference occurs because the next relay node forwards the received packet at the same time. Intra-flow interference includes the interference caused by the signals transmitted from the next relay node and from the relay nodes that are more than one hop away. If the relay nodes fail to forward the packets because of the intra-flow interference, the multihop transmission would eventually be unsuccessful. Because of this intra-flow interference, the number of concurrent transmissions on a multihop path is significantly limited, even though the relay nodes have a full-duplex communication capability.

To solve the problem of intra-flow interference in full-duplex wireless relay networks, we propose a new MAC protocol called pipelined medium access control protocol (PiMAC) that suppresses the intra-flow interference caused by the relay nodes and enables the relay nodes to concurrently perform full-duplex forwarding on the multihop path to expedite multihop transmissions. The proposed MAC protocol consists of four phases: i) the request phase for estimating the channel state information of the self-interference, ii) the response phase for stabilizing the self-interference cancellation and for estimating the channel state information of the intra-flow interference, iii) the DATA transmission phase, and iv) the acknowledgement (ACK) transmission phase. Our contributions are summarized as follows:

- We first analyze the characteristics of the intra-flow interference in multihop wireless networks and design a system model to suppress the intra-flow interference and to perform concurrent full-duplex forwarding at the relay nodes on the multihop path.
- To fully exploit the full-duplex capability of wireless relay networks, we propose PiMAC, which enables a source node to perform pipelined transmission to a destination node. By suppressing both self-interference and intra-flow interference, the relay nodes on a multihop path concurrently perform full-duplex transmissions. PiMAC can expedite multihop delivery with a small end-to-end delay in full-duplex wireless multihop networks.
- We compare the network performance of the PiMAC protocol and a half-duplex scheme on a multihop chain topology through extensive simulations. In the simulations, PiMAC reduces the per-hop delay from 2.4 ms to 0.27 ms when the number of hops increases. Further, we conduct software-defined radio (SDR)-based experiments to confirm the intra-flow interference cancellation (IFIC) effect of the PiMAC protocol. The experimental results indicate that PiMAC suppresses the intra-flow interference at each relay up to 11 dB for a three-hop chain topology.

The remainder of this paper is organized as follows: Section II presents the related works on multihop full-duplex relaying in full-duplex wireless networks. Section III describes the system model for a full-duplex wireless relay network. Section IV proposes a pipelined MAC protocol for suppressing the intra-flow interference and successfully forwarding a packet to the destination node. Section V presents various simulation results to verify the performance of the proposed MAC protocol. Section VI shows the experimental results using SDR-based hardware. Finally, Section VII summarizes our findings and concludes the paper.

II. RELATED WORK

A. TWO-HOP RELAY NETWORKS

Several studies on full-duplex relaying in wireless networks have been conducted. Riihonen *et al.* [14] proposed a hybrid relaying scheme that selects between the full- and half-duplex relaying modes. They derived the signal-to-interference-plus-noise ratio (SINR) in the full- and half-duplex relaying modes and calculated the spectral efficiency for each mode using the signal-to-noise ratio (SNR) derivation. On the basis of this calculated spectral efficiency, the hybrid scheme opportunistically selects an appropriate relaying mode and performs transmit power adaptation to maximize the spectral efficiency.

In [15], a multipair full-duplex relaying scheme was presented, where all source and destination nodes have a single antenna, and the relay nodes have massive antenna arrays. The achievable rates and spectral efficiencies for the maximum-ratio-combining/maximum-ratio-transmission (MRC/MRT) processing and zero-forcing (ZF) processing schemes were derived. Moreover, an optimal transmit power allocation scheme was proposed to maximize the energy efficiency for the MRC/MRT and ZF processing schemes. In [16], a full-duplex relaying scheme was presented for a multiple-input multiple-output (MIMO) two-way relay channel, where two source nodes with a transmit and receive antenna pair exchange information through a relay node with multiple transmit and receive antenna arrays. To maximize the end-to-end performance, the authors proposed an iterative algorithm and a one-dimensional (1-D) search to find the achievable-rate region and maximize the sum rate. The iterative algorithm jointly optimizes the beamforming matrix at the relay node using the amplify-and-forward relaying scheme and the transmit power at the source node.

In [17], a joint precoding/decoding design for the relay nodes was proposed to maximize the end-to-end SNR performance, where the source, relay, and destination nodes have multiple antennas. The beamforming vectors were designed to suppress the ZF loopback self-interference at the relay node, and the closed-form outage probability and high-SNR expressions were derived. To reduce the system complexity and maximize the end-to-end SNR, an antenna-selection scheme and a simple power-allocation scheme were proposed. In [18], a two-way amplify-and-forward relay scheme was presented, in which two source nodes transmit a packet stream to each other through a full-duplex relay node. To avoid the interference that is incurred by the source nodes, each source node transmits a packet at different times. A source node transmits a packet to the full-duplex relay node at the odd time slots, while the source node should receive a packet from the full-duplex relay node at the even time slots. The outage probability and ergodic capacity for a two-way full-duplex relay channel were derived, and the capacity of the two-way full-duplex relay mode was compared with those of various half-duplex modes.

Most of the past studies on full-duplex relaying have considered the case where only one relay node exists between the source and destination nodes. They did not consider the intra-flow interference that may occur among the relay nodes on a multihop path. When multiple relay nodes exist in wireless relay networks, the mitigation of the intra-flow interference should be investigated to improve the network performance.

B. MULTIHOP FULL-DUPLEX NETWORKS

To take full advantage of the full-duplex relaying capability over multihop networks, several MAC protocol schemes for multihop full-duplex relay networks have been proposed. In [19], an outage probability analysis was presented for a multihop full-duplex relay network, which included the echo interference by the signals sent from the relay nodes. A path-loss-to-interference ratio (PLIR) was defined, which is the ratio of the received power of the desired signal to that of the interference (including the echo interference). According to the PLIR value, the optimal number of relay nodes was identified to minimize the outage probability. In [20], a capacity analysis of the full-duplex wireless networks was presented. Through an analysis of the half- and full-duplex capacity gains, it was shown that the network can achieve a double capacity gain only in the case of one-to-one communication. In large-scale wireless networks, it was proved that the full-duplex capacity gain mainly decreases owing to intra-flow interference.

Tamaki *et al.* [8] proposed a MAC protocol for full-duplex wireless relay networks. The protocol performs primary and secondary transmissions to avoid packet collisions. While a primary transmission is being performed, the protocol selects a secondary transmission node on the basis of the collected 1-bit information from each frame. However, the intra-flow interference that can occur in multihop full-duplex relay networks was not considered. Chen *et al.* [21] proposed a MAC protocol that enables a wireless cut-through transmission using full-duplex relaying. For wireless cut-through transmissions, they considered three types of interference: self-interference, the forwarder interference caused by the next relay node, and the cross-hop interference caused by the relay nodes that are more than one-hop away. Since channel estimation and interference cancellation incur a significant overhead, a hierarchical structure for the channel estimation and cancellation was designed to reduce the overhead. The relay node transmits a training sequence and receives the superposed sequences, which have traveled the interference paths. Using these superposed sequences, the hierarchical structure sequentially estimates the interference channels in reverse order. The MAC protocol can cancel the causal interference originating from each other relay node. However, the hierarchical estimation and cancellation structures may cause estimation error propagation if the channel estimate of the interference is inaccurate.

In [11], a joint power allocation and routing algorithm for full-duplex wireless relay networks was proposed. Joint route and transmit power allocation was presented to maximize the throughput performance when both self-interference and the interference among neighboring nodes are present. This scheme can obtain an optimal solution for the joint route and transmit power when only one-hop interference exists. If the interference caused by neighboring nodes that are more than one-hop away exists, the scheme can provide a constant bound for the optimal solution. Han *et al.* [22] investigated multihop decode-and-forward full-duplex relaying systems. They considered two full-duplex relaying cases; the relay node knows the channel state information of only the previous node, and the relay node knows the perfect channel state information of all other relay nodes. For each case, the outage probability, symbol error probability, and ergodic capacity are derived. Through simulation, they compared the performance of multihop full-duplex relaying cases with that of the half-duplex relaying case.

In summary, most of the past studies on full-duplex transmission over multihop links focused on a performance analysis of network parameters such as the transmission capacity and outage probability for multihop networks with full-duplex capability relay nodes. A few studies on full-duplex communication considered the effect of intra-flow interference on multihop delivery, but most of them did not propose a method to directly estimate and suppress the intra-flow interference itself for pipelined multihop transmission. By suppressing the intra-flow interference, it is possible to further reduce the outage probability and energy consumption caused by packet retransmissions.

III. SYSTEM MODEL

We consider a wireless relay network that consists of source, relay, and destination nodes, which all have full-duplex capabilities. Because the source and destination nodes can become relay nodes in other transmissions, they also have full-duplex capabilities. If a relay node receives a packet sent from a previous relay node, it forwards the received packet to the next relay node or to the destination node. It is assumed that each relay node can identify the next relay node through the upper layer (i.e., the network layer) when it receives a frame from the previous node. Each node has transmitting and receiving antennas for full-duplex communication. In addition, we assume that all nodes for a transmission period consist of the transmissions of control frames, DATA, and ACK.

Figure 1 shows the system model of full-duplex relaying in wireless networks. S and R_i have the codewords X_S and X_{R_i} for transmitting and forwarding the signals, respectively, and R_i and D receive signals Y_{R_i} and Y_{D}, respectively. $G_{\mathrm{R}_i,\,\mathrm{R}_j}$ is the channel coefficient from the nodes R_i to R_j, and $G_{\mathrm{R}_i,\mathrm{R}_i}$ is the channel coefficient between two antennas of node R_i. In Figure 1, the received signals of the relay nodes consist of the signal of interest and the interference signals. Except for the last relay node, each relay node is affected by both self-interference and intra-flow interference. Intra-flow interference occurs when the next relay nodes forward a signal to the node after the next. Since each relay node transmits the signal that it received from the previous node, intra-flow interference occurs among the relay nodes. The intra-node interference signals transmitted by the next relay nodes contain the same information as that transmitted by the source node. Therefore, the intra-flow interference can be inferred if the channel coefficient and the time difference due to the propagation delay are available.

We first outline a system model for the full-duplex relay network shown in Figure 1. Let T_{P} denote the processing delay for packet forwarding of the relay nodes and δ_i denote the propagation delay of the ith hop. The processing delay for packet forwarding is the amount of time for receiving and forwarding the signal. It is a constant value depending on the forwarding scheme and the hardware characteristics of the node. In case of an amplify-and-forward (AF) scheme, each node amplifies and forwards the received signal without digital decoding while receiving the signal. In case of a decode-and-forward (DF) scheme, each node can forward the received signal after performing digital decoding while receiving the signal. As a result, the processing delay for the DF scheme can be slightly longer than that for AF scheme. The propagation delay is the amount of time for transmitting the head of a signal from the sender node to the receiver node. Then, the received signals Y_{R_i} and Y_{D} are expressed as

$$\begin{aligned}
Y_{\mathrm{R}_1}[t] =\ & \underbrace{G_{\mathrm{S},\mathrm{R}_1} X_{\mathrm{S}}\,[t]}_{\text{signal of interest}} + \underbrace{G_{\mathrm{R}_1,\mathrm{R}_1} X_{\mathrm{R}_1}\,[t]}_{\text{self-interference}} \\
& \underbrace{+\sum_{i=2}^{r} G_{\mathrm{R}_i,\mathrm{R}_1} X_{\mathrm{R}_1}\left[t-\left(\sum_{k=2}^{i}(2\delta_k+T_{\mathrm{P}})\right)\right]}_{\text{intra-flow interference}} + N_{\mathrm{R}_1}, \\
Y_{\mathrm{R}_m}[t] =\ & G_{\mathrm{R}_{m-1},\mathrm{R}_m} X_{\mathrm{R}_{m-1}}\,[t] + G_{\mathrm{R}_m,\mathrm{R}_m} X_{\mathrm{R}_m}\,[t] \\
& + \sum_{i=m+1}^{r} G_{\mathrm{R}_i,\mathrm{R}_m} X_{\mathrm{R}_m}\left[t-\left(\sum_{k=m+1}^{i}(2\delta_k+T_{\mathrm{P}})\right)\right] \\
& + I_{\mathrm{R}_m} + N_{\mathrm{R}_m} \quad \text{for } m = 2,\cdots,(r-1), \\
Y_{\mathrm{R}_r}[t] =\ & G_{\mathrm{R}_{r-1},\mathrm{R}_r} X_{\mathrm{R}_{r-1}}\,[t] + G_{\mathrm{R}_r,\mathrm{R}_r} X_{\mathrm{R}_r}\,[t] + I_{\mathrm{R}_r} + N_{\mathrm{R}_r}, \\
Y_{\mathrm{D}}[t] =\ & G_{\mathrm{R}_r,\mathrm{D}} X_{\mathrm{R}_r}\,[t] + I_{\mathrm{D}} + N_{\mathrm{D}}, \qquad (1)
\end{aligned}$$

where r is the number of relay nodes, I_{R_i} is the sum of the intra-flow interference from all previous relay nodes at R_i, and N_{R_i} is a complex Gaussian random variable with zero mean at R_i. In (1), at R_m for $m \geq 2$, the signals from all previous relay nodes except R_{m-1} incur interference. This interference from the previous relay nodes cannot be mitigated by any suppression scheme because R_m does not have information about the signal that the interferers are transmitting. Therefore, the interference from previous relay nodes is modeled separately as I_{R_i} in (1). In addition, the codewords of the intra-flow interference of $Y_{\mathrm{R}_1}[t]$ in (1) are the same as the codewords previously transmitted by the source node because the intra-flow interference sent from the relay nodes is composed of the signal forwarded from the source node. Therefore, we can model the intra-flow interference as a function of X_{R_1} with each channel gain and the time difference caused by the propagation and processing delays. The intra-flow interference from the previous relay nodes that are more than two hops away does not significantly affect the reception of the desired signal, which will be discussed in detail in Section V-D.

Here, the self-interference and intra-flow interference can be canceled by injecting cancellation signals. Let $C_{\mathrm{SI},\mathrm{R}_m}$ and $C_{\mathrm{IFI},\mathrm{R}_m}$ denote the cancellation signals for the self-interference and intra-flow interference, respectively, at the

mth relay node. Then, they can be modeled as follows:

$$\begin{aligned} C_{\mathrm{SI},\mathrm{R}_m}[t] &= \widehat{G}_{\mathrm{R}_m,\mathrm{R}_m} X_{\mathrm{R}_m}[t], \\ C_{\mathrm{IFI},\mathrm{R}_m}[t] &= \sum_{i=m+1}^{r} \widehat{G}_{\mathrm{R}_i,\mathrm{R}_m} X_{\mathrm{R}_m}\left[t-\left(\sum_{k=m+1}^{i}\left(2\widehat{\delta}_k+\widehat{T}_{\mathrm{P}}\right)\right)\right], \end{aligned} \tag{2}$$

where $\widehat{G}_{\mathrm{R}_i,\mathrm{R}_j}$ is the channel estimate of $G_{\mathrm{R}_i,\mathrm{R}_j}$, $\widehat{\delta}_i$ is the estimate of the propagation delay of the ith hop, and $\widehat{T}_{\mathrm{P}}$ is the processing delay for packet forwarding.

For perfect self-interference and intra-flow interference cancellation, $C_{\mathrm{SI},\mathrm{R}_m}$ and $C_{\mathrm{IFI},\mathrm{R}_m}$ should be equal to the self-interference and intra-flow interference signals, respectively. The ith relay node is already aware of $X_{\mathrm{R}_j}[t]$ for $i < j \leq r$. Because $X_{\mathrm{R}_j}[t]$ to be transmitted by the jth relay node is the signal received from the ith relay node, $X_{\mathrm{R}_j}[t]$ is the same as the signal previously transmitted by the ith relay node. To achieve perfect self-interference and intra-flow interference cancellation, we need accurate estimates of $G_{\mathrm{R}_i,\mathrm{R}_i}$ and $G_{\mathrm{R}_j,\mathrm{R}_i}$. Even if the channel information of the self-interference and intra-flow interference is completely estimated, residual interference may exist owing to various causes such as the transmitter distortion and phase noise in a practical wireless environment. Note that $\widehat{\delta}_i$ and $\widehat{T}_{\mathrm{P}}$ are readily available once they are measured. Using $C_{\mathrm{SI},\mathrm{R}_m}$ and $C_{\mathrm{IFI},\mathrm{R}_m}$, the received signals can be rewritten as

$$\begin{aligned} Y_{\mathrm{R}_1}[t] &= G_{\mathrm{S},\mathrm{R}_1} X_{\mathrm{S}}[t] + \underbrace{G_{\mathrm{R}_1,\mathrm{R}_1} X_{\mathrm{R}_1}[t] - C_{\mathrm{SI},\mathrm{R}_1}[t]}_{\text{self-interference cancellation}} \\ &\quad \underbrace{+\sum_{i=2}^{r} G_{\mathrm{R}_i,\mathrm{R}_1} X_{\mathrm{R}_1}\left[t-\left(\sum_{k=2}^{i}(2\delta_k+T_{\mathrm{P}})\right)\right] - C_{\mathrm{IFI},\mathrm{R}_1}[t]}_{\text{intra-flow interference cancellation}} \\ &\quad +N_{\mathrm{R}_1}, \\ Y_{\mathrm{R}_m}[t] &= G_{\mathrm{R}_{m-1},\mathrm{R}_m} X_{\mathrm{R}_{m-1}}[t] + G_{\mathrm{R}_m,\mathrm{R}_m} X_{\mathrm{R}_m}[t] - C_{\mathrm{SI},\mathrm{R}_m}[t] \\ &\quad + \sum_{i=m+1}^{r} G_{\mathrm{R}_i,\mathrm{R}_m} X_{\mathrm{R}_m}\left[t-\left(\sum_{k=m+1}^{i}(2\delta_k+T_{\mathrm{P}})\right)\right] \\ &\quad -C_{\mathrm{IFI},\mathrm{R}_m}[t] + I_{\mathrm{R}_m} + N_{\mathrm{R}_m} \quad \text{for } m=2,\cdots,(r-1), \\ Y_{\mathrm{R}_r}[t] &= G_{\mathrm{R}_{r-1},\mathrm{R}_r} X_{\mathrm{R}_{r-1}}[t] + G_{\mathrm{R}_r,\mathrm{R}_r} X_{\mathrm{R}_r}[t] - C_{\mathrm{SI},\mathrm{R}_r}[t] \\ &\quad +I_{\mathrm{R}_r} + N_{\mathrm{R}_r}, \\ Y_{\mathrm{D}}[t] &= G_{\mathrm{R}_r,\mathrm{D}} X_{\mathrm{R}_r}[t] + I_{\mathrm{D}} + N_{\mathrm{D}}. \end{aligned} \tag{3}$$

To indicate the degree of self-interference and intra-flow interference cancellation using the canceling signals, we define $S_{\mathrm{SI},\mathrm{R}_m}$ and $S_{\mathrm{IFI},\mathrm{R}_m}$ as the suppression levels of the self-interference and intra-flow interference at the mth relay node, respectively, which can be expressed as

$$\begin{aligned} &S_{\mathrm{SI},\mathrm{R}_m}[t] \\ &= \frac{\mathbb{E}(|G_{\mathrm{R}_m,\mathrm{R}_m} X_{\mathrm{R}_m}[t]|^2)}{\mathbb{E}(|G_{\mathrm{R}_m,\mathrm{R}_m} X_{\mathrm{R}_m}[t] - C_{\mathrm{SI},\mathrm{R}_m}[t]|^2)}, \end{aligned} \tag{4}$$

$$\begin{aligned} &S_{\mathrm{IFI},\mathrm{R}_m}[t] \\ &= \frac{\mathbb{E}\left(|\sum_{i=2}^{r} G_{\mathrm{R}_i,\mathrm{R}_1}\mathrm{R}_j\right) X_{\mathrm{R}_1}\left[t-\sum_{k=2}^{i}(2\delta_k+T_{\mathrm{P}})\right]|^2)}{\mathbb{E}(|\sum_{i=2}^{r} G_{\mathrm{R}_i,\mathrm{R}_1} X_{\mathrm{R}_1}\left[t-\sum_{k=2}^{i}(2\delta_k+T_{\mathrm{P}})\right] - C_{\mathrm{IFI},\mathrm{R}_1}[t]|^2)}. \end{aligned} \tag{5}$$

Note that the denominators in (4) and (5) represent the residual interference after cancellation while the numerators represents the interference itself. The cancellation performance depends on the accuracy of the estimates of $G_{\mathrm{R}_i,\mathrm{R}_i}$ and $G_{\mathrm{R}_j,\mathrm{R}_i}$. Let $\tau_{\mathrm{R}_i,\mathrm{R}_i}$ and $\tau_{\mathrm{R}_j,\mathrm{R}i}$ denote the self-interference and intra-flow interference channel estimation accuracies of the ith relay node, respectively, i.e., $\widehat{G}_{\mathrm{R}_i,\mathrm{R}_i} = \tau_{\mathrm{R}_i,\mathrm{R}_i} G_{\mathrm{R}_i,\mathrm{R}_i}$ and $\widehat{G}_{\mathrm{R}_i,\mathrm{R}_j} = \tau_{\mathrm{R}_i,\mathrm{R}_j} G_{\mathrm{R}_i,\mathrm{R}_j}$. The parameter values represent the discrepancy between the actual and estimated interference and depend on analog and digital cancellation techniques for full-duplex communication. In (4), $S_{\mathrm{SI},\mathrm{R}_m}$ can be simplified to $|1-\tau_{\mathrm{R}_m,\mathrm{R}_m}|^{-2}$. If $\tau_{\mathrm{R}_m,\mathrm{R}_m} = 0$ in the case of an inaccurate estimate of $G_{\mathrm{R}_m,\mathrm{R}_m}$, $S_{\mathrm{SI},\mathrm{R}_m} = 1$. If $\tau_{\mathrm{R}_m,\mathrm{R}_m} = 1$, $S_{\mathrm{SI},\mathrm{R}_m}$ becomes ∞, and this implies that the interference is completely canceled. In Section V, the performance of the PiMAC protocol will be evaluated with respect to $S_{\mathrm{SI},\mathrm{R}_m}$ and $S_{\mathrm{IFI},\mathrm{R}_m}$.

IV. PIMAC PROTOCOL FOR SUPPRESSING INTRA-FLOW INTERFERENCE

In this section, we present the design of a pipelined MAC protocol to suppress the intra-flow interference in full-duplex relay networks. To suppress the intra-flow interference and successfully forward a packet to the destination node, a precise estimate of the processing delay for packet forwarding and the channel state information between the relay nodes are required, as described in Section III. To this end, we design an acquisition phase to estimate the channel state information and the processing delays as well as a pipelined data-transmission phase with an appropriate coordination protocol.

Figure 2 shows the operation of the proposed PiMAC protocol. In short, the overall procedure is based on the request-to-send/clear-to-send (RTS/CTS) handshaking of the IEEE 802.11 standard MAC protocol and can be regarded as RTS/CTS handshaking extended for pipelined multihop transmission. In addition, the pipeline RTS and CTS handshaking for pipelined multihop transmission can overcome the hidden-terminal problem surrounding the pipelined transmission path. The proposed PiMAC protocol consists of four phases: pipeline transmission request, pipeline transmission response, DATA transmission, and ACK transmission. The pipeline transmission request phase is defined as the period for conveying the multihop transmission path information from the source node to the destination node. In addition, the request phase enables each node to estimate the channel state information of the self-interference and to calculate the processing delay for packet forwarding of each hop. In the pipeline transmission response phase, each node estimates the channel state information of the multihop intra-flow

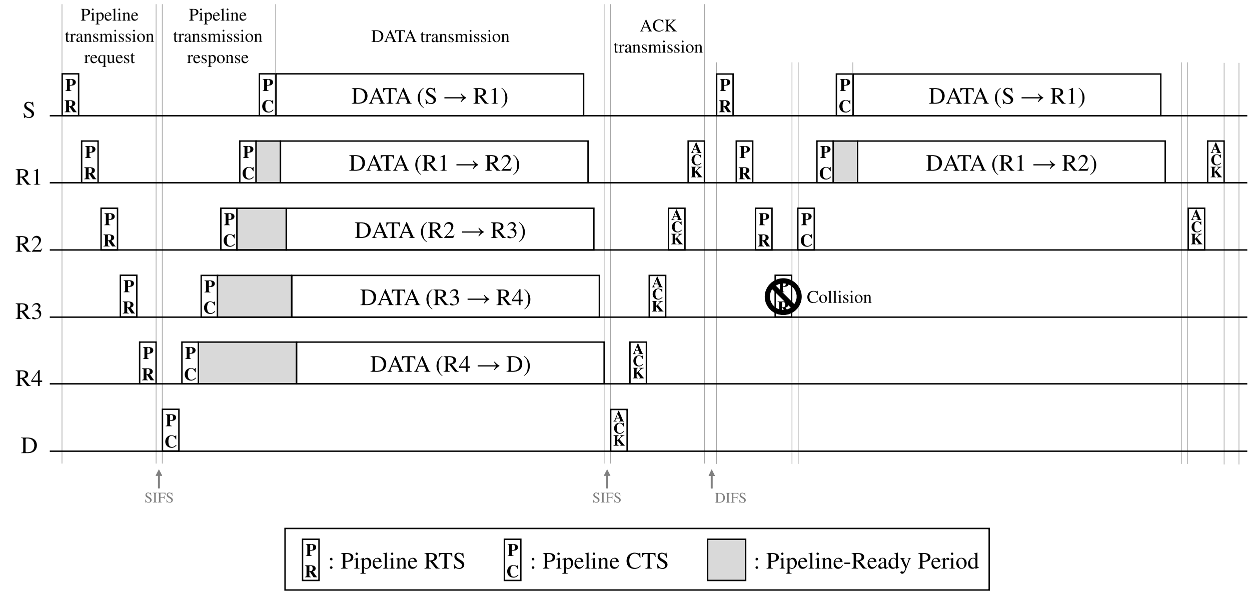


FIGURE 2. Operation of the proposed PiMAC protocol for suppressing intra-flow interference.

interference and performs stabilization of the self-interference and intra-flow interference cancellation by starting pipeline CTS transmissions from the destination node to the source node. After completing the pipeline transmission response phase, the source node starts the DATA transmission; each relay node simultaneously forwards the signal to the next relay node with a short processing delay.

In Figure 2, if a collision occurs during pipeline RTS-CTS handshaking or DATA-ACK transmission, pipelined multi-hop transmission is performed up to the last hop without the collision. For example, if the pipeline RTS sent by R_2 is lost owing to simultaneous transmissions, as shown in the second transmission period of Figure 2, R_2 fails to receive the pipeline CTS from R_3 within a timeout interval, which is determined by its hop count and the maximum bound of multiple hops. In this case, R_2 sends the pipeline CTS to R_1, and pipeline transmission is performed up to the second hop. After completing the pipeline transmission from the source node to R_2, R_2 sends the pipeline RTS to R_3. As a source node, R_2 starts the pipeline transmission of the received DATA in the next transmission period. If the source node experiences a collision during RTS/CTS handshaking, it performs the binary exponential backoff (BEB) procedure defined in the IEEE 802.11 MAC standard.

From Figure 2, it can be observed that each relay node has a variable-length pipeline-ready period after completing the transmission of the pipeline CTS. The node transmits a signal with a specific pattern at a predetermined transmit power as soon as the pipeline CTS is transmitted. In fact, the signal does not include any meaningful data for this DATA transmission. However, this signal is very important for preparing the nodes for receiving the data signal during the DATA transmission phase by nullifying the self-interference and intra-flow interference and stabilizing the interference cancellation, starting from the pipeline transmission response phase. The details are described in Section IV-B.

A. PIPELINE TRANSMISSION REQUEST PHASE

For forwarding a packet from a source node to a destination node, the source node should notify the relay nodes about the impending packet transmission. Before starting the DATA transmission, the source node sends a pipeline RTS frame with the source and destination information. If a relay node receives the pipeline RTS frame sent from the source node, it will immediately forward it to the next relay node after increasing the hop count in the pipeline RTS frame. This period is defined as the pipeline transmission request phase, as shown in Figure 2. Through this pipeline transmission request phase, each relay node is informed of the forwarding path for the transmission and estimates the channel state information of the self-interference channel. When each node transmits the pipeline RTS frame, only the node sends a signal at that time. Therefore, the node can obtain the channel state information of the self-interference without the intra-flow interference.

In addition, when R_3 sends the pipeline RTS frame to R_4 in the example in Figure 2, R_2 can estimate the processing delay for packet forwarding between R_2 and R_3. The time from the moment when the transmission of the pipeline RTS frame of R_2 is finished to the moment when R_2 starts to overhear the pipeline RTS frame of R_3 is twice the propagation delay between R_2 and R_3. Therefore, each relay node can estimate the propagation delay in this period. In addition, the processing delay for packet forwarding is a constant value depending on the forwarding scheme and the hardware characteristics of the node, as described in Section III. Therefore, each relay

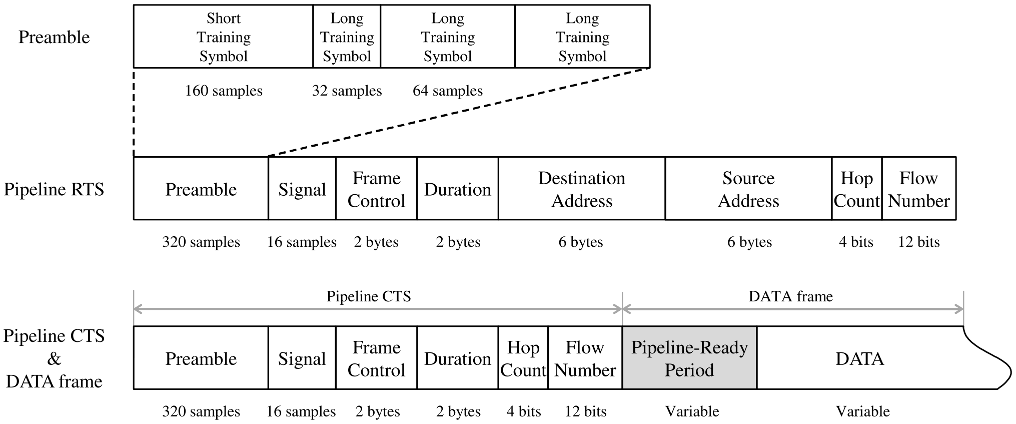


FIGURE 3. Frame structures of the training signal and DATA frame.

node is aware of the processing delay in the period. Namely, each node can estimate the values of $G_{\mathrm{R}_i,\mathrm{R}_i}$, δ_i, and T_{P} during this pipeline transmission request phase. Using the estimated information, we can obtain $C_{\mathrm{SI},\mathrm{R}_m}$ in (2) for self-interference cancellation at relay nodes.

B. PIPELINE TRANSMISSION RESPONSE PHASE

After the pipeline transmission request phase, the destination node sends a pipeline CTS frame back towards the source node through the reverse path. If a relay node receives the pipeline CTS frame from a previous relay node on the reverse path, it sends its own pipeline CTS frame to the next relay node on the reverse path or to the source node. This period is called the pipeline transmission response phase. For effective self-interference cancellation, each node needs to nullify the self-interference caused by its own transmitting signal . When each relay node starts transmitting a pipeline CTS frame, self-interference cancellation begins using $\widehat{G}_{\mathrm{R}_i,\mathrm{R}_i}$ estimated during the pipeline transmission request phase. Then, the self-interference is canceled and stabilized at the noise level.

It is also possible to cancel the intra-flow interference by gathering the channel state information from the CTS frames received during the pipeline transmission response phase. For example, as shown in Figure 2, when R_4 is transmitting the pipeline CTS frame, R_1, R_2, and R_3 can estimate the channel state information of the three-, two-, and one-hop intra-flow interference, respectively. For IFIC, $\widehat{G}_{\mathrm{R}_j,\mathrm{R}_i}$ should be estimated to generate the IFIC signal in (2).

Once channel estimation has been completed during the pipeline CTS frame transmission phase, a pipeline-ready period is observed at each relay node until DATA transmission starts. During this pipeline-ready period, each relay node transmits a signal with a specific pattern, and the relay nodes keep suppressing both the self-interference and intra-flow interference due to the dummy signal before actual data transmission. After the pipeline transmission response phase, the source node starts DATA transmission to the next relay node on the forwarding path. Because the cancellation process starts to operate before the DATA transmission phase, each node can successfully forward DATA frames without self-interference and intra-flow interference. It has been known that this approach, which makes the relay node start transmitting and canceling the self-interference before receiving the data signal in full-duplex communication, can cancel the self-interference more effectively [23].

C. FRAME STRUCTURE

As described in Sections IV-A and IV-B, estimation of the channel state information, self-interference cancellation, and IFIC is required before starting the pipelined DATA transmissions. For the pipeline transmission request and response phases, we design pipeline RTS and CTS frames and a pipeline-ready period, which is a variable-length frame.

1) PIPELINE RTS

In the pipeline transmission request shown in Figure 2, each node sequentially transmits the pipeline RTS frame to the next relay node. The frame structure of the pipeline RTS frame is shown in Figure 3. The pipeline RTS frame consists of a preamble, signal field, and generic 802.11-like MAC frame. The preamble field contains 10 repetitions of a 16-sample short training symbol and 2.5 repetitions of a 64-sample long training symbol. The training symbols in the preamble are used for automatic gain control, carrier frequency offset estimation, and symbol timing estimation. The signal field consists of pseudo-random binary phase-shift keying (BPSK) symbols for channel training. After the two fields, the remaining fields are the same as a generic 802.11 MAC frame, except that the sequence control field in the 802.11 MAC frame is used as a hop count and flow number for multihop transmission control. The hop-count field indicates the number of hops from the source node to the current node. When each relay node transmits the pipeline RTS frame, it increases the value in this field. The flow number is a unique identifier for each multihop flow. Each node transmits two 6-byte address fields that contain information about the source and destination nodes. All processes follow the orthogonal frequency division multiplexing (OFDM) standard.

2) PIPELINE CTS AND DATA FRAMES

After the source node and all relay nodes sequentially transmit the pipeline RTS frames, the destination node transmits a pipeline CTS frame to the last relay node. Then, the last relay node starts the transmission of the pipeline CTS frame to the next relay node on the reverse path. As soon as the last relay node completes the pipeline CTS frame transmission, it waits for the start of the DATA frame transmission while transmitting a signal with a specific pattern at a predetermined transmit power. During the pipeline-ready period, the self-interference and intra-flow interference at the previous node on the reverse path can be canceled at the noise level. When the pipeline CTS transmission reaches the source node, the self-interference and intra-flow interference cancellation at all relay nodes have been stabilized, and the node then starts the transmission of the DATA frame containing the actual DATA.

3) LENGTH OF THE PIPELINE-READY PERIOD

To observe the pipeline-ready period for the full-duplex stabilization described in Section IV-B, we need to precisely calculate the duration of the pipeline-ready period. The pipeline-ready period depends on the number of hops and the processing delay for packet forwarding at each relay node. In other words, the pipeline-ready period is the sum of the propagation delay, the processing delay, and the transmission durations of the pipeline CTS frames from the previous relay nodes. Let T_{CTS} denote the transmission duration of the pipeline CTS frame. T_{CTS} of all relay nodes is assumed to be the same and is expressed as

$$\begin{aligned} T_{\mathrm{CTS}} &= \frac{\text{Length of the pipeline CTS frame}}{\text{Transmission rate}} \\ &= \frac{384 \text{ samples}}{6 \text{ Mbps (basic rate)}} = 62.5\ \mu\mathrm{s}. \end{aligned}$$

Then, the pipeline-ready period of the ith relay node $T_{\mathrm{P,R}_i}$ is given by

$$T_{\mathrm{P,R}_i} = \sum_{j=1}^{i} \left(2\delta_j + T_{\mathrm{CTS}} + T_{\mathrm{P}}\right). \tag{6}$$

Each relay node transmits a signal with a specific pattern during the pipeline-ready period $T_{\mathrm{P,R}_i}$ after the pipeline CTS frame transmission and then starts the transmission of the DATA frame.

V. PERFORMANCE ANALYSIS

We analyze the effects of the various features of the PiMAC protocol on the network performance. We first perform extensive simulations for the saturated end-to-end throughput and delay performance of the PiMAC protocol using MATLAB. In addition, we investigate the effect of the intra-flow interference that can be generated by the relay nodes in a multihop path. Finally, we analyze the effects of the overhead caused by the pipeline transmission request and response phases on the end-to-end throughput.

TABLE 1. Parameters Used for the Performance Analysis

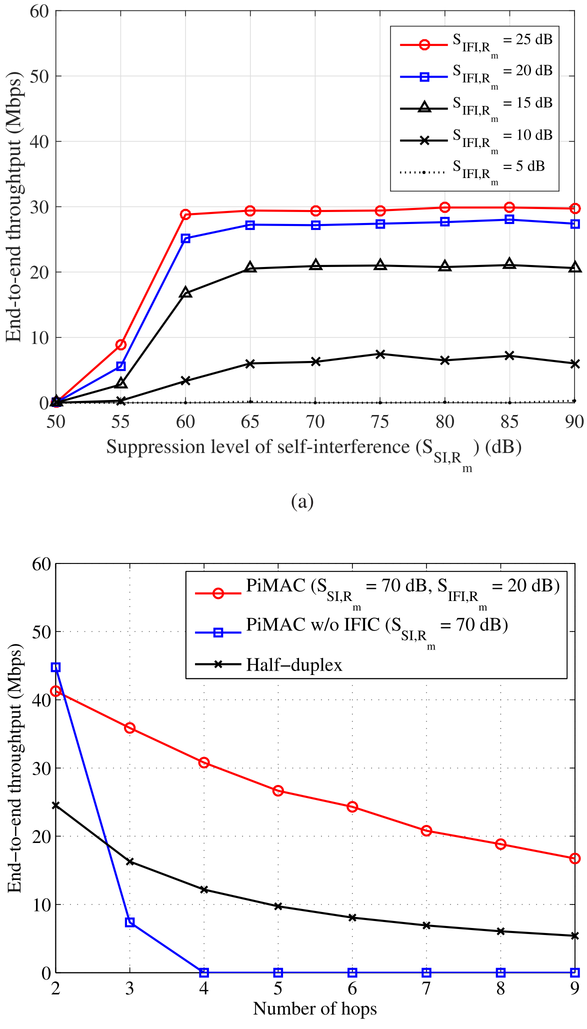
Average distance between hops	50 m	Tx–Rx antenna distance	0.25 m
Pipeline RTS	480 bits	Pipeline CTS	384 bits
DATA frame	15000 bytes	ACK	384 bits
Basic rate	6 Mbps	Data rate	54 Mbps
DIFS	28 μs	SIFS	10 μs
SINR threshold	6 dB	Background noise	-70 dBm
Propagation delay	46 ps	Processing delay	100 μs

We perform simulations for the single chain topology shown in Figure 1. In the simulations, we evaluate the performance with respect to the number of hops, which changes from 2 to 9. The distance of each hop is 50 m, and the distance between the Tx and Rx antennas at each relay node is 0.25 m. We assume that the source node has backlogged user-datagram protocol (UDP) packets for the saturation condition. The transmission rates are set to 6 Mbps for the control frames and 54 Mbps for the DATA frames. The reported values for the simulation results represent the average of 1,000 transmission sessions. The parameter values used in the simulations are listed in Table 1.

A. END-TO-END THROUGHPUT

We first verify the end-to-end throughput performance of the PiMAC protocol with respect to the suppression levels and the number of hops. Figure 4(a) shows the end-to-end throughput performance of the PiMAC protocol with the suppression levels $S_{\mathrm{SI,R}_m}$ in (4) for the self-interference and $S_{\mathrm{IFI,R}_m}$ in (5) for the intra-flow interference when the number of hops is 6. As $S_{\mathrm{SI,R}_m}$ increases, the end-to-end throughput performance rapidly increases up to 60 dB and levels off (except for the case when $S_{\mathrm{IFI,R}_m}$ = 5 dB). Because the self-interference can be sufficiently suppressed when $S_{\mathrm{SI,R}_m}$ is greater than 60 dB, there is no improvement in the end-to-end throughput performance by the increases in $S_{\mathrm{SI,R}_m}$. If $S_{\mathrm{IFI,R}_m}$ is too small, it implies that the relay nodes have strong intra-flow interference, and as a result, most transmissions are unsuccessful. It is observed that the end-to-end throughput performance significantly improves as $S_{\mathrm{IFI,R}_m}$ increases. However, the throughput improvement is less noticeable after $S_{\mathrm{IFI,R}_m} = 20$ dB.

To verify the saturated end-to-end throughput performance in full-duplex wireless relay networks, we compare the PiMAC protocol, the PiMAC protocol without IFIC, and a simple half-duplex relay transmission scheme. Figure 4(b) shows the end-to-end throughput performance with respect to the number of hops. In this simulation, the suppression levels of the self-interference and intra-flow interference are set as 70 and 20 dB, respectively, for the PiMAC protocols. The conventional full-duplex relay transmission scheme achieves the best performance only in the two-hop relay transmission case because it performs DATA transmission without any additional phases and does not compensate for the



(a)

(b)

FIGURE 4. **End-to-end throughput performance with respect to the suppression levels of self-interference and intra-flow interference and the number of hops. (a) Suppression levels of self- and intra-flow interference. (b) Number of hops.**

intra-flow interference. The end-to-end throughput performance of PiMAC without IFIC rapidly decreases as the number of hops increases because of the strong intra-flow interference. When the number of hops is four or more, PiMAC without IFIC cannot forward a packet from the source to a destination node at all. The PiMAC protocol (with IFIC) can effectively suppress the intra-flow interference by utilizing the pipeline transmission request and response phases; thus, it can achieve much higher end-to-end throughput performance than the other schemes.

B. DELAY PERFORMANCE

The transmission delay from the source to the destination node is also an important factor in wireless relay networks. In this section, we compare the transmission-delay performance of the PiMAC protocol with that of the half-duplex transmission scheme. Figure 5 shows the transmission delay with respect to the number of hops. All of the parameters and configurations in this simulation are the same as those presented in Section V-A. In the half-duplex transmission scheme, nodes cannot concurrently perform multihop transmissions from the source node to the destination node. As a result, the end-to-end delay of the half-duplex transmission scheme linearly increases as the number of hops increases. On average, it increases by 2.408 ms when the number of hops along the path increases by 1. While the end-to-end delay of the PiMAC protocol increases linearly, its increase per hop is 0.271 ms in Figure 5. The end-to-end delay of PiMAC for a nine-hop chain topology is 2.411 ms, which is almost same as the delay increase per hop of the half-duplex scheme.

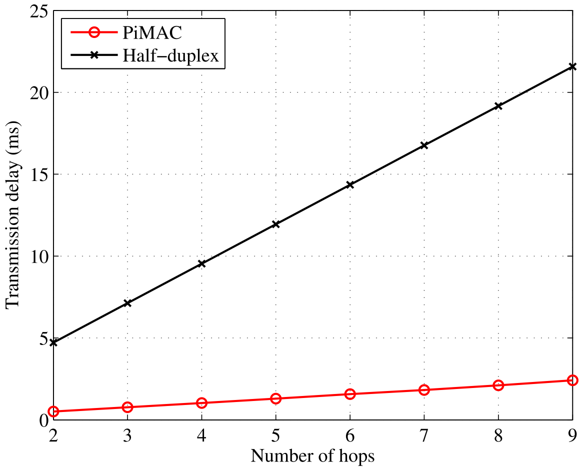


FIGURE 5. **Delay performance with respect to the number of hops.**

C. OVERHEAD RATIO

In Sections IV-A and IV-B, we presented the design of the pipeline transmission request and response phases for the pipelined multihop transmission. The time elapsed during these phases is regarded as an additional overhead, which may cause a throughput performance degradation in full-duplex wireless relay networks. We investigated the amount of protocol overhead caused by these additional phases for each multihop transmission session. The overhead ratio is given by the ratio of the time elapsed during the exchange of control frames to the total time required for entire multihop transmission session for the configuration in Table 1. For the overhead analysis, it is assumed that the self-interference and intra-flow interference are sufficiently suppressed.

Figure 6 shows the overhead ratio. In fact, the overhead includes the time required for transmitting the pipeline RTS, CTS, and ACK frames. In Figure 6, the overhead ratio of the PiMAC protocol is observed to be higher than that of the half-duplex scheme because of the additional phases for the transmissions of the pipeline RTS and CTS frames. However, without these phases, it is not possible to perform the pipelined transmission in practical full-duplex wireless relay networks. In spite of the high overhead ratio, the PiMAC protocol achieves significantly high throughput performance, as shown in Figure 5-A, by efficiently suppressing the intra-flow interference.

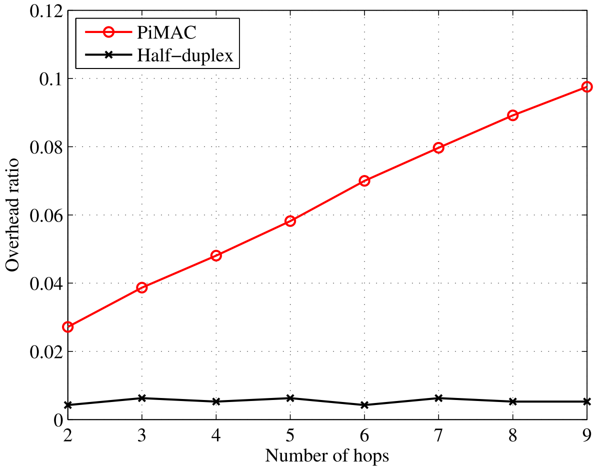


FIGURE 6. **Overhead ratio of the control frames with respect to the number of hops.**

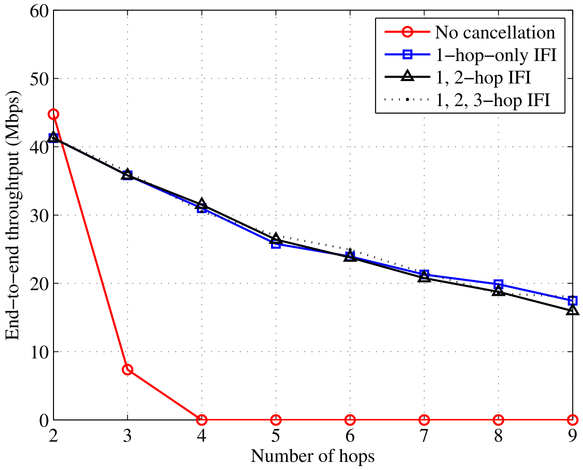


FIGURE 7. **End-to-end throughput performance of the PiMAC protocol according to different cancellation levels of multihop intra-flow interference.**

D. INTRA-FLOW INTERFERENCE CANCELLATION LEVEL

In wireless relay networks, each relay node is affected by not only the one-hop intra-flow interference but also the multihop intra-flow interference as the number of relay nodes increases. In fact, the one-hop intra-flow interference is the most significant degradation factor in the multihop network performance. We present the end-to-end throughput performance of the PiMAC protocol for different cancellation levels of multihop intra-flow interference. It is possible to cancel the most significant intra-flow interference from the one-hop-distance relay node; however, owing to the implementation complexity, it is rather difficult to cancel the intra-flow interference from all of the relay nodes on the path. Figure 7 shows the end-to-end throughput performance for different levels of multihop IFIC. From a comparison of the throughput in the case without IFIC, it is observed that IFIC significantly improves the throughput performance. A remarkable point to note here is that no significant differences in performance exist between the one-hop-only IFIC case and the multihop IFIC cases. This result implies that the end-to-end throughput performance is dominantly affected by the one-hop intra-flow interference. As a result, accurate estimation and sufficient suppression of the one-hop intra-flow interference are the most important factors for full-duplex wireless networks in practice.

VI. EXPERIMENTAL RESULTS

To experimentally verify the performance of the PiMAC protocol, we implemented the full-duplex pipelined multihop transmission scheme on the Wireless Open Access Research Platform (WARP) [24]. We carried out experiments using the WARPLab framework with four WARP v3 hardware devices. To use multiple antennas for simultaneous transmission and reception of a signal, we added an additional module with two dual-band RF interfaces on the WARP v3 hardware devices. All WARP hardware devices use a carrier frequency of 2.4 GHz with an OFDM physical layer along with quadrature phase shift keying (QPSK) modulation. In addition, we used an RF signal divider for analog self-interference cancellation. We set the transmit power to -16 dBm in all experiments. For the experimental configuration of the multihop full-duplex relay network, we set up the WARP hardware devices in a row, as shown in Figure 8. The source and destination nodes have a single antenna for transmitting and receiving, respectively, whereas the relay nodes have two antennas for simultaneous transmission and reception. The distance between two antennas on the same device is 40 cm. Data packets are transmitted from the source node to the destination node via the relay nodes.

For self-interference cancellation, the analog and digital cancellation algorithms in [4] are sequentially used. The analog cancellation algorithm upconverts the inverse waveform of the transmitted signal on the basis of the estimated coefficient of the self-interference channel. Then, the upconverted inverse waveform is added to the received signal. The residual self-interference after analog cancellation is canceled using a digital cancellation algorithm that removes the residual self-interference in the baseband after analog-to-digital conversion. Unlike the self-interference, the intra-flow interference cannot be directly canceled by analog cancellation. Therefore, only digital cancellation was used to suppress the intra-flow interference. Through the experiments, we verified the amount of interference reduction achieved by the proposed scheme at the relay nodes.

Figure 9 shows the amount of residual interference for three different cancellation schemes in our experimental environment, where both self-interference and intra-flow interference exist. The distance between nodes is 1.0 m. Without interference cancellation, the measured interference is in the range of -35 to -32 dBm. When the self-interference cancellation scheme is used, it is found that the interference is reduced by about 7 dB in Figure 9. When both the self-interference and intra-flow interference cancellation schemes are used, the amount of residual interference is significantly reduced by about 12 dB on average and about 8 dB at the 50th percentile

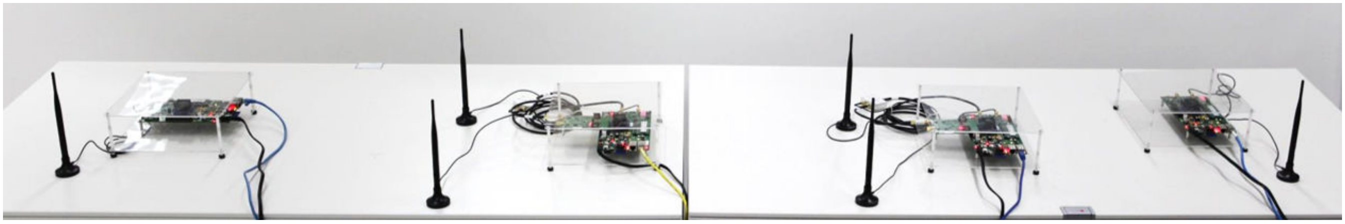


FIGURE 8. Experimental setup of a three-hop chain topology using WARP hardware devices.

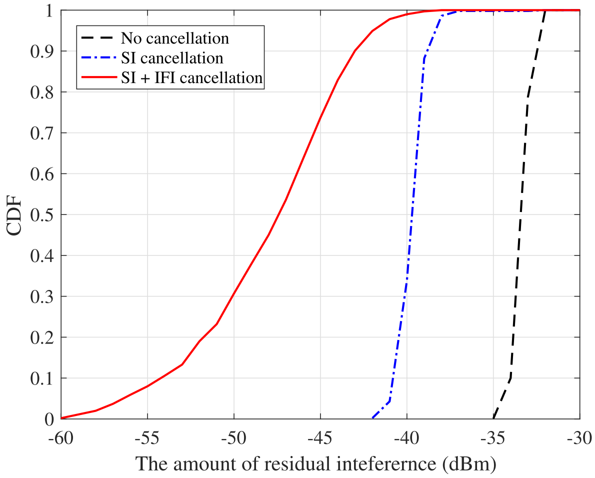


FIGURE 9. The amount of residual interference with respect to the cancellation schemes.

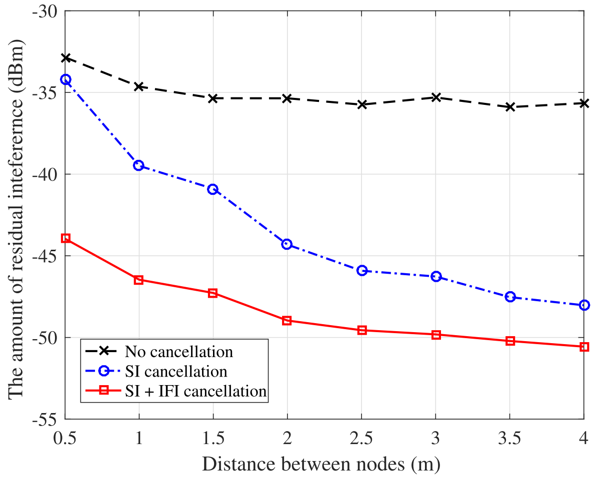


FIGURE 10. The amount of residual interference with respect to the distance between nodes and the cancellation schemes.

in comparison with the self-interference cancellation scheme. These experimental results indicate that IFIC is essential in multihop full-duplex relay networks.

Figure 10 shows the amount of residual interference with respect to the distance between nodes. We carried out experiments where the distances between nodes ranged from 0.5 to 4.0 m. The amount of residual interference without interference cancellation is reduced when the distance between nodes is in the range of 0.5–1.5 m. When the distance between nodes is more than 1.5 m, however, the amount of residual interference without interference cancellation converges. This means that the intra-flow interference is a larger part of the overall interference than the self-interference in the case of a short distance between nodes. When the distance between nodes is large, the intra-flow interference decreases, and only the self-interference remains.

The amount of residual interference with only self-interference cancellation decreases as the distance between nodes increases. However, the self-interference cancellation scheme reduces the overall interference by about 1.5 dB when the distance between nodes is 0.5 m. That is, this result indicates that the self-interference cancellation scheme cannot sufficiently suppress interference under strong intra-flow interference. When both the self-interference and intra-flow interference cancellation schemes are used, the amount of residual interference significantly decreases over the entire range. For a 0.5 m distance between nodes, the IFIC scheme reduces the amount of interference by about 11 dB. These results imply that IFIC is more effective when the intra-flow interference is strong owing to the short distance between neighboring relay nodes. The experimental results confirm that IFIC is crucial for multihop full-duplex relay networks, especially in dense multihop wireless networks with short distances between nodes. As part of our future work, we will extend our SDR-based experiments using a chain topology network in a large scale to show the feasibility of the proposed PiMAC in more realistic scenarios.

VII. CONCLUSION

For full-duplex relaying in multihop wireless networks, we proposed a pipelined MAC protocol, PiMAC, to suppress both the self-interference and intra-flow interference from the relay nodes on a multihop path. We designed a multihop channel acquisition procedure consisting of pipeline transmission request and response phases to estimate the channel state information and the processing delay for packet forwarding. Using the estimated multihop channel information, the relay nodes concurrently perform multihop transmissions by simultaneously canceling the self- and intra-flow interference. We conducted extensive simulations to evaluate the end-to-end throughput and delay performance of the PiMAC protocol and analyzed the effects of the multihop intra-flow interference and the overhead due to the additional phases. In addition, we carried out SDR-based experiments to verify the performance of the PiMAC protocol in a real wireless network. The simulation and experimental results indicate that the PiMAC protocol significantly improves the network performance in terms of the end-to-end throughput and transmission delay.

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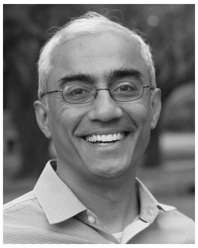

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