Hidden Chain: A Full-Duplex MAC Protocol using Hidden Terminal Relationships in WLANs

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***Abstract*—Full-duplex radio allows signals to be transmitted and received simultaneously by utilizing Self-Interference Cancellation (SIC). At a maximum, it can double the throughput of traditional half-duplex systems. To enhance throughput as much as possible, it is important to utilize downlink and uplink transmissions simultaneously. This paper proposes Hidden Chain MAC protocol, which improves throughput by using hidden terminal relationships to balance downlink and uplink traffic; it also allows access point and stations to transmit data without contention, and reduces ACK overhead. We conduct simulations to evaluate the throughput gains provided by our MAC protocol in a scenario with densely deployed stations. Through the simulation results, we show that the proposed protocol provides significant throughput improvements over the IEEE 802.11 DCF and naive full-duplex MAC protocols.**

I. Introduction

IEEE Wireless Local Area Networks (WLANs) have propagated during the past two decades. Wireless mobile devices such as smartphones have caused WLANs highly dense deployed environment in which many stations (STAs) are associated with an AP so that collisions frequently occur because of increasing number of neighboring STAs. Many novel technologies have been proposed to solve the issues of densely deployed WLANs, such as uplink Multi User-MIMO (MU-MIMO), Overlapping Basic Service Sets (OBSSs) interference handling, Orthogonal Frequency Division Multiple Access (OFDMA), and full-duplex radio [1]. Among them, we believe that full-duplex radio is a promising technology for IEEE next-generation standardization because it allows simultaneous transmission and reception over the same channel using Self-Interference Cancellation (SIC) [2] [3]. Theoretically, full-duplex radio is able to twice the spectral efficiency of conventional half-duplex radio.

Recently, many researchers have proposed full-duplex MAC protocols. Jain *et al.* and Duarte *et al.* explored the physical properties of SIC and full-duplex radio [4] [5]. A study conducted by Goyal *et al.* investigated a distributed full-duplex MAC protocol design based on the Distributed Coordination Function (DCF) [6]. Choi *et al.* proposed a full-duplex MAC protocol for Cognitive Radio Networks [7]. However, they did not consider the imbalances of real-world traffic. According to the measurements of real-world WLAN traffic, there are six times as many downlinks as uplinks [8]. This leads to imbalances between the frame sizes of downlinks and

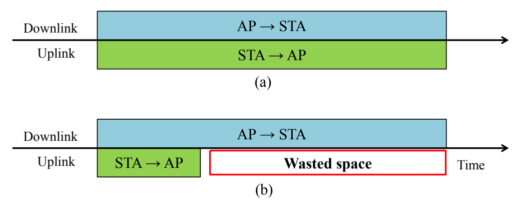

Fig. 1. Uplink and downlink frame size comparison. (a) Ideal full-duplex frame size. (b) Full-duplex frame size in real-world traffic.

uplinks, which may deteriorate the performance of full-duplex enabled WLANs. Ideal full-duplex throughput is achieved only if uplink frame sizes are the same as downlink frame sizes, as shown in Fig. 1 (a). However, in most cases, throughput gains are reduced significantly because severe imbalance between downlink and uplink frame sizes as shown Fig. 1 (b).

In order to increase the spectral efficiency of uplink, we must balance the downlink and uplink traffic by utilizing stations that are hidden from the downlink station. The hidden terminal problem is a well-known WLAN issue. It can occur when two STAs, A and B, exist within the transmission range of the AP, but out of each other's transmission ranges. As a result, A and B cannot detect each other, and they may attempt to transmit data frames to the AP at the same time; in this case, the frames will collide. In this paper, we refer to this type of relationship between A and B as a hidden terminal relationship.

Full-duplex radio can take advantage of hidden terminal relationships. That is, A transmits data to the AP, while the AP can simultaneously transmit data to B. Note that B can successfully receive the data transmitted by the AP without collision.

In this paper, we propose a MAC protocol called Hidden Chain, which consists of two schemes that deal with the issue of imbalanced traffic in full-duplex enabled WLANs. The first scheme enables an uplink ACK to be transmitted simultaneously with the next downlink if the ACK uplink STA and the data downlink STA have a hidden terminal relationship. This may reduce the waste of uplink space. In the second scheme, the AP sends a query to provide an uplink data transmission opportunity to another STA after the current uplink transmission as long as the remaining downlink period is available. A STA receiving a query must be the downlink

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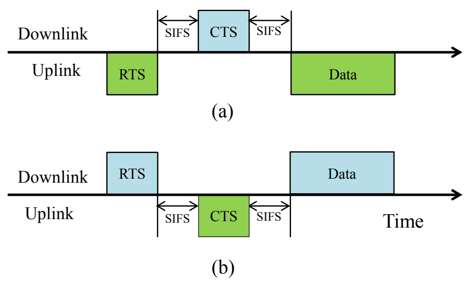

Fig. 2. RTS/CTS handshake in WLANs. (a) STA wins the contention. (b) AP wins the contention.

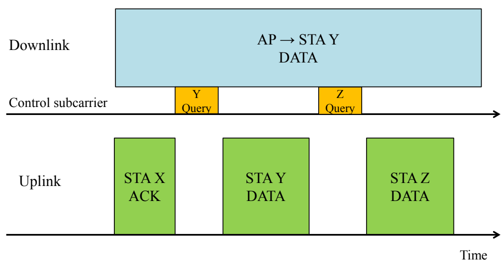

Fig. 3. Control subcarrier query operation. Y is hidden from X and Z. Hidden Chain provides an uplink data opportunity to Y and Z by sending a query via the control subcarrier.

STA or hidden from the downlink STA. For both schemes, it is essential for AP to collect hidden relationships from as many stations as possible. In the proposed MAC, AP learns more hidden relationships as time goes by.

II. Hidden Chain

A. Hidden Terminal Relationship Detection

To use Hidden Chain, the AP must know the hidden terminal relationships between STAs. Request to Send (RTS)/Clear to Send (CTS) control frames were employed to solve the hidden terminal problem in legacy WLAN standards. These can also be used to detect hidden terminal relationships. Each STA can detect a hidden terminal relationship with contention-winning STAs by overhearing an RTS/CTS handshake. If a STA is exposed to a winning STA, it can overhear the entire RTS/CTS frame handshake, while if a STA is hidden from the winning STA, it cannot overhear the entire RTS/CTS handshake.

Fig. 2 shows the RTS/CTS handshake operation. In the case shown in 2(a), if a STA is hidden from the winning STA, then the STA only overhears CTS frame transmitted by the AP. The RTS and uplink data frames cannot be overheard because they are transmitted by the hidden STA. In the case shown in 2(b), the AP transmits an RTS frame to the downlink STA. The downlink STA transmits a CTS frame to the AP. If the STA and downlink STA have a hidden terminal relationship, then the STA only overhears the RTS and downlink data frames. Therefore, the STA can determine whether it is hidden from the winning STA or downlink STA, and report its own hidden terminal relationship information to the AP, by including it on the header of the uplink data frame. As a result, the AP learns all of the hidden terminal relationships of the STAs, and

TABLE I. Hidden Terminal Relationship Table

STA	Hidden Terminal Relationship
STA A	STA B
STA B	STA A, C, D
STA C	STA B, E
STA D	STA B
STA E	STA C
STA F	STA H, G

will use this information to manage the Hidden Chain MAC protocol.

B. Control Subcarrier Query

To balance the frame sizes, AP transmits a query via a control subcarrier to provide additional uplink opportunities to other STAs when the uplink transmission is completed and the downlink period has sufficient remaining time. Downlinks in our MAC protocol allocate 51 subcarriers for data transmissions and one subcarrier for control tasks, while uplinks use 52 subcarriers for data transmissions. Thus, downlink throughput losses of up to 1.9% occur, owing to control subcarrier overhead. However, whenever a sufficient downlink transmission remains, our MAC protocol can increase the spectral efficiency of uplink transmission.

The query includes the STA's Association ID (AID), which must be the current downlink STA's AID or the AID of another STA that is hidden from the current downlink STA; the STA receiving the query is entitled to immediately transmit the uplink data frame when it has uplink data. However, if it has no data, it transmits a signal that includes its own AID. The current downlink STA has the priority to receive queries first, because other STAs can recognize up-to-date hidden terminal relationships with the current downlink STA. If a STA cannot decode the current downlink after a bi-directional full-duplex transmission has been started, it recognizes that it is no longer hidden from the current downlink STA. If the STA receiving the query is no longer hidden from the current downlink STA, then it does not transmit anything. The AP waits to receive the response to query for two OFDM symbols duration. The AP recognizes that this STA is no longer hidden from the current downlink STA, and updates the hidden terminal relationships. Query listening STAs are synchronized via downlink pilot subcarrier.

Fig. 3 shows an overview of the query operation. After STA X's ACK uplink is completed, the AP sends a query to current downlink STA Y. After finishing Y's uplink data transmission, the AP sends another query to STA Z, because sufficient downlink time is still available.

C. Hidden Chain MAC protocol

The Hidden Chain is generated by the AP; it randomly selects the next Hidden Chain STA, which must satisfy the following two rules. First, the next Hidden Chain STA must be hidden from the current downlink STA. Second, in order to prevent STA chains from being circulated infinitely, it must not overlap with the previous Hidden Chain's STAs.

Prior to the description of the Hidden Chain, we assume that the downlink frames of STAs A, B, C, and F are in the AP

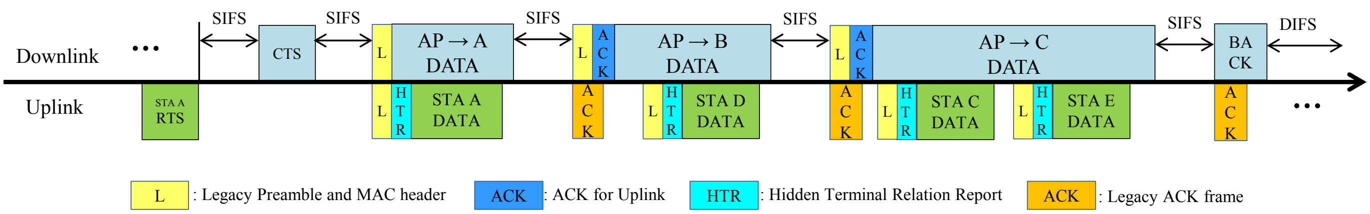

Fig. 4. STA A is the winner of the contention. Downlinks for STA B and STA C are transmitted by Hidden Chain. AP and STAs allow contention-free transmission of data frames during the Hidden Chain period.

buffer, and the hidden terminal relationships between stations are as shown in Table I.

Fig. 4 shows an example of a Hidden Chain operation. STA A is the winner of the contention. The AP and A are exchanging RTS/CTS frames and transmitting data frames simultaneously. The AP does not send a query, because the remaining downlink period is insufficient.

After finishing the downlink transmission to A, the AP generates a Hidden Chain by selecting a next downlink. The AP selects the first Hidden Chain by sending a downlink data frame to STA B. This downlink data frame includes the ACK for A's uplink data frame. While the AP transmits a downlink data frame to B, A sends an ACK frame for AP's downlink. The AP and A can identify each ACK through SIC. After A's uplink ACK transmission is completed, the AP sends a query as explained in Section 3. In this example, STA D receives a query and transmits a data frame to the AP, because B does not have uplink data.

The AP selects STA C into the second Hidden Chain. The downlink data frame to C, and B's uplink ACK frame to the AP, are transmitted simultaneously. The AP identifies B's uplink ACK through SIC. D also identifies the ACK that is included in the header of the downlink frame. It successfully decodes the ACK because B and D are in a hidden terminal relationship. C is also hidden from B. It receives the downlink data frame successfully, without interference from B's uplink ACK. After B's uplink ACK is completed, C and E have the opportunity to transmit uplink data frames via queries.

In this example, STA F's downlink remains in the AP buffer, but it cannot be transmitted using the Hidden Chain because it is exposed to C. Therefore, the AP does not have the downlink that is hidden from C. It stops the Hidden Chain and sends a multi-block ACK frame for the uplink data of C and E. The AP and STAs will operate as a legacy WLAN until a new winning STA is determined for the contention.

III. Analysis

We conducted an analytical evaluation of our proposed MAC protocol, the IEEE 802.11 DCF protocol, and the naive full-duplex method. Let $T_{roundtime}$ be the total time required to transmit data payloads, from the DCF Interframe Space (DIFS) wait time through the completion of the ACK frame transmission. $T_{roundtime} = DIFS + T_{cw} + T_{dataframe} + SIFS + T_{ackframe}$, where T_{cw} is the average contention window size, $T_{dataframe}$ is the time required to perform a data frame transmission, and $T_{ackframe}$ is the time required to perform an ACK frame transmission. We obtain the throughput($Tput_{dcf}$) using the IEEE 802.11 DCF method shown in Eq. (1).

$$Tput_{dcf} = \frac{payload}{T_{roundtime}} \tag{1}$$

The naive full-duplex method is IEEE 802.11 DCF equipped with a full-duplex radio. We assume that AP of this method has already all of the hidden terminal relationships of the STAs without additional control overhead. We obtain the throughput ($Tput_{FD}$) of the naive full-duplex method from Eq. (2).

$$Tput_{FD} = \frac{DLpayload + ULpayload}{T_{roundtime}} \tag{2}$$

The Hidden Chain can have various chain lengths ($K = 0, 1, 2, ...$), and can transmit multiple uplink data frames per chain. The throughput($Tput_{HC_K}$) of the Hidden Chain with chain length K can be analytically obtained in Eq. (3), where N is the average number of uplink data frames which are transmitted by query per chain, $T_{rts/cts}$ is the time required to perform the RTS/CTS handshake and α is control subcarrier overhead. Whenever one chain is added, Hidden Chain obtains throughout gain: $N \times ULpayload$, and reduces overhead: $DIFS$, T_{cw}, $T_{ackframe}$ than naive full-duplex and $2DIFS$, $2T_{cw}$, $2T_{ackframe}$ than IEEE 802.11 DCF without collisions.

$$\begin{aligned} &Tput_{HC_K} \\ &= \frac{(K+1)DLpayload + (1 + N(K+1))ULpayload}{T_{rts/cts} + T_{roundtime} + (K)(T_{dataframe} + SIFS + \alpha)} \end{aligned} \tag{3}$$

IV. Evaluation

We conducted a simulation to evaluate the throughput of the Hidden Chain MAC protocol using Visual Studio 2013. Our simulation measured the total system throughput of the three MAC protocols: IEEE 802.11 DCF, naive full-duplex, and Hidden Chain, while varying the number of STAs from 10 to 100. Parameters were set based on the specification of IEEE 802.11ac. The length of the data frame header for Hidden Chain was increased by 24 bytes, which was allocated to report hidden terminal relationships to the AP in uplink, or to send ACKs for uplink data in downlink. We set the hidden terminal relationship ratio per STA to an average of 15% [9]. We used a downlink-heavy traffic model. Thus, the size of the downlink data payload was set to 1500 bytes, while the uplink data payload was set to 250 bytes. We assumed that STAs

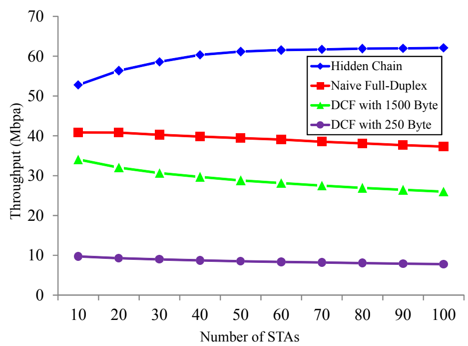

Fig. 5. Simulation results from IEEE 802.11 DCF, naive full-duplex, and Hidden Chain. The results show the total throughput of the network in relation to the number of STAs. The data payload of IEEE 802.11 DCF was set to 1500 bytes or 250 bytes.

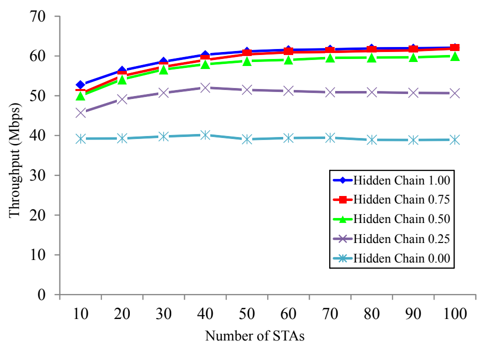

Fig. 6. Simulation results from Hidden Chain with various query success probabilities.

continuously generate data, and used a 20 MHz bandwidth and a single spatial stream.

Fig. 5 shows the total system throughput results of the simulation. The throughput of naive full-duplex method is almost same as the sum of IEEE 802.11 DCF with 1500 bytes and 250 bytes, because it allows simultaneous transmission and reception of data frames. The Hidden Chain provides a significant throughput gain compared to IEEE 802.11 DCF and naive full-duplex, even though the number of stations are increased, because the length of chain becomes longer and it leads to the throughput gain per chain: multiple data frames transmission in contention-free, and reduce overheads such as DIFS, back-off time, ACK transmission time, and collisions. Our proposed MAC protocol provides throughput gains of between 29% and 66% compared to naive full-duplex in densely deployed scenarios.

Fig. 6 shows the Hidden Chain throughputs in relation to the query success probability. Our proposed MAC protocol obtains sufficient throughput gain compared to naive full-duplex method when the success query probability is greater than or equal to 25%. Even the query success probability is zero; the Hidden Chain shows almost the same throughput as naive full-duplex method, because downlink data frames are transmitted without contention.

V. Conclusion

In this paper, we discussed the imbalances between downlink and uplink traffic in full-duplex enabled WLANs. To solve this issue, we proposed the Hidden Chain MAC protocol. This protocol balances downlink and uplink frame sizes by transmitting an uplink ACK and another uplink data frame when the current uplink is completed, but the downlink continues. In addition, our MAC protocol improves throughput because the AP and STAs allow contention-free transmission of data frames, and reduces ACK overhead during the Hidden Chain period. We demonstrated the throughput gain of our MAC protocol through an analytical evaluation and simulation in a dense WLAN deployment environment. Compared with the naive full-duplex MAC protocol, our proposed MAC protocol achieved throughput gains of between 29% and 66%.

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References

[1] W. Sun, O. Lee, Y. Shin, S. Kim, C. Yang, H. Kim, and S. Choi, "Wi-fi could be much more," *Communications Magazine, IEEE*, vol. 52, no. 11, pp. 22–29, Nov 2014.

[2] D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," *SIGCOMM Comput. Commun. Rev.*, vol. 43, no. 4, pp. 375–386, Aug. 2013.

[3] A. Sahai, G. Patel, and A. Sabharwal, "Pushing the limits of full-duplex: Design and real-time implementation," *CoRR*, vol. abs/1107.0607, 2011. [Online]. Available: http://arxiv.org/abs/1107.0607

[4] M. Jain, J. I. Choi, T. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, and P. Sinha, "Practical, real-time, full duplex wireless," in *Proceedings of the 17th Annual International Conference on Mobile Computing and Networking*, ser. MobiCom '11. New York, NY, USA: ACM, 2011, pp. 301–312.

[5] M. Duarte, A. Sabharwal, V. Aggarwal, R. Jana, K. Ramakrishnan, C. Rice, and N. Shankaranarayanan, "Design and characterization of a full-duplex multiantenna system for wifi networks," *Vehicular Technology, IEEE Transactions on*, vol. 63, no. 3, pp. 1160–1177, March 2014.

[6] S. Goyal, P. Liu, O. Gurbuz, E. Erkip, and S. Panwar, "A distributed mac protocol for full duplex radio," in *Signals, Systems and Computers, 2013 Asilomar Conference on*, Nov 2013, pp. 788–792.

[7] N. Choi, M. Patel, and S. Venkatesan, "A full duplex multi-channel mac protocol for multi-hop cognitive radio networks," in *Cognitive Radio Oriented Wireless Networks and Communications, 2006. 1st International Conference on*, June 2006, pp. 1–5.

[8] H. Falaki, D. Lymberopoulos, R. Mahajan, S. Kandula, and D. Estrin, "A first look at traffic on smartphones," in *Proceedings of the 10th ACM SIGCOMM Conference on Internet Measurement*, ser. IMC '10. New York, NY, USA: ACM, 2010, pp. 281–287.

[9] S. Gollakota and D. Katabi, "Zigzag decoding: Combating hidden terminals in wireless networks," in *Proceedings of the ACM SIGCOMM 2008 Conference on Data Communication*, ser. SIGCOMM '08. New York, NY, USA: ACM, 2008, pp. 159–170.