An Embedded Secondary Contention Window for In-Band Full-Duplex Enabled WLAN

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Abstract-In-band full-duplex wireless techniques have provided an attractive opportunity to double both spectrum efficiency and network throughput. A shared wireless channel permits two sets of directional paths, one called by primary and the other by secondary, onto which two different pairs of wireless stations can send simultaneously their packets with no collision. The complexity emerges in station selection for multiple access due to random distribution, especially for WLAN. We propose in this paper an elaborate scheme to address the competition in secondary path access while keeping primary path fully compatible to the conventional 4-way handshaking of IEEE 802.11 Distributed Coordination Function (DCF). A generic framework of throughput analysis is discussed and a formulation specific to a simplified topology is deduced. Numeric evaluations show that the proposed scheme promises a maximum speedup factor beyond double in magnitude.

Keywords-in-band full-duplex; WLAN; secondary path access; embedded contention window; p-consistence CSMA; throughput performance

I. INTRODUCTION

Recent advances in wireless in-band Full-Duplex (FD) techniques have provided an attractive opportunity to double not only spectrum efficiency but also transmission throughput in comparison with half-duplex (HD) counterpart [1]. The common and shared wireless channel permits two packets being transmitted simultaneously by two neighbor stations in case each is capable of self-interference cancellation. However, this good feature cannot be utilized directly for a multiple random access network such as conventional WLAN. The complexity of contention collision on channel and also hidden node effect should be re-examined and re-devised elaborately and properly.

An FD channel shared by two wireless stations can employ two transmission paths with opposite direction [2]. This simplest topology is referred to as bi-directional pair. As for WLAN applications, a relay-like topology emerges where two mutual hidden stations are reachable to the third one, and can form two co-directional accessible paths [3], or a chain-typed structure, as depicted in Fig.1.

In Fig.1, we assume all stations are FD enabled and their receiving (Rx) and transmitting (Tx) blocks plotted in a split manner and filled by different color. The station A is assumed in further to transmit a data frame to it neighbor B, and the station C and D are hidden to A and B, respectively, due to distance fading or obstacle screening. From Fig.1, one can find three types of accessible path combination. Using the note (A, B) for the primary path, the secondary path can be denoted by (B, A) for bi-directional pair, (B, C) for forward chain, and (D, A) for backward chain. However, the three secondary paths are mutual exclusion, i.e., only one of them can be selected in order to avoid the resolvable interference or collision in frames transmission. Meanwhile, any exposed station like the node E in Fig.1 must be excluded in the selection for that such station will disturb inevitably the primary path transmission.

Generally, the selection of primary and secondary path can be carried out either simultaneously or sequentially. A simultaneous manner requires all participants support full-duplex operations [4], while a sequential one is easy to work with legacy HD stations. In this paper, we present a design of sequential scheme which consists of two stages, the first adopting 4-way handshaking DCF for primary path and the second using p-persistent CSMA for secondary path. The key to scheme is to embed a so-called Secondary Contention Window (SCW) by Network Allocation Vector (NAV) of primary RTS control frame in its duration field.

The rest of this paper is organized as follows: Section II describes our scheme design. Section III presents a generic analysis on the performance of throughput and related HD compatibility. Results of numeric evaluation are presented in Sections IV, followed by a discussion and conclusion section.

Figure 1. Illustration of 3 types of path structure of FD channel.
II. SCHEME DESIGN

Our scheme is based on a wireless station with FD enabled physical layer, and focuses on Media Access Control (MAC) layer to select efficiently secondary path. In order to make it feasible to practical deployment, the scheme, named by full-duplex DCF (FDCF), is set to work with conventional station with HD operations.

Aiming at HD compatible, RTS/CTS handshaking defined in IEEE 802.11 DCF remains unchanged but a bit of modification on NAV computation as showed in Fig.2. An example of frames flow is described for a forward chain, in comparison with that of conventional DCF. The cases of bidirectional pair and backward chain are the same except an extra delay in secondary path contention in the latter.

The SCW interval covers in time both S-RTS and S-CTS transmission, plus some necessary inter-frame spaces. At the end of SCW, double data frames, as denoted by Data and S-Data in Fig.2, are sent simultaneously onto the primary and secondary path, respectively. On successfully received, double ACK frames are acknowledged also simultaneously.

Comparing with conventional DCF, the FDCF will take a little more time, i.e., a SCW, to complete its data frame(s) transmission. This overhead can be compensated in the performance of throughput by the doubling of data frame transmission if the secondary path can be accessed without any interference or collision.

It can be imagined that collision happens if more than one station, such as the node B, C and D in Fig.1, contends the secondary path. Also, there is a probability the receiver of the secondary path fails to response to S-RTS which is addressed to the exposed node such as E. These two cases result in a degradation in effective utilization and throughput. We propose to adopt the conventional p-consistent CSMA method by assigning a probability of S-RTS sending. The probability for D can be optimized dynamically according to \( N_C \), the number of backward chains. For simplicity, we set the probability, \( p = 1 / N_B \), as defined in [5].

HD compatibility of the FDCF is straightforward. For the case the primary sender, A, operates in HD mode, it starts to send its waiting data frame at the very end of SIFS after CTS transmission. Since the delay of S-RTS has been defined as PIFS or PIFS + TRTS, longer than SIFS, any attempt to secondary path will quit and result in no interference to A in HD mode. Actually, for a primary sender in HD mode, the proposed FDCF goes back to conventional DCF.

For the primary receiver, B, operating in HD mode, it will block data transmitting procedure according to DCF specification until the end of RTS-NAV indicated by the primary sender A. The only difference between FDCF and DCF in this case is the unemployed time of SCW. The little low utilization result is also valid for the case the node D operating in HD mode.

III. PERFORMANCE ANALYSIS

The probability of successful channel contending for conventional DCF is denoted by \( p_{DCF} \). Generally, this probability represents the condition only one pair of stations starting RTS/CTS handshaking, referring [6], as follows,

\[
p_{DCF} = \frac{nq(1-q)^{n-1}}{1-(1-q)^n},
\]

where, \( n \) is the number of stations contending on the common channel with the same probability \( q \) of RTS sending.

Given that, there is a probability, \( 1 - p_{DCF} \), an RTS/CTS handshaking disturbed and interrupted by collision.

As for FDCF, a primary receiver, the node B in Fig.1 and Fig.2, can always succeed in contending secondary path if it has waiting data addressed to the primary sender A, i.e., \( p_{BA} = 1 \).

Also, the succeed probability on the path from the node B to C is direct, \( p_{BC} = N_C / (N_C + N_D) \), assuming B select...
randomly its neighbor nodes other than A, and \( N_E \) and \( N_C \)
denoting the number of exposed nodes and that of accessible
forward chains, respectively.

By the same consideration, we denote the number of
accessible backward chains by \( N_D \). It is equal to the number of
nodes similar to the node D in Fig.1. The succeed probability
on the path from D to A, given that the node B has no data
waiting to send, is then,

\[
p_{DA} = (1 - p)^{N_D - 1} = (1 - \frac{1}{N_D})^{N_D - 1}, \tag{2} \]

where, \( N_D \) is assumed greater then 0, otherwise \( p_{DA} = 0 \).
Again we use the assumption \( p = 1 / N_D \), as mentioned before.

The total probability of the collision-free secondary path
contending is then the sum as follows,

\[
P_{SP} = q_{BA}p_{BA} + (1 - q_{BA})q_{BC}p_{BC} + (1 - q_{BA})(1 - q_{BC})q_{DA}p_{DA}, \tag{3} \]

where, \( q_{BA} \) is the probability of the node B has data waiting
to send to A, \( q_{BC} \) is that from B to C, and \( q_{DA} \) that from D to A.

As one can see, \( q_{BA} \) is equal to the average request, \( q \),
defined in Eq.(1), between any pair of nearest neighbors.
Under a fully randomized traffics, one can derive the following
two equations,

\[
q_{BC} = 1 - (1 - q)^{N_C + N_E}, \tag{4} \]
\[
q_{DA} = 1 - (1 - q)^{N_D}. \tag{5} \]

For a simple case, let \( N_C = 1, N_E = 0 \) and \( N_D = 1 \), a 4-node
chain-like topology, it can get then,

\[
q_{AB} = q_{BC} = q_{DA} = q, \tag{6} \]
\[
p_{BA} = p_{BC} = p_{DA} = 1. \tag{7} \]

By replacing Eq.(6) and (7) into Eq.(3), we have,

\[
P_{SP} = q + (1 - q)q + (1 - q)^2q = q(3 - 3q + q^2) \tag{8} \]

That means, there is probability \( q(3 - 3q + q^2) \) in the 4-node
chain-like topology to send two packets within one successful
transmission period, \( T_{FDCE} \), headed by RTS/CTS handshaking.

Since our FDCF scheme has only an embedded SCW
interval in comparison with the conventional DCF, it can be
represented by,

\[
T_{FDCE} = T_{DCF} + T_{SCW} \tag{9} \]

Assuming all packets is fixed in length, \( L_{data} \), and requires
the time \( T_{data} \) to transmit them, it is then,

\[
T_{DCF} = T_{RTS} + T_{CTS} + T_{data} + T_{ACK} + DIFS + 3 \times SIFS \tag{10} \]

where, \( T_{RTS}, T_{CTS} \) and \( T_{ACK} \) are, in turn, the time to transmit
the frame of RTS, CTS and ACK, DIFS for the time for
channel idle sensing, and SIFS for inter-frame spacing among
the four frames.

The time, \( T_{SCW} \), is determined by the longest reserved
interval for the node D in Fig.1, including the time to transmit
two RTSs, one CTS, the leading PIFS and two SIFSs, that is,

\[
T_{SCW} = 2 \times T_{RTS} + T_{CTS} + PIFS + 2 \times SIFS \tag{11} \]

The average time spent for unsuccessful contention in DCF
can be expressed as, approximately,

\[
T_{OH} = T_{RTS} + T_{CTS} + DIFS + SIFS \tag{12} \]

The average throughput of DCF is approximately,

\[
S_{DCF} = \frac{P_{DCF} \times L_{data}}{T_{DCF} \times P_{DCF}}, \tag{13} \]

where the average back-off time to channel access is
regarded as so small to be considered. The counterpart of
FDCF is then,

\[
S_{FDCE} = \frac{(1 + P_{SP}) \times P_{DCF} \times L_{data}}{T_{OH} \times (1 - P_{DCF}) \times P_{DCF} \times P_{DCF}}, \tag{14} \]

The ratio of the throughput of FDCF over that of DCF, or
speedup factor, is,

\[
f = \frac{S_{FDCE}}{S_{DCF}} = (1 + P_{SP}) \frac{T_{OH}(1 - P_{DCF}) + T_{FDCE} \times P_{DCF}}{T_{OH}(1 - P_{DCF}) + T_{DCF} \times P_{DCF}} \tag{15} \]

Eq.(14) has a closed form since both \( P_{SP} \) and \( P_{DCF} \) are the
function of the probability \( q \), the average rate of data sending
from one station to another. Thus, the benefit of FD operation
to the throughput of WLAN can be figured out as the average
loaded traffics.

IV. NUMERIC EVALUATION

We use parameters of DCF specified in IEEE 802.11b [7]
and those of FDCF are showed in Tab.I for the calculation
according to Eq.(15). The length of data frame and the
probability station sends the frame, are the only that affects the
speedup factor.
Table I. Parameters Used for Numeric Evaluations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>11 Mbit/s</td>
<td>T_{CTS}</td>
<td>10.2 μs</td>
</tr>
<tr>
<td>SIFS</td>
<td>10 μs</td>
<td>T_{ACK}</td>
<td>10.2 μs</td>
</tr>
<tr>
<td>PIFS</td>
<td>30 μs</td>
<td>T_{DCF}</td>
<td>114.9 μs + T_{data}</td>
</tr>
<tr>
<td>DIFS</td>
<td>50 μs</td>
<td>T_{SCW}</td>
<td>89.2 μs</td>
</tr>
<tr>
<td>RTS</td>
<td>20 Bytes</td>
<td>T_{FDCF}</td>
<td>204.1 μs + T_{data}</td>
</tr>
<tr>
<td>CTS/ACK</td>
<td>14 Bytes</td>
<td>T_{data}(64 B)</td>
<td>46.5 μs</td>
</tr>
<tr>
<td>T_{RTS}</td>
<td>14.5 μs</td>
<td>T_{data}(1500 B)</td>
<td>1090.9 μs</td>
</tr>
</tbody>
</table>

Fig. 3 shows the result of speedup factor, $f$, varying along with the probability of data sending, $q$, of a four-node chain-type WLAN. The number of station, $n = 4$ for PDCF by Eq.(1), and PSP is determined by Eq.(8).

From Fig. 3, it can be seen that the speedup factor for both short packet (64B) and long (1500B) packet have values greater than two. And, most significantly, the maximum speedup factor of short packet is about 2.33 at $q = 0.4$, and that of long packet is about 2.05 at $q = 0.68$.

Figure 3 The throughput speedup factor $f$ varies with the neighbor packet sending probability $q$, for an FD WLAN containing three accessible secondary paths.

Fig. 4 shows a curve of maximum speedup factor varying with the length of packet, and a curve of sending probability by which the maximum factor obtains.

The reason for the throughput upgradation being greater than double relates to the reduction by FDCF in random contention.

V. DISCUSSION AND CONCLUSION

In-band full-duplex wireless techniques have provided an attractive approach to double both spectrum efficiency and channel capacity without needing extra radio resources. The good feature can not be utilized directly for WLAN which typically accessed randomly by multiple stations. There are three types of secondary path on a common channel leads to a more complex issue in contention collision. In this paper, we proposed a new DCF compatible scheme which focus on secondary path control of FD channel.

Specifically, a $p$-consistent CSMA method has been introduced in this paper to be embedded in DCF operations. The details of the proposed two stage control scheme is present followed by a closed form of performance analysis and numeric evaluations. Results show clearly a throughput speedup factor beyond double can be obtained for a simplified 4-node chain-typed topology.

The benefit of FD to upgrading WLAN throughput, we think, should be much more significant for complex topologies where much more part of contending collisions can be reduced due to secondary path employed.

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REFERENCES


