Coexistence Wi-Fi MAC Design for Mitigating Interference Caused by Collocated Bluetooth

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Abstract—A non-collaborative coexistence mechanism for wireless-fidelity (Wi-Fi) and bluetooth (BT) systems based on dynamic packet fragmentation is proposed in this work. The basic idea is to adapt the packet length of Wi-Fi in the MAC layer such that the fragmented packet has a better chance to survive the interference from the nearby BT devices. We first develop an analytical model that specifies the information required by the Wi-Fi MAC layer to decide the best fragmentation strategy. Then, this model is extended to analyze the throughput and transmission delay of the Wi-Fi device. The analytical model is validated by computer simulation. Furthermore, it is demonstrated by simulation results that the proposed coexistence mechanism improves the performance of Wi-Fi in throughput and transmission delay significantly while relatively smaller performance improvement is observed for BT.

Index Terms—Fragmentation, Wi-Fi, Bluetooth, non-collaborative coexistence mechanism, medium access control, unlicensed spectrum

1 INTRODUCTION

THE ISM unlicensed (UL) band is presently populated by various wireless devices [2]–[5]. Most of these devices are used for wireless local area networking (WLAN) with the wireless-fidelity (Wi-Fi) technology [2] or wireless personal area networking (WPAN) with the Bluetooth (BT) technology [3]. Since WLAN and WPAN are complementary rather than competing technologies, it is likely that Wi-Fi and Bluetooth devices will operate concurrently in close proximity. Since both devices use the same frequency band and their radio coverages overlap with each other, the interference between them can be very severe [6]–[18]. To provide a ubiquitous communication environment through the shared frequency band, we should not only enable devices to access the UL band efficiently but also develop a coexistence mechanism that detects and mitigates the interference between different types of wireless devices.

Due to the importance of coexistence, IEEE has created a coexistence task group, called the IEEE 802.15 TG2 [19], to study and reduce the interference impact on the throughput of coexisting wireless devices. The task group has defined two classes of coexistence mechanism, namely, collaborative and non-collaborative. Although the classification scheme is mainly developed for BT, the principle can be applied to other coexisting scenarios. The collaborative mechanism

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reprints@ieee.org, and reference the Digital Object Identifier below. Digital Object Identifier no. 10.1109/TC.2013.224 works only when the information exchange is possible among coexisting heterogeneous networks [12]–[14], [19], [20], and thus is feasible only when the two systems are installed on the same device and controlled by a centralized controller, *e.g.* a common driver. On the other hand, a non-collaborative mechanism is free from such a requirement and it is likely to be employed in most of the practical scenarios [1], [15], [21]. Under non-collaborative coexistence, each device simply takes its own maneuver to reduce the interference.

A non-collaborative coexistence solution for Wi-Fi is the main focus of this paper. The proposed mechanism dynamically adjusts the fragmentation level based on the current level of the packet error rate (PER). Thus, it is called the dynamic fragmentation (DF) scheme, which is triggered only when it is needed. Our mechanism has two versions. The version for mobile networks is named DF-I while the version for static networks is named DF-II. We first develop an analytical model to evaluate the PER of Wi-Fi and BT devices under interference, and then show that the model can be employed to effectively determine the right time (in terms of PER) for further fragmentation.

Furthermore, with the proposed DF scheme, 802.11 MAC can distinguish whether the failed transmission is due to *interference* caused by a BT device or due to *collision* caused by a Wi-Fi station so that different actions can be taken to achieve higher throughput. It will be shown by simulation results that our DF mechanism could reduce the interference between Wi-Fi and BT and significantly improve the performance of Wi-Fi in both throughput and transmission delay, although only slight performance improvement is observed for BT.

The rest of the paper is organized as follows. Previous work on coexistence is reviewed in Section 2. The dynamic fragmentation (DF) scheme is described in Section 3, where the analytical model for interference is given in Section 3.2, transmission time and transition threshold are analyzed in

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Section 3.3, throughput and transmission delay are studied in Sections 3.4 and 3.5, respectively. Simulation results are given in Section 4 to validate our analytical model and to show the performance improvement on throughput and transmission delay. Concluding remarks are drawn in Section 5.

2 REVIEW OF PREVIOUS WORK

Coexistence issue of different types of wireless network systems has already been rigorously studied [5], [6], [12], [16], [22]–[27]. Some works focus on investigating the effects of interference between different types of wireless systems and most of those works are performed at the physical layer, while other works focus on devising techniques to mitigate interference between the different systems. Our work focuses on the issue of mitigating interference between Wi-Fi and BT.

With the rapid frequency hopping mechanism and a broader operating frequency band, BT is more capable of avoiding interference caused by Wi-Fi devices. The BT performance in the presence of Wi-Fi has been studied in [8], [10], [13], [14], [15], [21], [28], and [29]. There have been works on non-collaborative mechanisms developed to further strengthen the interference mitigation capability of BT, including AFH (Adaptive Frequency Hopping) [15], [19], [30], BIAS (Bluetooth Interference Aware Scheduling) [31], D-OLA (Data-OverLap Avoidance) [32], DAFH (Dynamic Adaptive Frequency Hopping) [10]. These mechanisms control the hopset to avoid overlapping in frequency. The basic idea is to distinguish good channels from bad ones and then let the hopping sequence visit good channels more frequently than bad ones.

In contrast, Wi-Fi is more vulnerable to interference caused by BT devices due to its longer data packet and lack of frequency agility. Thus, it is crucial to develop some coexistence mechanisms for Wi-Fi. Unfortunately, not much such research work has been done so far. A scheduling mechanism, known as V-OLA (Voice-OverLap Avoidance) [32], has been proposed to avoid the interference from the BT voice traffic by squeezing Wi-Fi transmission into the idle period between consecutive BT voice packets. However, it works when BT devices have voice traffic only and, otherwise, requires collocated BT devices to run D-OLA [32]. Consequently, it is not a pure non-collaborative solution. More recently, packet fragmentation has been proposed as an effective way to mitigate interference. An analytical model is presented in [34] for finding the optimal fragmentation with respect to PER by solving involved differential equations. However, though the developed model is quite helpful in investigating the effects of interference between Wi-Fi and BT, it may not be a useful tool to mitigate interference between the two systems due to the burdensome complexity of the model, i.e. by the time when optimal fragmentation is obtained, the interference status may have already been changed. Therefore, instead of finding the optimal packet length in arduous effort as what [34] does, we aim to provide immediate performance boost rather than gradual performance adjustment. In this paper, we will show that to find the right timing for fragmentation is more effective than to costly determine the optimal fragmentation. To the best of our knowledge, so far we have not yet seen any other pure non-collaborative interference mitigation mechanism developed for MAC protocol of Wi-Fi.

Interference can be modeled in different ways [35]–[38], and, in general, can be categorized into two groups, namely physical model and protocol model. In the physical model [35], [36], SNR_{ij} denotes the signal-to-noise ratio at node n_j for transmissions received from node n_i . The total noise at n_i consists of the ambient noise plus the interference due to other ongoing transmissions in the network. A transmission from node n_i to node n_i is successful if $SNR_{ij} \ge SNR_t$, where SNR_t is a threshold signal-to-noise ratio. In the protocol model [36], there are V number of nodes in a wireless network, where nodes are denoted by n_i , $1 \le i \le V$, and d_{ij} represents the distance between nodes n_i and n_j . Each node, n_i , is equipped with a radio with communication range R_i and a larger interference range R'_i . In this model, if there is a single wireless channel, a transmission from n_i to n_j is successful if both of the following conditions hold: (i) $d_{ij} \leq R_i$, and (ii) any other node n_k , such that $d_{kj} \leq R'_{k'}$ is not transmitting. It has been indicated in [38] that caution should be exercised before interpreting results based on different interference models. Due to the nature of this work, we took the approach of *protocol model*.

3 PROPOSED DYNAMIC FRAGMENTATION (DF) MECHANISM

3.1 Description of DF Mechanism

There are two fundamental issues that Wi-Fi has to cope with to mitigate interference in a coexistence environment. First, a Wi-Fi station cannot determine if a packet loss is due to collision or interference. The impotence of the PHY layer resolution on such an incident limits the capability of MAC to improve the coexisting performance. As a result, Wi-Fi's collision avoidance mechanism (which is CSMA/CA) would treat all packet loss incidents in the same way, *i.e.* double the backoff window and retransmit the packet. This leads to the second issue: CSMA/CA is not efficient in dealing with interference. Basically, CSMA/CA is designed to solve the traffic congestion problem among Wi-Fi stations. With a longer backoff window, the traffic is expected to average out over time and thus lower the collision rate. However, the interference rate (caused by BT) will not be lowered by simply increasing the backoff time due to the fact that there is no backoff window mechanism on the BT side. Failing to lower the interference rate by increasing the backoff time, CSMA/ CA is ineffective and simply introduces unnecessary overhead. We would like to devise a new mechanism to address the problem of packet loss due to interference, which motivates our work of dynamic fragmentation (DF) mechanism.

The basic idea is to develop an algorithm that adjusts the Wi-Fi packet length using the existing fragmentation function of 802.11 [2] and the latest PER information to reduce the interference rate caused by BT. In other words, legacy 802.11 MAC will be enhanced by the proposed DF algorithm so that it can handle the interference problem at run time. It is worthwhile to emphasize that the DF algorithm aims at reducing the interference rate but not the collision rate. The task of collision rate reduction is still on the shoulder of CSMA/CA.

As depicted in Fig. 1, there are two states in the proposed DF mechanism; namely, states 1 and 2. The entire communication payload is transmitted in one piece without



Fig. 1. Flowchart of dynamic fragmentation mechanism.

fragmentation in state 1. On the other hand, the entire communication payload of a single packet is divided into η fragments, which are transmitted sequentially, in state 2. The system collects the packet error rate (PER) information periodically in a fixed time interval. For state transition, we compare PER and threshold p. If the current system is in state 1 and the latest PER is higher than *p*, the system transits from state 1 to state 2. If the current system is in state 2 and the latest PER is lower than *p*, then the system transits from state 2 back to state 1. For all other situations, the system remains in its original state without state transition. Determining a proper threshold value, *p*, is critical in the proposed DF algorithm. This can be achieved by comparing the fragmentation cost and the throughput gain, which will be elaborated later. Although the proposed DF mechanism employs two states only, to be generic, our analytical model is developed to model the transition from the state of n fragments to the state of ηn fragments such that it can be applied to other scenarios with more complicated fragmentation schemes as well.

Before discussing the selection of p, we explain how fragmentation works below. Fig. 2(a) shows the basic packet



Fig. 2. Successful transmission of (a) legacy 802.11 with no fragmentation and (b) two fragments with no retransmission; and retransmission of (c) DF-I for mobile WLAN and (d) DF-II for static WLAN.



Fig. 3. Illustration of the Wi-Fi packet transmission and the BT time slot.

transmission of legacy 802.11 without fragmentation. It waits for a DIFS, keeps listening until the end of backoff window BW (or contention window) and then sends data in one piece. Finally, an *ACK* completes the transmission. Fig. 2(b) shows the packet transmission with fragmentation. In this example, the payload is divided into two fragments, i.e., DATA_1 and DATA_2. The first fragment is sent with the full contention mechanism. Then, after SIFS, the second fragment is sent without contention. Fragments are ACKed separately. Fig. 2(c) shows what happens when some fragment suffers from transmission failure. Each of the failed fragments has to be retransmitted with the full contention mechanism. The bottom line is that the prior fragment has to be successfully received before any attempt of the next fragment. For transmissions in the sequel, if it is not a retransmission, the contention mechanism could be saved.

3.2 Interference Rate Analysis

Since the performance affected by interference is of our main concern, following [32], we assume that there is no hidden node problem and the effect of RTS/CTS is ignored to simplify the analysis. Nevertheless, according to our study, the outcome remains unaffected even with the intervention of RTS/CTS. To conduct the analysis, we need to develop an interference model first. Interference between Wi-Fi and BT occurs when transmissions of the two systems overlap both in frequency and time. Whenever the residual signal strength of one is higher than the SINR threshold of the other, it results in a packet loss. Depending on the spatial relation, transmission power, the carrier sensing threshold and channel conditions, there are three scenarios of transmission failure: BT packet loss, Wi-Fi packet loss, or both. Since the nature of collision due to BT/Wi-Fi interference is different from that due to the contention of multiple Wi-Fi stations, we refer the packet loss caused by interference between BT and Wi-Fi as an interference incident and use collision exclusively for the packet loss caused by the contention of Wi-Fi stations throughout the rest of this paper.

Normally, a Wi-Fi packet has a length equal to that of several BT time slots. Let T_W be the time duration of Wi-Fi packet transmission, 1T_B be the BT time slot and T_{BA} represent the active time within each BT time slot. Furthermore, we use t to denote the time interval between the beginning of Wi-Fi packet and the beginning of the first overlapped BT time slot as shown in Fig. 3.

1. T_W contains both DATA and ACK, and if any portion of the duration is interfered, it will cause retransmission.

According to [32], the number of BT time slots, N, that overlap with a Wi-Fi packet could be calculated by

$$N = \begin{cases} \begin{bmatrix} \frac{T_W}{T_B} \end{bmatrix}, & \text{if } t \le \begin{bmatrix} \frac{T_W}{T_B} \end{bmatrix} T_B - T_W, \\ \begin{bmatrix} \frac{T_W}{T_B} \end{bmatrix} + 1, & \text{otherwise.} \end{cases}$$
(1)

If the packet length in Eq. (1) is a random variable, we can replace T_W and N by $E[T_W]$ and E[N], respectively. The probability that a BT device hops on the frequencies that would interfere Wi-Fi transmission is denoted by P_f . Since there is an inactive period in each BT time slot, the utilization rate of a BT time slot is denoted by σ . If there are multiple collocated WPANs, the number of WPANs is n_{BT} . For the *i*th piconet π_i , we define the traffic load (or piconet activity) G_i to be the probability of a packet in a time slot.

For a single WPAN and a single WLAN, we can express the PER of a Wi-Fi station as

$$PER_{Wi-Fi} = 1 - (1 - P_f G\sigma)^N \approx NP_f G\sigma, \text{ where } \sigma = \frac{T_{BA}}{T_B}.$$
(2)

For multiple collocated WPANs, the PER becomes

$$PER_{Wi-Fi} = 1 - \prod_{i=1}^{n_{BT}} (1 - P_f G_i \sigma)^N \approx \sum_{i=1}^{n_{BT}} NP_f G_i \sigma.$$
(3)

The PER of WPAN under the interference from Wi-Fi will not be needed in our model and is thus omitted.

3.3 Transmission Time and Threshold Analysis

Following [34], for a successful transmission with no fragmentation as shown in Fig. 2(a), the total time of a complete transmission can be written as

$$DIFS + BW + T_h + T_{DATA} + SIFS + T_{ACK}, \qquad (4)$$

where DIFS and SIFS are two kinds of inter-frame intervals, BW is the time of the backoff window (or contention window) and T_h , T_{DATA} and T_{ACK} are the transmission times for the header, DATA and ACK of a packet, respectively. BW is a random number times the Wi-Fi time slot.

If the packet is divided into n fragments as shown in Fig. 2(b), the total transmission time with no retransmission can be expressed as

$$DIFS + BW + T_h + \frac{T_{DATA}}{n} + SIFS + T_{ACK} + (n-1)\left(SIFS + T_h + \frac{T_{DATA}}{n} + SIFS + T_{ACK}\right), \quad (5)$$

which can be further simplified to

$$DIFS - SIFS + BW + n \left(SIFS + T_h + \frac{T_{DATA}}{n} + SIFS + T_{ACK}\right).$$
(6)

Note that $T_{oh} = T_h + T_{ACK} + 2 \times SIFS$ is a fixed overhead for each fragment. It is easy to check that Eq. (4) is a special case

of Eq. (5) when n = 1. Thus, the total transmission time, T_s , for n fragments without any retransmission is equal to

$$T_s = DIFS - SIFS + BW + n\left(T_{oh} + \frac{T_{DATA}}{n}\right).$$
(7)

If there is a fragment loss, a retransmission would take place such as the scenario in Fig. 2(c). Then, the time for a single retransmission is

$$T_r = DIFS - SIFS + BW + T_{oh} + \frac{T_{DATA}}{n}.$$
 (8)

Finally, we could determine the total transmission time of a packet, which is divided into n fragments and suffers a total R retransmissions. The total transmission time would be the successful transmission time of n fragments plus R times the single retransmission time, *i.e.*

$$T_{n,R} = DIFS - SIFS + BW + n\left(\frac{T_{DATA}}{n} + T_{oh}\right) + R\left(DIFS - SIFS + BW + T_{oh} + \frac{T_{DATA}}{n}\right) = (R+1)(DIFS - SIFS) + \sum_{1+R} BW_i + (n+R)\left(T_{oh} + \frac{T_{DATA}}{n}\right).$$
(9)

After the above analysis, we would like to determine the threshold for state transition. In the proposed DF scheme, the decision on state transition depends on whether the transition could reduce the expected transmission time. If the total transmission time can be reduced by a new state, the state transition will be conducted. From the state of *n* fragments to the next state, the number of fragments changes from *n* to $n'(=\eta n)$ and the retransmission number will change accordingly. We use *R* and *R'* to denote the numbers of retransmission before and after the state transition, respectively. Then, the condition for a transition to occur can be expressed as

$$E\left[(R+1)(DIFS - SIFS) + \sum_{i=1}^{1+R} BW_i + (n+R)\left(\frac{T_{DATA}}{n} + T_{oh}\right)\right] > E\left[(R'+1)(DIFS - SIFS) + \sum_{i=1}^{1+R'} BW_i + (n'+R')\left(\frac{T_{DATA}}{n'} + T_{oh}\right)\right].$$
(10)

After rearranging the terms, the inequality becomes

$$(E[R] - E[R'])(DIFS - SIFS) + (E[R] - E[R'] - (\eta - 1)n)T_{oh} + \left(E[R] - \frac{E[R']}{\eta}\right)\frac{T_{DATA}}{n} + E\left[\sum_{i=1}^{R} BW_i\right] - E\left[\sum_{i=1}^{R'} BW_i\right] > 0.$$
(11)

To calculate the threshold, we need to find all the expected values in Eq. (11). First, we have

$$E[R] = E\left[\sum_{i=1}^{n} R_i\right],\tag{12}$$

where *R* is the total number of retransmissions and $E[R_i]$ is the expected number of retransmission for each fragment, and ntimes the value would be the expected value of the total number of retransmission. It is assumed that R_i is geometrically distributed, whose probability is in the form of $f_{R_k}(k) = p^k(1-p)$, where k is the retransmission count. Then, E[R] can be expressed as

$$E[R] = n \times E[R_i] = \frac{np}{1-p}.$$
(13)

Next, we want to find E[R']. For terms in Eqs. (2) and (3), P_f , *G* and σ will remain the same after state transition, only *N*, which is a function of n, will change. Based on Eqs. (2) and (3), we can obtain the following:

$$\frac{PER_{Wi-Fi}}{PER'_{Wi-Fi}} = \frac{p}{p'} = \frac{N}{N'},$$

and then

$$p' = \frac{N'}{N}p.$$
 (14)

Therefore,

$$E[R'] = \frac{n'p'}{1-p'} = \frac{n'\frac{N}{N}p}{1-\frac{N'}{N}p} = \frac{n'p}{\frac{N}{N'}-p} = \frac{\eta np}{\kappa - p},$$
 (15)

where $\kappa = \frac{N}{N'}$ and $\eta = \frac{n'}{n}$. To find $E[\sum_{i=1}^{R} BW_i]$ and $E[\sum_{i=1}^{R'} BW_i]$, we have to calculate a few parameters. Let CW_{min} and CW_{max} be the minimum and maximum sizes of the backoff window (or contention window), and constants a and b are defined by $CW_{min} = 2^a - 1$ and $CW_{max} = 2^b - 1$. For a fragment enters its *k*th retransmission, we have

$$BW(k) \in [0, 1, 2, \dots, 2^{k+a} - 1] \times T_{slot},$$

so that the expected backoff window can be expressed as

$$E[BW(k)] = \frac{1}{2}(2^{k+a} - 1) \times T_{slot}.$$
 (16)

For any fragment, E[BW(k)] is the average backoff of the kth retransmission. Since the expected value of total retransmissions of a packet is E[R], the expected value of total backoff of a fragment is $\sum_{k=1}^{E[R_i]} E[BW(k)]$. For a packet divided into nequal length fragments, the total backoff of all fragments is

$$E\left[\sum_{i=1}^{R} BW_i\right] = n \times \sum_{k=1}^{E[R_i]} E[BW(k)].$$

Since the backoff window is doubled only up to the upper bound CW_{max} , we consider the following two cases.

Case A: $E[R_i] \leq b - a$ and the backoff window is not greater than the maximum contention window size. Then, we have

$$E\left[\sum_{i=1}^{R} BW_{i}\right] = n \times \sum_{k=1}^{E[R_{i}]} E[BW(k)]$$

= $n \times \sum_{k=1}^{E[R_{i}]} \frac{1}{2} (2^{k+a} - 1) \times T_{slot}$
= $\frac{1}{2} (2^{a+1} (2^{E[R_{i}]} - 1) - E[R_{i}]) \times nT_{slot}.$

Case B: $E[R_i] > b - a$ and the backoff window reaches the maximum contention window size. Then, we get

$$E\left[\sum_{i=1}^{R} BW_{i}\right] = n \times \sum_{k=1}^{E[R_{i}]} E[BW(k)]$$

= $n \times \left\{\sum_{k=1}^{b-a} \frac{1}{2}(2^{a+k} - 1) + \sum_{k=b-a+1}^{E[R_{i}]} \frac{1}{2}(2^{b} - 1)\right\} \times T_{slot}$
= $\frac{1}{2}(2^{a+1}(2^{b-a} - 1) - 2^{b}(b-a) + (2^{b} - 1)E[R_{i}]) \times nT_{slot}$

Without loss of generality, we consider the case with $E[R_i] \leq b-a$ and $E[R'_i] \leq b-a$. Then, the following expressions can be derived:

$$E\left[\sum_{i=1}^{R} BW_{i}\right] = \sum_{k=1}^{E[R_{i}]} \frac{1}{2} (2^{k+a} - 1) \times nT_{slot}$$
$$= \frac{1}{2} (2^{a+1} (2^{E[R_{i}]} - 1) - E[R_{i}]) \times nT_{slot}, \qquad (17)$$

and

$$E\left[\sum_{i=1}^{R'} BW_i\right] = \sum_{k=1}^{E[R'_i]} \frac{1}{2} (2^{i+a} - 1) \times \eta n T_{slot}$$
$$= \frac{1}{2} (2^{a+1} (2^{E[R'_i]} - 1) - E[R'_i]) \times \eta n T_{slot}.$$
(18)

Since all terms in Eq. (11) are now available, we could plug them in to calculate the threshold. That is, we have

$$F(p) = (E[R] - E[R'])(DIFS - SIFS) + (E[R] - E[R'] - (\eta - 1)n)T_{oh} + \left(E[R] - \frac{E[R']}{\eta}\right)\frac{T_{DATA}}{n} + E\left[\sum_{i=1}^{R} BW_i\right] - E\left[\sum_{i=1}^{R'} BW_i\right].$$
(19)

We can solve F(p) = 0 with $F(p^{-})F(p^{+}) < 0$ for p.

3.4 Throughput Analysis

As defined in [39], the throughput is the fraction of the total transmission time dedicated to the payload transmission. Mathematically, we have

throughput =

$$\frac{I_{DATA}}{E[(R+1)(DIFS-SIFS) + \sum_{i=1}^{1+R} BW_i + (n+R)(\frac{T_{DATA}}{n} + T_{oh})]}$$
(20)

According to Eq. (20), to improve the throughput, one can either cut down overhead or reduce the number of retransmissions. For fragmentation, there is a tradeoff between retransmission and overhead. The more a transmission is fragmented, the more overhead it will incur. However, the fewer and cheaper retransmission is expected. When the gain of reducing the retransmission number cannot balance off the loss of the increased overhead, fragmentation is not a good solution. This explains the necessity of a careful analysis of the fragmentation cost so as to guarantee the performance improvement.

We investigate the overhead cost and find an opportunity for further performance improvement below. The total overhead cost can be broken down into four parts: the header, the inter-frame space, the ACK message and the backoff window. The first three parts are fixed while the last one varies with PER. Moreover, the overhead of the backoff window grows exponentially with PER.

For a normal Wi-Fi transmission in a static environment (without mobility), there should be no collision in the middle of a transmission session. Collision happens only when two Wi-Fi stations randomly choose the same backoff window and they start their transmission at the same time. In other words, collision either happens from the beginning of a transmission or it does not happen at all. This scenario is quite different from that of interference. Since BT has no carrier sensing mechanism, interference could happen at any time during a Wi-Fi transmission. Since Wi-Fi performs carrier sensing, interference is unlikely to happen at the beginning of a transmission.

Without DF, CSMA/CA alone cannot exploit this interesting feature. With DF, we can associate some suitable interpretation with the transmission status of a certain fragment. For example, if the first fragment in a sequence of multiple fragments is lost, it is most likely a collision. On the other hand, if subsequent fragments encounter a transmission failure, it is quite likely due to interference. In CSMA/CA with DF, if a station enters a fragmentation state but does not observe a reduction in PER or any transmission failure in the second fragment and beyond, it is likely that the high PER is caused by collision only. Thus, we should switch back to the non-fragmentation state since, under such a scenario, fragmentation will fail to reduce PER but just decreases the throughput by introducing some unnecessary overhead.

Except for the first fragment, retransmission of subsequent fragments is most likely caused by interference so that the backoff window assigned by the collision avoidance mechanism for those subsequent fragments will simply introduce unnecessary overhead but has no impact on reducing the interference probability. Consequently, we should simply bypass them as shown in Fig. 2(d). Under this new procedure, when a sender encounters a transmission failure for the second fragment or its subsequent ones, it will retransmit the fragment immediately after the ACK timeout without waiting for the backoff window. This revised scheme is called *DF-II*. The original scheme, called *DF-I*, can be used for mobile networks while DF-II can improve the performance of static networks.

For DF-II, since collision may incur the retransmission of the first fragment, we should keep the backoff window for the retransmission of the first fragment. Let r be the retransmission count of the first fragment. Then, R - r is the retransmission count for subsequent fragments which are free from the backoff procedure. In analogy with Eq. (9), we can derive the total transmission time for successful transmission of n fragments plus R retransmissions for DF-II as

$$T_{n,R,II} = \left(DIFS - SIFS + BW + n\left(\frac{T_{DATA}}{n} + T_{oh}\right)\right) + r\left(DIFS - SIFS + BW + \frac{T_{DATA}}{n} + T_{oh}\right) + (R - r)\left(DIFS - SIFS + \frac{T_{DATA}}{n} + T_{oh}\right) = (R + 1)(DIFS - SIFS) + \sum_{i=1}^{1+r} BW_i + (n + R)\left(\frac{T_{DATA}}{n} + T_{oh}\right).$$
(21)

The threshold decision function for DF-II can be derived by modifying Eq. (19) as

$$F(p) = (E[R] - E[R'])(DIFS - SIFS) + (E[R] - E[R'] - (\eta - 1)n)T_{oh} + \left(E[R] - \frac{E[R']}{\eta}\right)\frac{1}{n}T_{DATA} + E\left[\sum_{i=1}^{r} BW_{i}\right] - E\left[\sum_{i=1}^{r'} BW_{i}\right].$$
(22)

By removing unnecessary backoff windows, we can lower the price of fragmentation so that the threshold of entering the fragmentation state is lowered.

With the system parameters given in Table 1, we can study the relationship between throughput and PER under different schemes and then determine threshold p accordingly. Three cases are examined in Fig. 4. They are the legacy 802.11 without fragmentation, DF-I and DF-II with fixed fragmentation ($\eta = 2$). The dashed lines in Fig. 4 are analytical throughput values as functions of different PER levels while the solid lines are the values obtained by computer simulation. We see a close match between analytical and simulated results. Furthermore, the throughput performance favors no fragmentation in lower PER values but fragmentation in higher PER values, and fragmented DF-II outperforms fragmented DF-I. These are consistent with our above analysis.

The legacy 802.11 intersects with fragmented DF-I and DF-II at PER equal to 0.4 and 0.3, respectively. It means that we should choose these values as threshold values. For example, if PER is less than 0.3, DF-II should stay in state 1 (no fragmentation). Otherwise, DF-II should be in state 2. It is worthwhile to mention that the threshold values are sensitive to the fixed transmission overhead, T_{oh} , which accounts for the majority of the fragmentation cost, and the ratio of overlapped BT time slots in one Wi-Fi fragment of the current and the previous state, which is κ in Eq. (15).

Parameters for Wi-Fi and BT Systems Assigned Value Parameter Slot time $20 \ \mu s$ $50 \ \mu s$ DIFS SIFS $10 \ \mu s$ PHY header 192 bits MAC header 224 bits Payload 12000 bits ACK 112 bits $\overline{CW_{min}}$ 32 \overline{CW}_{max} 1024 **BlueTooth Parameters** 625 µs T_B $366 \ \mu s$ T_{BA}

TABLE 1

3.5 Delay Analysis

When a Wi-Fi packet is sent without retransmission nor fragmentation, the transmission delay for such perfect transmission comes from requirements of the standard such as DIFS, the contention window, SIFS, time for the ACK message and headers. However, besides these factors, there is another type of delay caused by interference, *i.e.* time due to retransmissions. Here, transmission delay is defined as the difference between the actual transmission time and the transmission time for the non-fragmented payload. It is basically the extra time caused by retransmission, the fragmentation overhead and the spacing time set by the standard. Mathematically, we have

$$delay = n \times T_{oh} + (E[R] + 1) \times \left(DIFS - SIFS + T_{oh} + \frac{T_{DATA}}{n} \right) + \sum_{i=1}^{E[R]} BW_i.$$
(23)

Since fragmentation decreases the retransmission penalty, the proposed DF mechanism can decrease the delay caused by retransmissions. DF makes the state transition, *i.e.* performs fragmentation, only when the expected transmission time is less than that of the non-fragmentation case, thereby reducing the transmission delay. In other words, as far as the delay is concerned, DF in general outperforms scheduling-based algorithms, *e.g.* [32], in terms of packet transmission delay, which will be verified by computer simulation in the next section.

4 COMPUTER SIMULATION

4.1 Simulation Environment Setup

Our computer simulation environment consists of one WLAN network and several piconets in proximity. A Wi-Fi device and a BT device are separated in less than 3 meters since such a distance results in the most severe interference effect [17], [18]. This scenario is common in offices, households, airports, *etc.* For example, a PDA is connected to a laptop via Wi-Fi (11 *Mb/s*), and a nearby piconet, *e.g.* cellphone/headset, is communicating over the BT link. The device separation distance is



Fig. 4. Throughput as a function of PER for three schemes.

intentionally assigned to capture the specific interference scenario. That is, if a BT device operates at Wi-Fi frequency band, and if some Wi-Fi stations are also active, then both transmissions would fail. However, if BT transmits outside the Wi-Fi frequency band, concurrent transmission is possible. In other words, P_f is exactly 22/79 in our simulation. To reduce the simulation complexity, the following assumptions have been made without loss of generality: (i) the propagation delay of WLAN and WPAN is neglected due to the short operational distance; (ii) WLAN is of low mobility, which is the most common scenario of Wi-Fi; and (iii) piconets may be mobile, yet its mobility would have little impact on the interference pattern due to the wide coverage of Wi-Fi.

The arrival rate of Wi-Fi packets is exponentially distributed. The Wi-Fi packet length is fixed in simulation.² The Wi-Fi and BT parameters used in simulation are summarized in Table 1. The header part in each Wi-Fi fragment consists of the PHY header (or called the preamble) and the MAC header. With these parameters, we can calculate the best η , which is equal to two in our simulation, with respect to the assigned packet length. A higher η value, *i.e.* with more number of fragments, will not decrease κ of Eq. (15), but just increase the overhead.

Both SCO and ACL traffic scenarios are simulated for BT. For the SCO link, the most popular HV3-type link is used and a packet is generated every six time slots in both directions. A BT slave can support up to three SCO links from the same master or two SCO links if the links are originated from different masters. An SCO packet needs no ACK nor retransmission. If a BT slot is not reserved by SCO, the master could establish the ACL link on per slot basis. Each ACL link packet needs to be ACKed in the next time slot. In the ACL simulation, the DH1-type link is used such that one data packet occupies one BT time slot. The packet arrival rate of ACL is also exponentially distributed.

2. For a variable payload length, parameter *max_Fragment* (*Payload*)_*length* can be used to control the fragment length.



Fig. 5. The Wi-Fi PER as a function of the BT traffic load.

With different BT traffics, we consider three scenarios:

- Wi-Fi runs on legacy 802.11 without any fragmentation;
- Wi-Fi runs on dynamic fragmentation DF-I;
- Wi-Fi runs on dynamic fragmentation DF-II.

Each plotted value shown in the figures is the average results of at least 50 runs.

4.2 Simulation Results and Discussion

To verify our analysis, we first see that the state transition threshold obtained from the analytical model is close to that obtained by simulation as shown in Fig. 4. Based on Eqs. (19) and (22), the threshold values for DF-I and DF-II are 0.38 and 0.31, respectively. They are also confirmed in Fig. 4. Furthermore, the relation between the PER of Wi-Fi and the BT traffic load is shown in Fig. 5 which verifies Eq. (2). It is clear that simulation curves are consistent with our analytical prediction. These results demonstrate the accuracy of our analytical model, which can capture the interference phenomenon between Wi-Fi and BT well.

Fig. 6 shows the throughput improvement of Wi-Fi with DF in the log scale. In our calculation, the Wi-Fi throughput is defined in Eq. (20), which is the ratio of time dedicated to payload to the total transmission time, including the time spent on retransmissions. When the PER of Wi-Fi is equal to 0.5 and 0.6, the throughput improvement of DF-I is equal to 15% and 30% respectively. For DF-II, the throughput improvement becomes 28% and 56%, respectively.³ One noticeable trend is that the throughput improvement grows exponentially with PER. On the other hand, one might think that we might have negative throughput improvement for low PER since the gain in reducing retransmissions caused by interference could be lower than the induced overhead. However, since our algorithm is dynamically adjusted based on the PER level, no negative improvement would actually happen. That is, when PER is below the threshold, there will be no fragmentation.



Fig. 6. Throughput improvement for Wi-Fi with DF-I and DF-II.

Fig. 7 shows the Wi-Fi throughput as a function of different Wi-Fi traffic loads when there are two SCO links in presence. Since our mechanism is neither collaborative nor scheduling, our mechanism will not have an extra benefit from the recursive nature of SCO traffic. Two SCO links present a substantial traffic load on the BT side. Thus, the DF mechanism outperforms legacy 802.11 even with a low Wi-Fi traffic load.

Simulation results of the Wi-Fi throughput as a function of the BT ACL traffic load with two background Wi-Fi traffic loads are shown in Figs. 8 and 9. We see a significant improvement on the Wi-Fi throughput in Fig. 9 and the improvement increases exponentially with the BT traffic load. The crossing points between DF-I/DF-II and legacy 802.11 represent appropriate thresholds. This threshold is a function of the background Wi-Fi traffic load. Intuitively, a higher background traffic load will trigger the state transition earlier. Fig. 8 gives the result of the same simulation setup except for a lower background Wi-Fi traffic load. We see a higher threshold, which is consistent with our intuition.



Fig. 7. Throughput of the Wi-Fi network, which coexists with two SCO links on the BT piconet.

^{3.} One may argue that the PER of a Wi-Fi is not supposed to be as high as 0.3. This is true if the collision is only caused by other Wi-Fi devices. However, if there are BT devices in a close proximity, it is quite possible to have PER of up to 0.6. As an example, a common scenario of collocated Wi-Fi and BT in a very close proximity is a smartphone user using BT earphone to have a Skype chat through Wi-Fi.



Fig. 8. Throughput of the Wi-Fi network in the presence of ACL link on the BT piconet, where the background Wi-Fi traffic is given by $\tau_{Wi-Fi} = 0.3$.

Fig. 10 shows a slight improvement on the BT throughput. The curves of DF-I,II and legacy 802.11 are close to each other when the Wi-Fi traffic load is low. We see more visible performance improvement when the Wi-Fi traffic load is sufficiently high. Even though the improvement is not impressive at the BT side, our scheme has no negative impact on the BT performance at any event. Note that the proposed DF scheme can significantly decrease the cost of Wi-Fi retransmission (only the fraction of the entire packet), but cannot prevent any Wi-Fi transmission failure. For the same reason, it can not prevent any BT transmission failure. The small improvement at the BT side comes from less interference due to shorter retransmission forced by DF. Thus, the improvement is more substantial when the retransmission time possesses a significant portion of the total transmission time, which is always the case when the traffic load is sufficiently high.

With two BT piconets that adopt ACL traffic and coexist with a Wi-Fi network, we show simulation results of the Wi-Fi



Fig. 9. Throughput of the Wi-Fi network in the presence of ACL link on the BT piconet, where the background Wi-Fi traffic is given by $\tau_{Wi-Fi} = 0.7$.



Fig. 10. Throughput of the BT piconet with ACL traffic $\tau_{BT}=0.7,$ which coexists with Wi-Fi.

throughput with respect to the combined BT traffic load in Fig. 11. We see that Figs. 9 and 11 are very similar. This implies that, regardless of the number of coexisting BT piconets, the degree of interference sensed by Wi-Fi is the cumulative contributions of all coexisting piconets, which corroborates Eq. (3).

Finally, Fig. 12 shows the average packet transmission delay of Wi-Fi as a function of the BT traffic load. In the simulation, we first calculate the total transmission time for files of fixed length, *e.g.* 1000 packets. Then, we subtract the time needed to transmit the payload from the total transmission time to determine the total delay. Then, the total delay is divided by the number of packets to get the average delay of a single packet. The improvement on packet transmission delay comes primarily from reduced retransmissions caused by interference. It is demonstrated by simulation results that DF can improve the transmission delay significantly.



Fig. 11. Throughput of the Wi-Fi network in the presence of ACL links on multiple BT piconets, where the background Wi-Fi traffic is given by $\tau_{Wi-Fi} = 0.7$.



Fig. 12. The average Wi-Fi delay as a function of the BT traffic load, where the background Wi-Fi traffic is given by $\tau_{Wi-Fi} = 0.5$.

5 CONCLUSION AND FUTURE WORK

A non-collaborative mechanism, called Dynamic Fragmentation (DF), to improve the Wi-Fi performance in the presence of BT interference was proposed in this work. We first developed an analytical model to characterize the interference between Wi-Fi and BT. Then, we proposed DF to reinforce the coexistence ability of Wi-Fi networks. With DF, a Wi-Fi station can perform fragmentation dynamically to reduce interference and increase throughput. We also investigated the scenario of static networks and proposed an enhanced solution called DF-II to improve the performance furthermore. In addition to the throughput improvement, DF helps Wi-Fi differentiate between interference and collision. Thus, if transmission failures are mostly caused by collision at the first fragment, DF can recognize the difference and swiftly switch back to the non-fragmentation state to avoid unnecessary overhead. The fragmentation mechanism has already been described in the legacy 802.11 standard. Therefore, our proposed DF-I and DF-II solutions can be easily implemented. The derived analytical results were validated by simulation results. With the PER level higher than 0.6, we could get more than 56% improvement on throughput for static networks, and 30% throughput improvement for mobile networks. The improvements grow exponentially with PER. Substantial improvement on the delay has been observed as well. Due to the non-collaborative nature of our coexistence scheme, there is only slight throughtput improvement on the BT side. However, a non-collaborative coexistence scheme is preferable to a collaborative one.

The current DF mechanism divides the packet into fragments with equal length. It would be interesting to develop an extended model using more advanced fragmentation scheme as future work. Our analytical model can provide clues in the design of such fragmentation mechanism. Besides, in addition to devise coexistence schemes, efforts on regulation, standards, *etc.* are also needed to enhance the coexistence of various kinds of wireless networks. Though there have been various kinds of wireless networks, the standardized MACs for the networks using 2.4 GHz ISM unlicensed band can be generally categorized into two types, namely CSMA/CA (e.g. Wi-Fi or Zigbee) and frequency hopping (e.g. BT). Our work provides important insights into the coexistence between CSMA/CA networks and frequency hopping networks, which offers feasible solutions when setting the standard for future wireless technologies for the networks using ISM unlicensed band.

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