An Efficient Data Burst Transmission Mechanism for Wireless LANs

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Abstract: In this paper, we present a data burst transmission mechanism named data flushing data transfer (DFDT) protocol for IEEE 802.11 wireless local area network (WLAN). The basic mechanism of DFDT is quite the same as the distributed coordination function (DCF) of the medium access control (MAC) of IEEE 802.11, which uses a random access delay backoff time after a busy medium condition and request-to-send/clear-to-send (RTS/CTS) dialogue before sending actual payload data (direct data/ACK could also be used). The enhancement introduced by DFDT is mainly produced by the *compilation process* (CP), which fits as many MAC layer frames as possible into one physical layer frame within the limit of a predetermined length. Compiling several data frames into one data frame before transmission can obviously reduce the contention overheads. Moreover, DFDT allows a station to send out multiple MSDUs destined for different receivers with one physical data frame after a successful contention. By using the CP, we lower the protocol overhead, the packet arrival rate of the physical layer, and network contention all with one action. The proposed DFDT takes the advantages of the RTS/CTS mechanism relative to traditional IEEE 802.11 protocol but has less the overhead. Simulation results backed by numerical analysis show growing improvement in performance, limited by the saturation of the network, as the network load gets higher.

Key–Words: Ad hoc, Compilation, LAN, MAC, Mechanism, Performance, Protocol, Wireless

1 Introduction

Next generation wireless networks are evolving to accommodate a variety of services and traffic types, including data transfer, voice, video and multimedia streaming, while allowing a user to roam within the service area of the network, or between networks without disrupting the quality-of-service (QoS) provided. Wireless local area networks (WLANs) cover single-hop or multi-hop communications, which can provide various network services within a limited service area. Research and deployment of these networks has been very rapid in the past few years, leading to the development of a number of wireless local area network technologies, like IEEE 802.11 (Wi-Fi), IEEE 802.15.3 [11] and HiperLAN. Even though these technologies can provide high speed (broadband) wireless access to IP networks, they have significant limitations, which must be overcome for allowing seamless, scalable and stable QoS for wireless mobile users.

Moreover, wireless communication is a rapidly emerging technology providing users with network connectivity without being restricted by a wired network. A mobile ad hoc network (MANET) [3, 16, 17] is a collection of mobile hosts, which forms a temporary network without the aid of any pre-established infrastructure or centralized administration. For example, the MANET is able to conveniently and rapidly setup communication links for information exchange between members in a working group, in an emergency rescue team or in a battle field, etc. As a result, wireless applications are becoming more and more popular for high-speed communications in small areas, where wiring for conventional networking is difficult or not economic. Since any transmission in a WLAN relies on a common and open radio medium, the medium access control (MAC) protocol in WLANs would be more important than in conventional wired networks. Many researches and proposals have been made on the topic of wireless MAC protocols [4, 9, 12, 15, 20].

The IEEE 802.11 Working Group provides detailed MAC and physical (PHY) layer specifications [10] for WLANs. The MAC layer of IEEE 802.11 WLAN standard includes a basic distributed coordination function (DCF) and an optional point coordination function (PCF). It is also possible to have both DCF and PCF coexist within the same basic service set (BSS). The DCF known as carrier sense multiple access with collision avoidance (CSMA/CA) [8] including an optional transmission mode based on request-to-send/clear-to-send (RTS/CTS) handshaking (DFWMAC [6]) is used as the basic channel access protocol to transmit asynchronous data in the contention period, and the PCF is a centralized MAC protocol only used with infrastructure network configuration that supports collision free and time bounded services.

In the past most researches on packet-radio focused on the issue of eliminating or lowering the probability of collisions [13, 14, 18] (two or more stations transmitting at the same time jamming each others signals) by increasing protocol overhead. The protocol overhead in packet-radio is essential to provide a reliable environment [5], but it also decreases the theoretical throughput of the network. The data burst transmission mechanism named data flushing data transfer (DFDT) protocol proposed in this article does not only concentrate on minimizing the collision by using appropriate handshaking but also tries to reduce the ratio of overhead in communication.

The remainder of this paper is organized as follows. Section 2 demonstrates the proposed data flushing data transfer (DFDT) protocol in details and the DFDT control frame format is also given in this section. We present the numerical analysis of DFDT in Section 3. The simulation environment and the simulation results are given in Section 4. Finally, some conclusions are made in Section 5.

2 The Data Burst Transmission Mechanism

The data flushing data transfer (DFDT) protocol is an enhancement for the DCF of IEEE 802.11 or other similar wireless ad hoc networks. The idea is to combine multiple MAC service data units (MSDU) to form a larger data packet which we call compiled MAC protocol data unit (CMPDU). This procedure has the effect of lowering the contention of the network, decreasing the ratio of the protocol overhead, and reducing the packet arrival rate for physical layer. This idea is mainly derived, with some modification, from the fragment burst transmission defined in IEEE 802.11 standard.

The most essential part of the DFDT is the compilation process (CP), shown in Fig. 1. Before describing the procedures of the CP, we define a parameter called compilation threshold (CT), which indicates the maximum length of the CMPDU. The compilation threshold is set equal to the fragmentation threshold (FT) defined in the IEEE 802.11 standard. The CT, for similar reason as FT, is implemented to prevent overlong frames from being transferred; as longer frames have higher probability of be corrupted. The compilation precess takes as many MSDUs from the transmit queue limited by CT, adds a MAC header and CRC to each packet forming MPDUs, and than combines them to form a CMPDU. A MPDU in the IEEE 802.11 holds one MSDU, while the CMPDU of the DFDT could carry multiple MSDUs with different destinations.

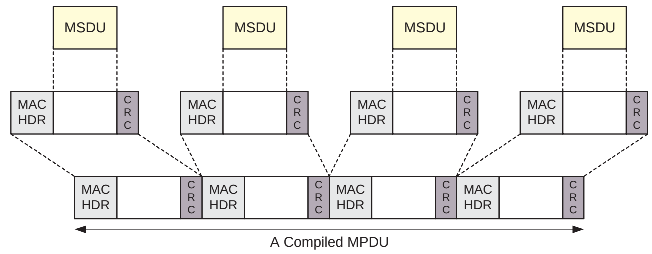


Figure 1: The compilation process.

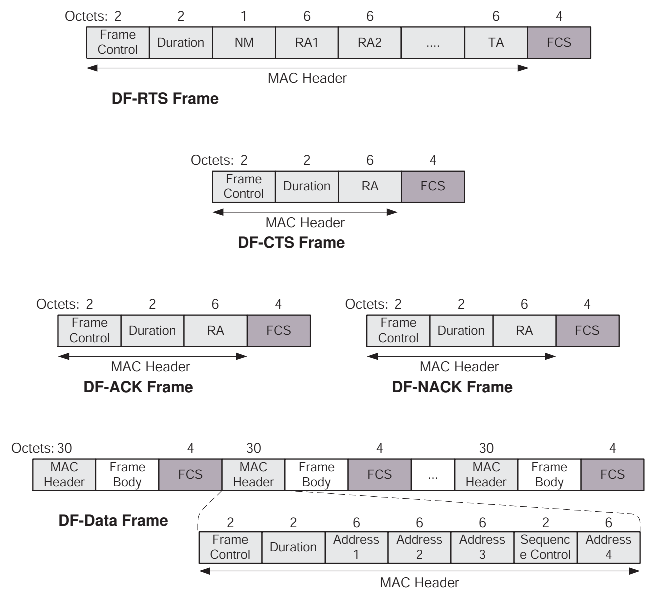


Figure 2: The frame format of DFDT.

In Fig. 2 the frame format of the control frame and data frame used by DFDT is illustrated. The frames include:

- data-flushing-request-to-send (DF-RTS)
- data-flushing-clear-to-send (DF-CTS)
- data-flushing-acknowledgment (DF-ACK)
- data-flushing-data (DF-Data).

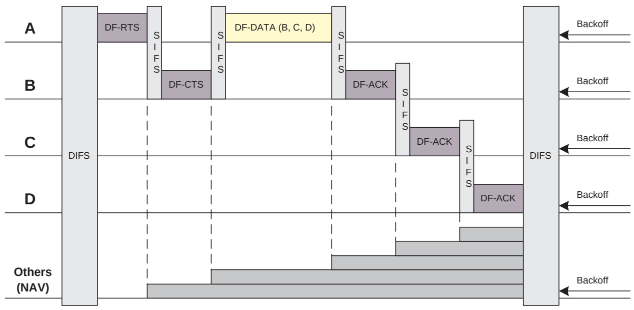


Figure 3: The mechanism of DFDT (In this diagram the data frame is compiled from three data packets).

Many features of the frame format of DFDT resemble the IEEE 802.11 frame formate. The DF-CTS and DF-ACK are exactly the same as the clear-to-send (CTS) and acknowledgment (ACK) of the IEEE 802.11. The DF-RTS and DF-Data are not the same but still similar to the request-to-send (RTS) and Data frame of the IEEE 802.11. The DF-RTS differs from the IEEE 802.11 RTS in having a field which indicates the number of MSDUs that will be in the upcoming data frame (NM), and a variable number of receiver address (RA) fields that is adjusted according to NM. It is obvious that the length of DF-RTS varies and it might be desired to limit the maximum length of DF-RTS. The DF-DATA frame is a collection of one or more sub-frames where each sub-frame is identical to a IEEE 802.11 MPDU. This feature makes it easier to implement into the existing IEEE 802.11 architecture and more robust than having a single MAC header carrying all information in the front.

The mechanism of DFDT works much like a normal RTS/CTS dialogue, an example is shown in Fig. 3 where the data frame carries three data packets. First, as a DF-Data frame is ready for transmission the source sends out a DF-RTS frame. Than the source will wait for the first destination node, which is RA1 in the DF-RTS frame, to reply a DF-CTS before starting the transmission of the DF-Data frame. Only one reply of DF-CTS is needed because in an ad hoc environment all nodes should be able to hear each other. If the source did not hear the DF-CTS in a certain time period, it will retransmit the DF-RTS a number of times. Following the DF-Data transmission, each destination node replies a DF-ACK consecutively separated by a SIFS and ordered according to the data sequence in the DF-DATA frame.

3 Numerical Analysis

The analysis of the throughput of DFDT is based on the model first introduced by Kleinrock and Tobagi [20] for CSMA protocols, and [1, 2, 7, 16] which discuss and analyze throughput of IEEE 802.11 protocol are taken as reference. According to these models and some assumptions we derive a lower bound for the throughput of DFDT protocol. The assumptions used on the model are as follows:

- A single unslotted channel is used for all communications (different to the simulator used in the next section).
- We do not consider channel noise; in other words, the bit error rate introduced by channel noise is zero.
- The propagation delay of the channel between any two stations is a fixed value τ.
- We assume that the network is fully-connected, which means there are no hidden terminals.
- All stations can detect collisions perfectly.
- We assume that there is limited station mobility, i.e., all stations that are currently transmitting or receiving data or control frame remain stationary until the completion of the transaction.

Here we will introduce some notations before proceeding to the equations. The length of a data frame in the MAC layer is denoted by l, and l_{type} is the length of a "type" frame where the "type" could be "DF-RTS", "DF-CTA", or "DF-ACK"; for example, $l_{\text{DF-RTS}}$ would refer to the length of a DF-RTS MAC frame. Let type $= \text{PHY}_{\text{hdr}} + l_{\text{type}}$ (for example, DF-RTS $= \text{PHY}_{\text{hdr}} + l_{\text{DF-RTS}}$) be the precise transmitting length in PHY layer, and the exact length of a transmitted data packet is $m = \text{PHY}_{\text{hdr}} + \text{MAC}_{\text{hdr}} + l_{\text{data}}$. All frame length are measured in normalized time units; different to the usual measure of number of bits or octets, the length of a packet is the the time required to transmit a data frame.

Before a successful handshake is completed *idle* periods, collisions, and interrupts from other competitors[1], may occur. An idle period is a time interval in which the transmission medium remains idle due to the backoff algorithm. Let T_s and T_c denote the expected length of the time interval between successive observations of the channel being idle more than DIFS when in the intervening renewal interval a successful transmission or at least one collision occur, respectively. Let us concentrate on a system completely managed by DFDT protocol, a superscript 4 is added to T_s and T_c to denote the 4-way handshake involved

[1]Any station within a range of radio signal of sender will be a competitive neighbors.

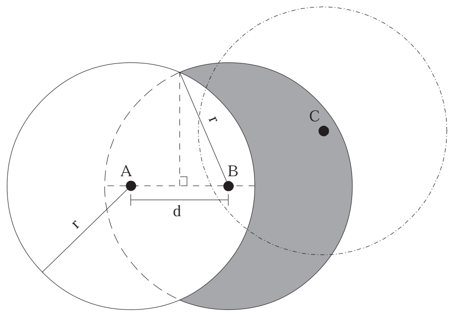


Figure 4: Analysis of the impact of hidden terminal problem: station A sends a packet and station B received the packet.

in the transfer of a data frame using DF-RTS/DF-CTS frames. A simple observation reveals that

$$\begin{cases} T_{\mathrm{c}}^{4} \leqslant \text{DF-RTS} + \tau + \text{SIFS} + \text{DF-CTS} + \tau \\ T_{\mathrm{s}}^{4} = \text{DF-RTS} + \tau + \text{SIFS} + \text{DF-CTS} + \tau + k\overline{m} \\ \qquad +\text{SIFS} + k(\text{DF-ACK} + \tau + \text{SIFS}) \end{cases}, \tag{1}$$

where τ is denoted as the air propagation delay and k is the number of MSDUs in the compiled MPDU and can be calculated by

$$k = \left\lfloor \frac{\text{CT}}{\overline{m}} \right\rfloor. \tag{2}$$

Since determining the exact value of k is nearly impossible, we use the upper bound of k in the analysis.

Now we want to know the average value of the hidden area from transmitter. Taking Fig. 4, we consider the simple scenario where station A transmits a message to station B. Let $\mathcal{A}_{\mathrm{A}}$ and $\mathcal{A}_{\mathrm{B}}$ denote the circle areas covered by A's and B's transmission range, respectively. The additional area that may suffer contention from station B is the shaded region of station B, denoted as $\mathcal{S}_{\mathrm{B}-A}$. Let r be the radius of $\mathcal{A}_{\mathrm{A}}$ and $\mathcal{A}_{\mathrm{B}}$, and d the distance between station A and station B. We can derive $|\mathcal{S}_{\mathrm{B}-A}| = |\mathcal{A}_{\mathrm{B}}| - |\mathcal{A}_{\mathrm{A}\cap B}| = \pi r^2 - I(d)$, where $I(d)$ is the intersection area of the two circles centered at two points distanced by d,

$$I(d) = 4 \int_{d/2}^{r} \sqrt{r^2 - x^2} dx. \tag{3}$$

When $d = r$, the coverage area $|\mathcal{S}_{\mathrm{B}-A}|$ is the largest, which equals $\pi r^2 - I(r) = r^2(\pi/3 + \sqrt{3}/2) \approx 0.61\pi r^2$. The average value $S(r)$ of $\pi r^2 - I(r)$ was approved by Tseng *et al.* in [19] and will be

$$\int_0^r \frac{2\pi x \cdot [\pi r^2 - I(x)]}{\pi r^2} dx \approx 0.41\pi r^2. \tag{4}$$

Thus the factor of hidden area $S(r) = 0.41\pi r^2/\pi r^2 = 0.41$.

We assume that once the channel is sensed idle and a time interval DIFS has elapsed, the time until a data frame is generated at station i which is destined for station j is assumed to be exponentially distributed with rate λ. Since DFDT protocol compiles several MSDUs into one CMPDU before sending it out at once, the Poisson arrival rate in each station denoted as $\lambda(i,j)$ will be altered to $\lambda(i,j) = \lambda/k$. Further, for notational convenience we define $\Lambda(i) := \sum_{j\in\mathcal{A}} \lambda(i,j)$ and $\Lambda := \sum_{i,j\in\mathcal{A}} \lambda(i,j)$.

A station which has a packet ready for transmission starts radio communication immediately after the end of its backoff countdown procedure. The radio communication starts with a DF-RTS packet, and the probability that the DF-RTS is successfully transmitted is given by

$$P_{\mathrm{s}} = e^{-\Lambda\tau}. \tag{5}$$

The average duration of any busy period always consists of at least an RTS/CTS handshake, the associated propagation delay, and the average time between the first and the last RTS of the busy period. The RTS/CTS handshaking may encounter a collision when more than one station attempt to transmit data frames within the propagation delay τ. Thus, the average time between the first and the last RTS of the busy period is denoted by $\overline{Y}$ and is the same as in CSMA [20],

$$\overline{Y} = \tau - \frac{1 - e^{-\Lambda\tau}}{\Lambda}. \tag{6}$$

If the busy period involves a successful transmission, the average data frame length $\overline{m}$ is also sent. The length of the average busy period in DFDT is given by

$$\begin{aligned} \overline{B} &= \overline{Y} + T_{\mathrm{s}}^{4} e^{-\Lambda\tau} + T_{\mathrm{c}}^{4}(1 - e^{-\Lambda\tau}) \\ &= \text{DF-RTS} + \text{SIFS} + \text{DF-CTS} + 3\tau - \frac{1 - e^{-\Lambda\tau}}{\Lambda} \\ &\quad + \Big[\text{SIFS} + k(\overline{m} + \text{DF-ACK} + \tau + \text{SIFS})\Big] e^{-\Lambda\tau}. \end{aligned} \tag{7}$$

The length of the average idle period $\overline{I}$ is

$$\overline{I} = 1/\Lambda + \text{DIFS} + T_{\mathrm{B}}, \tag{8}$$

where T_{B} is the mean random backoff time of each station and is given by

$$\begin{aligned} T_{\mathrm{B}} = &\sum_{n=0}^{4} \left[P_{\mathrm{s}}(\tau)\big(1 - P_{\mathrm{s}}(\tau)\big)^{n} 2^{n-1} W \right] \\ &+ \big(1 - P_{\mathrm{s}}(\tau)\big)^{5} 2^{4} W, \end{aligned} \tag{9}$$

where W is the minimum backoff window size (32 slots). This equation can be found in [16] and is approved by Sheu *et al.*

And the length of the average utilization period is

$$\overline{U} = k\overline{m}P_{\mathrm{s}} = k\overline{m}e^{-\Lambda\tau}. \tag{10}$$

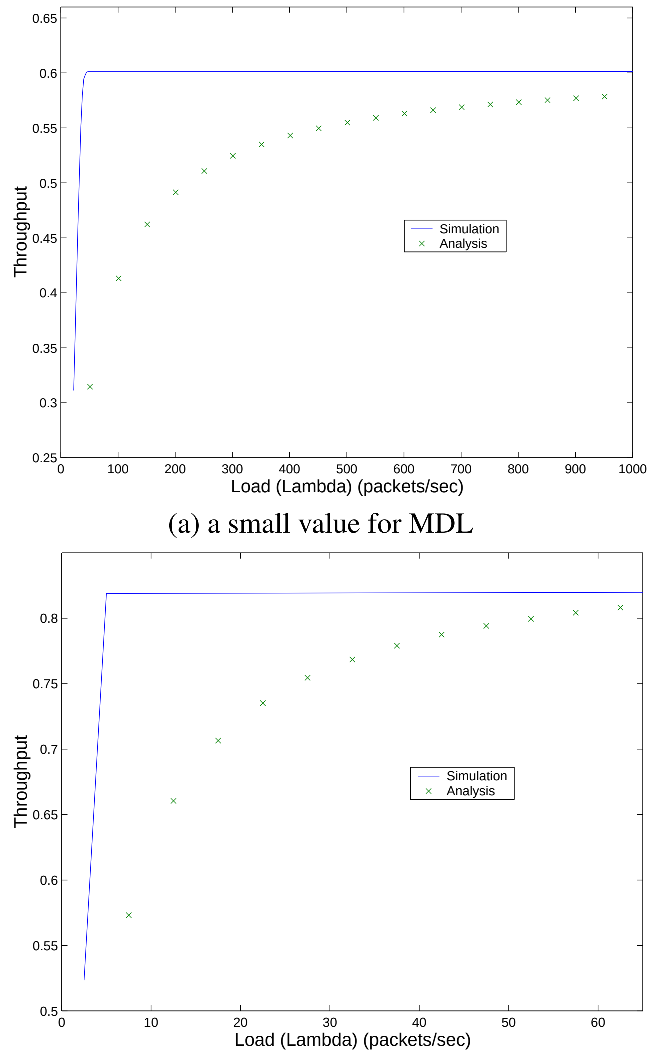
Thus, the throughput of DFDT protocol is given by

$$\begin{aligned} S &= \frac{\overline{U}}{\overline{B}+\overline{I}} \\ &= T_{\mathrm{s}}^{4}e^{-\Lambda\tau} \times \Bigg\{ \text{DF-RTS} + \text{SIFS} + \text{DF-CTS} + 3\tau \\ &\quad + \text{DIFS} + T_{\mathrm{B}} + \Bigg[(k+1)\text{SIFS} + 1/\Lambda \\ &\quad + k(\overline{m} + \text{DF-ACK} + \tau) \Bigg] e^{-\Lambda\tau} \Bigg\}^{-1}. \end{aligned} \tag{11}$$

Now we compare the results for system throughput of the numerical analysis with the simulation curve, shown in Fig. 5. The two figures differ from each other in the mean data length (MDL) they used for simulation and analysis, where Fig. 5(a) used a small value and Fig. 5(b) used a large value. Although the curves do not exactly match, we can see that the trend is the same. The lower throughput produced by the analysis results from the assumption that k is fixed for a fixed $\overline{m}$ regardless of λ (this gives the effect that a packet is only transmitted when the length reaches CT), this is somewhat different to DFDT that transmits a packet at any possible time point.

Table 1: Parameters used throughout this section

Parameters	Values
aSlotTime	20 μs
aSIFSTime	10 μs
aDIFSTime	50 μs
aPreambleLength	144 μs
aPLCPHeaderLength	48 bits
$\mathrm{CW}_{\mathrm{min}}$	31 slots
$\mathrm{CW}_{\mathrm{max}}$	1023 slots
dot11MaxTransmitMSDULifetime	512 ms
dot11MaxReceiveLifetime	512 ms



(a) a small value for MDL

(b)

Figure 5: Comparison of throughput of DFDT obtained by analysis and simulation using (a) a small value for MDL; (b) a large value for MDL.

4 Simulation

The simulator is custom made and follows the IEEE Standard 802.11b-1999 [10] using direct sequence spread spectrum (DSSS) at the physical layer with the long PLCP PPDU format and DCF at the MAC layer. Most of the parameters were taken from the standard and are listed in Table 1. Poisson distribution was used to determine the number of MSDU arrivals and the lengths of the MSDUs were decided by the exponential distribution function. Some assumptions were made to reduce the complexity of the simulation model:

- The data rate of all communications was fixed at 2Mb/s.
- The propagation delay was neglected.
- The channel was error-free.
- All stations were active (non in power-saving mode).

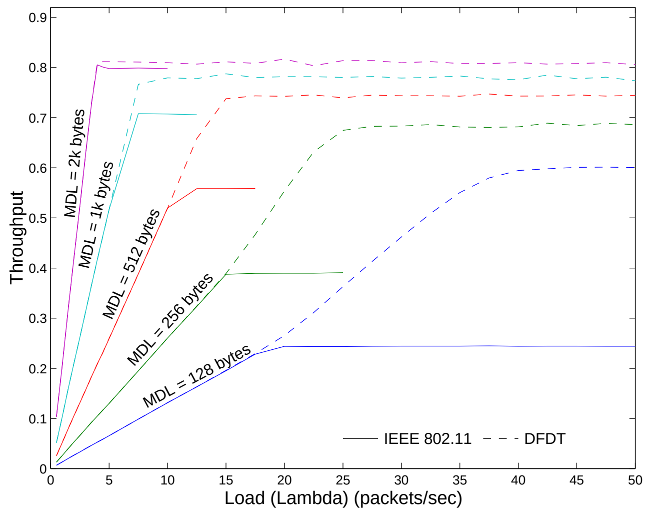


Figure 6: Comparison of throughput of IEEE 802.11 and DFDT with different MDLs when N = 25 and CT = 2312 octets.

- There was no interference from nearby BSS.
- The ad hoc network was perfectly fully connected, which means that there were no hidden terminals and each node had direct radio contact with other nodes.

In Fig. 6, the solid lines show the performance of the IEEE 802.11 MAC with the RTS/CTS mechanism always on, and the performance of the DFDT is indicated by dashed lines. The five pairs of lines present different MDL as the FT and the CT are set to the maximum value (2312 Octets). When the MDL is small we can see enormous performance improvement of the network. Inspecting MDL = 128 Octets, as the load reaches 20 packets/sec the network saturates with the throughput only at 0.24 for the IEEE 802.11 MAC, if the DFDT was used saturation would occur only when the load reaches 40 packets/sec with throughput up to 0.6. This gives a saturation throughput improvement of 150% and saturation load improvement of 100% for DFDT over IEEE 802.11 MAC. As for the other MDLs we can see a similar phenomenon, for MDL = 256, 512, 1k, and 2k octets the saturation throughput improvements are about 76%, 34%, 4%, and 1%, and saturation load improvements are about 66%, 20%, 1%, and 0% respectively. Although the improvements are not obvious when MDL is close to the maximum value, DFDT does not have negative effect on the network performance in any case.

The CT has a major influence on the saturation throughput of the DFDT protocol; using a larger CT will result in a higher saturation throughput. Note that this is only true for a error-free network (bit error rate (BER) = 0), because if we had a BER grater then zero

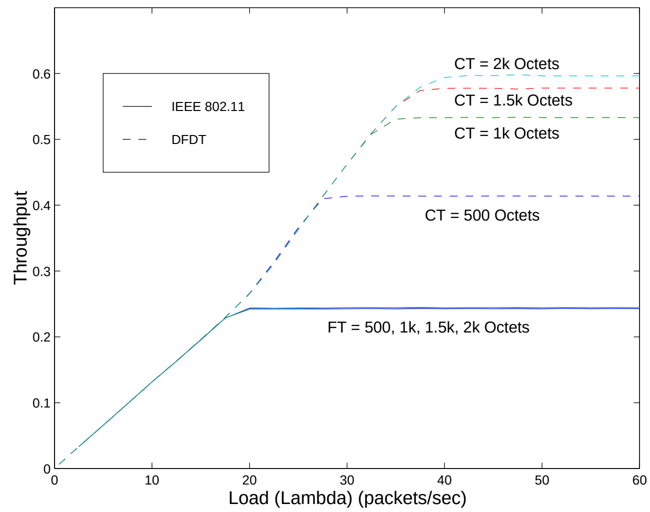


Figure 7: Comparison of throughput of IEEE 802.11 and DFDT with different CT and FT values when N = 25 and MDL = 128 octets.

the error penalty would be higher with a larger CT. In reality BER is always grater then zero and CT should be in inverse ratio with it. Fig. 7 shows the DFDT with different CT values and the IEEE 802.11 MAC with corresponding FT values, note that CT = FT. The different FT values actually do not effect the throughput of IEEE 802.11 much because the MDL in this simulation is quite small; we can see that the throughput curves with different FTs are all identical. For the curves of DFDT with different FT values, we see a higher performance with each grater FT value. The saturation throughput improvement of DFDT over the IEEE 802.11 MAC for FT = 500, 1k, 1.5k, 2k Octets are about 85%, 118%, 136%, and 144% respectively. As the CT decreases, the performance curve of DFDT and IEEE 802.11 will eventually overlap.

5 Conclusions

In this paper, we had introduced and analyzed the proposed data burst transmission mechanism named data flush data transfer (DFDT) for IEEE 802.11 ad hoc wireless network. DFDT allowed a station to send out multiple MSDUs destined for different receivers with one physical data frame after a successful contention. The improvement of performance archived by DFDT was based on three concepts: (a) lower the contention of the network, (b) decrease the percentage of overhead required for a transmission, and (c) reduce the packet arrival rate for physical layer. All three concepts worked to increase the performance of the wireless network and were achieved by compiling multiple MSDUs into one single CMPDU. When the percentage of short packets was high, which was often true for wireless networks, DFDT showed enormous improvements in performance over the IEEE 802.11.

Although we introduced DFDT as a protocol for one hop packet-radio network, this method also works well in infrastructure environment, and with a little modification it could also work in a multihop ad hoc wireless network. Summarizing the results of this paper, we can see that DFDT outperforms the IEEE 802.11 MAC and thus serves as an excellent add-on to the IEEE 802.11 or other WLAN MAC protocols.

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