The impact of transmission overheads on IEEE 802.11 throughput: analysis and simulation

1 author:

Nurul I Sarkar
Auckland University of Technology

The Impact of Transmission Overheads on IEEE 802.11 Throughput: Analysis and Simulation

Nurul I. Sarkar, *Senior Member, IEEE*

Abstract— **While various factors affecting the performance of a typical IEEE 802.11 DCF ("DCF") medium access control (MAC) protocol, transmission overhead is one of the main causes of DCF MAC inefficiency. This paper provides an analysis of DCF overhead to show that the network throughput degrades significantly due to its high transmission overhead for a single-user scenario. Simulation modeling is used to demonstrate the performance degradation of DCF for a multi-user network scenario. To reduce DCF's high transmission overheads and to improve the system performance, this paper introduces a simple packet scheduling mechanism called buffer unit multiple access (BUMA). The BUMA improves the system performance because it requires less overhead to send the same amount of payload than the DCF. Results obtained show that if BUMA is used in place of DCF, the network performance is improved significantly especially under medium-to-high loads.**

Index Terms—Distributed coordinated function (DCF), IEEE 802.11,Ttransmission overhead,Tthroughput.

I. Introduction

IEEE 802.11 DCF has been standardized and is gaining widespread popularity as a channel access protocol for wireless local area networks (WLANs). Unfortunately, the protocol has several potential limitations. High transmission overhead is a fundamental problem and is one of the main causes of DCF inefficiency [1]. This inefficiency results in low bandwidth utilization under medium-to-high loads.

A good understanding of the DCF transmission overhead and its effect on system performance is required for an efficient design and deployment of such systems. This paper addresses the following research questions:

- *What effect do transmission overheads have on a typical 802.11 network throughput?*
- *How can we reduce DCF's transmission overhead to improve system performance?*

To answer the questions posed we first provide a simple analysis of DCF transmission overhead and its impact on throughput for a single-user wireless ad hoc network. We then examines mean network throughput and packet delay of DCF for a multi-user system using ns-2 simulation [2]. This simulation methodology is considered appropriate in this study, recommended by many leading network researchers [3-7].

To reduce DCF's overhead and to improve system performance, we propose a simple packet scheduling method called buffer unit multiple access (BUMA). We show that if BUMA is used in place of DCF, the network throughput is improved up to 45% under medium-to-high traffic loads.

The remainder of this paper is organized as follows. Section II reviews literature on DCF overheads and methods of improving system performance. Section III introduces BUMA protocol, and DCF transmission overhead is analyzed in Section IV. The results and comparative analysis is presented in Section V. Section VI evaluates the performance of BUMA and DCF by simulation, and a brief conclusion in Section VII concludes the paper.

II. Literature Review

The 802.11 standard defines two types of MAC protocols: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). DCF is defined as a mandatory MAC protocol while PCF is optional [8, 9]. This paper focuses on the DCF mode in 802.11 which has been widely deployed because of its simplicity and low-cost. In the DCF, wireless stations (STAs) communicate with each other using a contention-based channel access method known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA).

While the performance of the DCF has been reported in numerous papers [10-13], very few researchers have actually analyzed the effect of transmission overheads on system performance.

Xiao [1] proposed methods to reduce the transmission overheads of DCF by concatenating multiple frames in a station's queue before transmission. Cali *et al.* [14] proposed an improvement to the DCF protocol by using a distributed algorithm for altering the size of backoff window. By observing the status of the channel, a station obtains an estimate of the network traffic and uses this estimate to tune the backoff window sizes.

Heusse et al. analyzed the performance anomaly of DCF theoretically and have addressed the issues of transmission overheads of DCF [15]. However, an efficient method of reducing DCF overheads is required for design and deployment of WLAN systems. In this paper we fill this research gap by proving an in-depth analysis and ways of reducing overheads to improve the system performance.

III. BUMA versus DCF

The BUMA is a simple packet scheduling mechanism that can be used to reduce transmission overheads of DCF and to improve the performance. The key idea is to create a temporary buffer unit at the MAC layer for each active connection on the network where multiple packets are accumulated and combined into a single large packet (with a header and a trailer) before transmission. The number of buffer units is determined by the number of active connections between the source and destination stations. Each link has its own buffer unit, and each buffer unit stores one or more packets where each packet appears as a MAC Protocol Data Unit (MPDU) in the MAC layer with the same destination address. Thus, the content of a buffer unit is a large packet that appears as a MAC Segment Data Unit (MSDU) in the MAC layer with a single header and a trailer. Now the question arises about the maximum length of an MSDU.

For both wired and wireless Ethernet LANs, the maximum length of a MAC frame is 2,346 bytes, which is a fragmentation threshold. The mean packet length is about 1,500 bytes with payload length ranges from 46 to 1,460 bytes. In the optimized BUMA ($BUMA_{opt}$), the maximum length of a buffer unit is 4,534 bytes, accommodating three 1,500-byte packets plus a 34-byte envelope (MAC header and cyclic redundancy check, CRC). In such cases, the MSDU would be fragmented into two frames before transmission since its length is greater than the fragmentation threshold.

The basic operation and the frame structure of the BUMA protocol are illustrated in Figs. 1 and 2, respectively. Each buffer unit contains multiple MPDUs (Fig. 2).

When a station fills the buffer unit, it first schedules the packet and then puts the next set of packets in the empty buffer unit from the same link. Under medium-to-high traffic loads, each station will always have packets for transmission and the buffer unit will be filled up with packets quickly within a time interval. When traffic is low, BUMA will perform as good as DCF by reducing the buffer unit length to one packet. DCF is effectively a special case of BUMA where the buffer unit length is one packet. Therefore, in the proposed method, the mean packet delay is bounded since a packet will not remain in the buffer permanently while waiting for the second and subsequent packets to arrive.

The proposed BUMA method has several benefits. Firstly, it transmits a greater payload (by scheduling a larger packet) and consequently achieves better throughput than DCF. Secondly, by adopting the buffer unit mechanism one can achieve higher bandwidth utilization than in DCF because it wastes less potential transmission time in the backoff and channel contention processes.

The actual number of MPDUs in a buffer unit will depend on packet length supported by upper protocol layers. For instance, for the transmission of a 500-byte IP datagram, a maximum of nine MPDUs would be stored in a buffer unit of 4,500 bytes. More details about BUMA protocol can be found in [16].

Referring to the Example 1 (Section IV) of the 46-byte IP datagram, instead of 50 contention periods, only one contention period is needed to transmit 50 IP datagrams. BUMA, therefore, dramatically reduces the average packet contention delay, especially for shorter packet lengths, while maintaining better throughput by transmitting a combined packet. Finally, the packet transmission overhead reduced significantly. Without the buffer unit mechanism, each packet transmission requires a separate set of overheads, including headers, inter-frame spaces, backoff time, CRC and acknowledgements; in contrast, only one set of overheads would be used with the buffer unit mechanism. However, all these benefits come with a trade-off, a small processing delay at the stations. The transmission overhead and throughput analysis of DCF and BUMA is presented next.

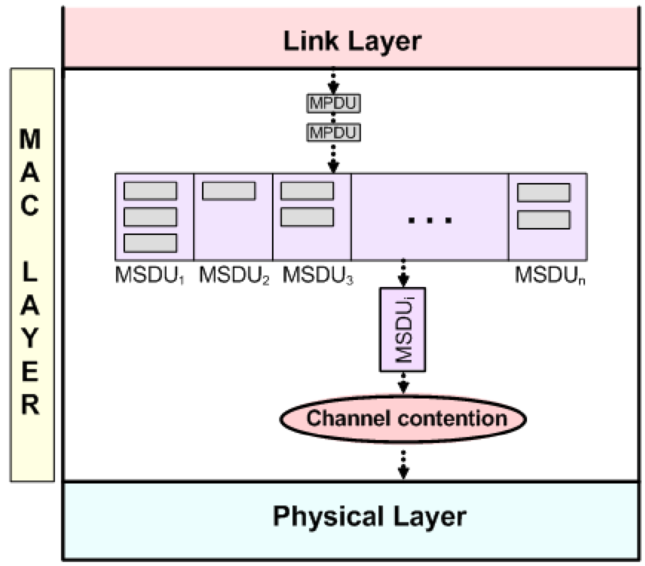


Figure 1. Basic operation of the BUMA protocol.

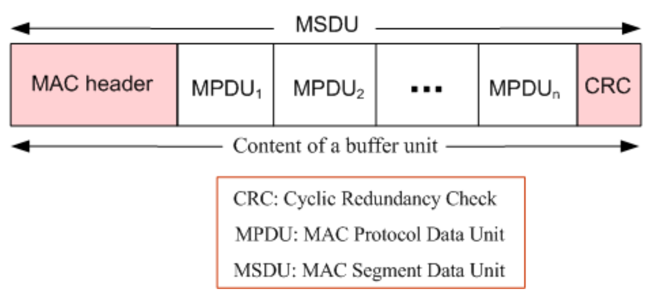


Figure 2. Frame structure of the BUMA protocol.

IV. Protocol Overhead and Throughput Analysis

Packet transmission overhead is one of the main factors in MAC inefficiency, especially for DCF. In this section the effect of transmission overhead on throughput of the DCF and BUMA protocols for a single user scenario is analyzed.

The overhead for a successful frame transmission in a DCF protocol is illustrated in Fig. 3. Each MSDU consists of a MAC header, one or more MPDUs and a CRC. The MAC header and CRC comprise 34 bytes and the ACK frame is 14 bytes long. The MSDU payload (i.e. IP datagram) varies between 46 and 2,346 bytes, including IP headers.

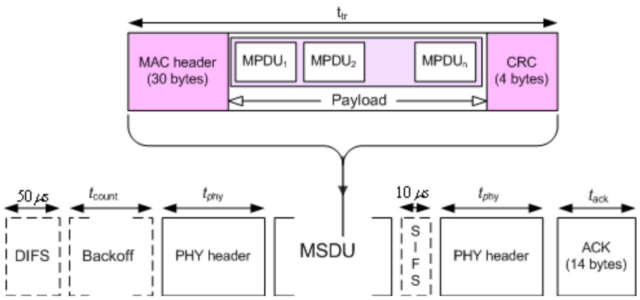


Figure 3. Overhead for a successful transmission of an MSDU.

A single user transmitting a data frame (i.e. no channel contention delay) is used to study the impact of packet transmission overhead on DCF throughput. If one neglects signal propagation times, then the total time (T) required for a successful frame transmission is given by

$$T = t_{tr} + t_{overhead} \tag{1}$$

Where t_{tr} is the data frame (i.e. an MSDU) transmission time and $t_{overhead}$ is the constant overhead. The t_{tr} and $t_{overhead}$ can be computed by (2) and (3), respectively.

$$t_{tr} = \frac{L}{R} \tag{2}$$

$$t_{overhead} = DIFS + t_{phy} + SIFS + t_{phy} + t_{ack} + t_{MAC} + t_{CRC} \tag{3}$$

where, L is the frame length (i.e. the length of an MSDU), R is the data rate, DIFS is the DCF inter-frame space, SIFS is the short inter-frame space, t_{phy} is the PHY header comprising PHY layer convergence protocol (PLCP) preamble and header. t_{ack} is the time required for sending an ACK frame at the MAC layer. t_{MAC} is the time required for sending MAC overhead. t_{CRC} is the time required for sending a CRC.

For 802.11b: DIFS = 50 µs; SIFS =10 µs; t_{phy} varies according to the data rate used by the station. t_{phy} = 192 µs when the long PLCP header is used at 1 Mbps and t_{phy} = 96 µs when the short PLCP header is used at 2, 5.5 or 11 Mbps. In the throughput calculation, the long PLCP header is used.

As the combined length of the ACK, frame MAC header and CRC is 48 bytes. 48 µs (1 Mbps) > t_{ack} + $_{tMAC}$ + t_{CRC} > 4.36 µs (at 11 Mbps), this value was rounded up to 56 µs to round up $t_{overhead}$.

By substituting these overhead parameters in (3), the constant overhead becomes

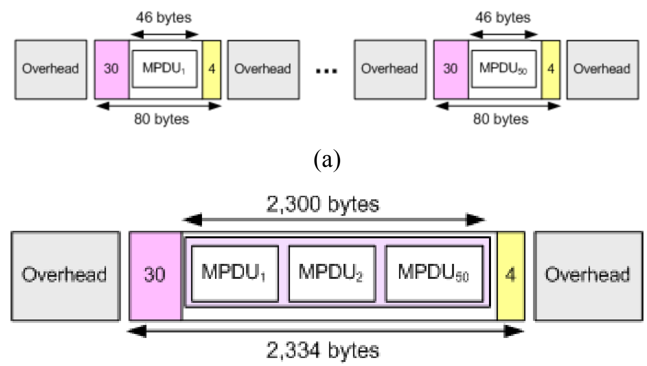
$$t_{overhead} \cong 500\ \mu s \tag{4}$$

The proportion of the useful throughput above the MAC layer is given by [15]

$$Throughput = \frac{t_{tr}}{T} \times \frac{payload}{L} \tag{5}$$

Example 1: Short IP datagram (46 bytes) transmission

The maximum MSDU length in BUMA is 4,534 bytes, this being the optimum length of the BUMA buffer unit. In this example, however, an MSDU of length < 2,312 bytes is used so that it can be transmitted without fragmentation (wireless Ethernet fragmentation threshold is 2,346 bytes [8, 17]). A buffer unit of payload = 2,300 bytes (2312/46 = 50 MPDUs after rounding down) was chosen, as illustrated in Fig. 4b. The length of the MSDU is 2,334 bytes (2,300 bytes payload and 34 bytes envelope). Therefore, in the BUMA protocol the minimum overhead time required to transmit 2,300 bytes of payload is given by Overhead $_{(BUMA)}$ = $t_{overhead}$.



(b)

Figure 4. Protocol overheads for the transmission of short IP datagrams of length 46 bytes for : (a) 802.11b DCF; and (b) BUMAnonopt.

For this payload, DCF's overhead is 50 times that of BUMA's. Consequently, BUMA achieves significantly better throughput than DCF, especially for the transmission of short IP datagrams. The effective throughput of BUMA and DCF is calculated as follows.

The frame transmission time (t_{tr}) of BUMA can be calculated by using (2) as follows.

$$t_{tr} = 2334 \times 8/11 \cong 1.69\ ms \tag{6}$$

By substituting the values of t_{tr} and $t_{overhead}$ in (1), the total time (T) for a successful packet transmission is given by

$$T = 1697 + 500 \cong 2.19\ ms \tag{7}$$

By using (5), the proportional non-optimized throughput (IP layer) of BUMA ($BUMA_{nonopt}$) is

$$BUMA_{nonopt} = (1.69/2.19) \times (2300/2334) \cong 0.76 \tag{8}$$

Similarly, the proportional throughput of the DCF is given by

$$Throughput_{802.11bDCF} = (0.058/0.558) \times (46/80) \cong 0.0599 \tag{9}$$

So, if a single user sends 56 bytes IP datagrams over a 11 Mbps channel, the maximum achieved throughputs using BUMA and DCF are 8.36 Mbps and 0.66 Mbps, respectively. Clearly, BUMA achieves significantly higher throughput than DCF even though the buffer unit was not optimized.

Example 2: Long IP datagram (1,500 bytes) transmission

In this example an MSDU of length 4,500 bytes (excluding MAC header and CRC) is used, which is an optimum length of the buffer unit containing three 1,500-byte MPDUs. However, this large payload is fragmented into two frames before transmission since the total length is greater than the fragmentation threshold for wireless Ethernet networks.

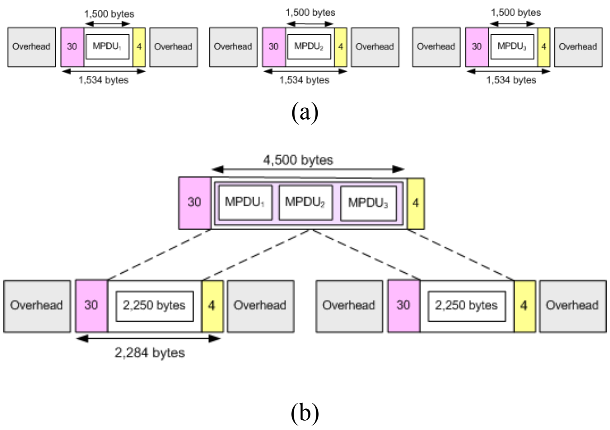


Figure 5. Protocol overheads for the transmission of large IP datagrams of length 1,500 bytes for: (a) 802.11b DCF; and (b) BUMAopt.

As shown in Fig. 5, BUMA transmits payloads three times greater than DCF with a marginally longer MAC overhead. In the case of long IP datagrams, BUMA achieves slightly better throughput than DCF.

By using (2), the frame transmission time (t_{tr}) of BUMA is given by

$$t_{tr} = 2 \times 2284 \times 8/11 \cong 3.32 \text{ ms} \quad (10)$$

The total time (T) for a successful transmission is

$$T = 3322 + 500 \cong 3.82 \text{ ms} \quad (11)$$

Therefore, by using (5), the proportional optimized IP throughput of BUMA ($BUMA_{opt}$) is

$$BUMA_{opt} = (3.32/3.82) \times (4500/4568) \cong 0.8562 \quad (12)$$

Similarly, the proportional throughput of DCF is

$$Throughput_{802.11bDCF} = (1.11/1.61) \times (1500/1534) \cong 0.674 \quad (13)$$

If a single user transmits 1,500-byte IP datagrams over an 11 Mbps channel, the maximum achieved throughputs using BUMA and DCF are 9.4 Mbps and 7.4 Mbps, respectively.

V. Results and Comparative Analysis

Figure 6 plots the proportion of the useful IP throughput versus IP datagram length for DCF, BUMAnonopt and BUMAopt for a single user network. The effective throughput of DCF increases with IP datagram length ('payload length') and is saturated at 2,000 bytes (close to the fragmentation threshold of 2,346 bytes). Increasing the payload length beyond 2,000 bytes does not increase the proportional throughput because of the protocol's high payload fragmentation overhead.

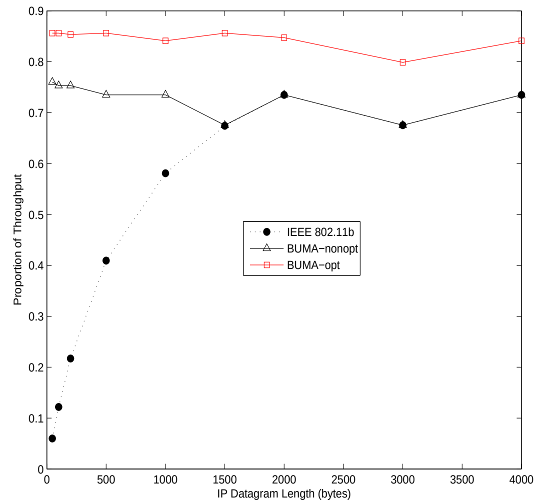


Figure 6. Throughput comparison of the 802.11b DCF, BUMAnonopt and BUMAopt protocols for a single user network.

In the case of BUMAnonopt, the maximum allowable MSDU is set to the wireless Ethernet fragmentation threshold (so that frames can be transmitted without fragmentation). Figure 6 illustrates that BUMAnonopt achieves higher proportional throughput than DCF for payload lengths ≤ 1,000 bytes i.e. the throughput gain is more significant for short payloads. Sending a larger payload with the same set of overheads causes this improvement. However, for payloads > 1,000 bytes, BUMAnonopt does not improve on DCF since the length of the wireless Ethernet fragmentation threshold limits the performance.

In the case of BUMAopt, the optimum length of the buffer unit (4,534 bytes) becomes the maximum allowable MSDU. BUMAopt offers higher proportional throughput than DCF irrespective of payload length. This is a notable result that clearly demonstrates the superiority of both BUMAnonopt and BUMAopt over DCF. Also, BUMA throughput is almost independent of IP datagram length, unlike that of DCF.

By comparing BUMAnonopt and BUMAopt, one can observe that BUMAopt offers 10 to 18% greater throughput than BUMAnonopt for payload lengths smaller than 4,000 bytes. This throughput improvement is due to $BUMA_{opt}$ transmitting a slightly larger payload than $BUMA_{nonopt}$ with the same set of overheads.

Figure 7 compares the total packet transmission time, T of DCF, BUMAnonopt and BUMAopt protocols for a single user network; it shows that T increases as payload length increases. For instance, at payload length of 46 bytes, DCF requires 0.558 ms to transmit an MSDU of 80 bytes (46-byte payload and 34-byte envelope). This is because proportionally less time is required to transmit a short payload as is illustrated in Example 1 (Fig. 4a). BUMA is not as good as DCF when only a few small packets are transmitted, e.g. T is smaller for DCF when there are only three 46-byte packets, or two 500-byte packets.

By considering the same payload length (46 bytes), the BUMAnonopt requires 2.13 ms to transmit an MSDU of 2,242 bytes (50 46-byte payloads and a 34-byte envelope). Thus, BUMAnonopt transmits a 50 times larger payload than DCF in a slightly increased total packet transmission time (Example 1, Fig. 4b) giving a 13-fold improvement in transmission speed. Consequently, BUMAnonopt achieves significantly better throughput than DCF except in the case of very small numbers of small packets. Further, BUMAopt requires 3.79 ms to transmit an MSDU of 4,530 bytes (4,462 bytes payload and 68 bytes envelope). This payload is 97 times greater than the payload carried by DCF, giving a 14-fold improvement in transmission speed.

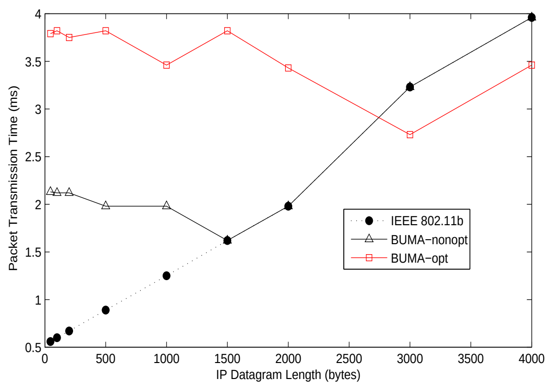


Figure 7. Packet transmission time versus IP datagram length of the 802.11b DCF, BUMAnonopt and BUMAopt protocols.

However, in case of larger payload length (say ≥ 4,000 bytes), DCF requires 4 ms to transmit two fragmented payloads of 2,000-byte each and BUMAnonopt performs no better than DCF as a result of the fragmentation threshold. In any case, BUMAopt achieves slightly lower packet transmission time (3.45 ms) than both DCF and BUMAnonopt. BUMA's channel access strategy of reducing overheads improves packet transmission time.

As shown in Fig. 7 the variability in packet transmission times (i.e. the difference between the highest and lowest transmission times) in DCF, BUMAnonopt, and BUMAopt is 3.40 ms, 2.34 ms, and 1.09 ms, respectively. Therefore, total transmission time in the BUMAopt is bounded since it achieves the lowest variability.

The proportional throughputs presented in this section are an upper bound that can be attained only for a single station passing packets to the MAC layer at the moment the previous transmission is completed. However, in real systems with multiple stations, the throughputs are much lower than these throughputs due to channel contention delays as well as time spend in the backoff process. The main conclusion (Figs. 6 and 7) is that transmission overhead has a significant effect on the throughput of DCF. Throughput degrades significantly for shorter frames due to high overheads except very small numbers of small packets.

VI. SIMULATION STUDY

A simulation model was developed using ns-2 simulator [2] to study the performance of BUMA and DCF for a multi-user ad hoc network. All stations communicate using identical half-duplex wireless radio based on the DCF, with data rate 11 Mbps. The RTS/CTS mechanism was turned off. Stations were stationary. The transmission and carrier-sensing ranges were set to 250 m and 550 m, respectively. The ad hoc on-demand distance vector (AODV) routing protocol and the two-ray ground propagation model were used. Streams of data packets generated at stations using Poisson processes. All data sources are user-datagram protocol (UDP) traffic streams with fixed packet length of 1500 bytes. To simplify the simulation model, we consider a perfect radio propagation environment (no noise and interference in the system), and no hidden and exposed station problems. The simulation results report the steady-state behavior of the network and have been obtained with the relative error < 1%, at the 99% confidence level.

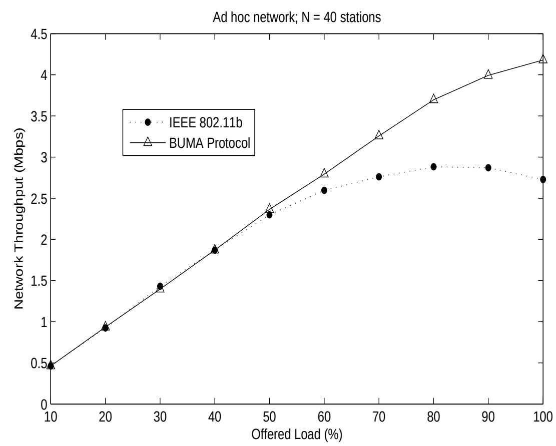


Figure 8. Throughput against offered load of BUMA and DCF.

The network throughput versus offered load of BUMA and DCF with N = 40 stations for an ad hoc network is shown in Fig.8. We found that BUMA achieves 45% higher throughput than DCF under medium-to-high traffic loads.

The network throughput versus the number of stations of BUMA and DCF for an ad hoc network is shown Fig 9. We observe that BUMA achieves higher throughput than DCF for N= 10 to 100 stations. For example, at N = 20 stations, BUMA's throughput is about 45% higher than that of DCF at 80% load. The main conclusion is that (Figs. 8 and 9) BUMA's throughput is significantly better than that of DCF, especially under medium-to-high traffic loads.

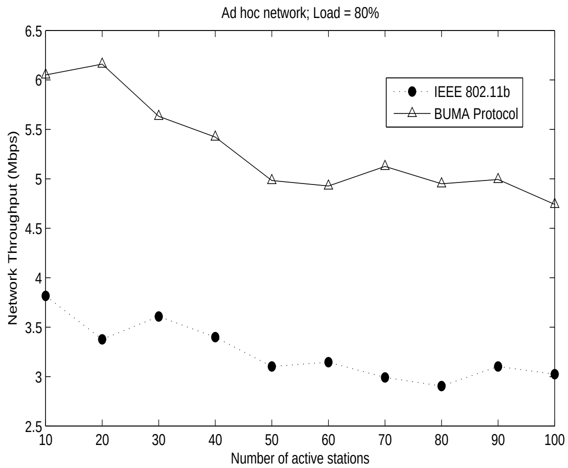


Figure 9. Throughput versus number of stations of BUMA and DCF.

The network mean packet delays of BUMA and DCF for N = 40 stations in an ad hoc network is shown in Fig. 10. Clearly, BUMA achieves lower packet delay than DCF especially at load greater than 40%. For example, for an ad hoc network with N = 40 stations, BUMA's mean packet delay is about 96% lower than DCF's at 70% load. The main conclusion is that stations using BUMA have a substantially lower mean packet delay than stations using DCF, especially under medium-to-high loads.

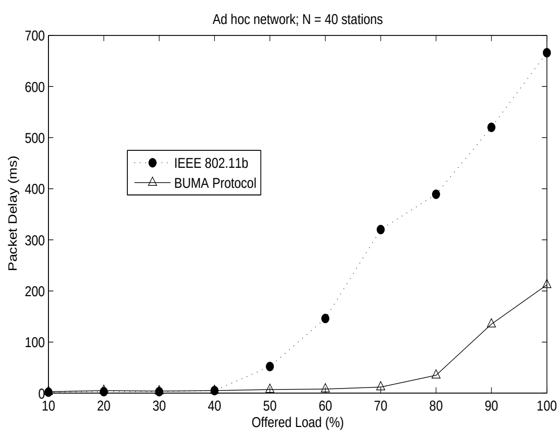


Figure 10. Mean packet delay versus offered load of BUMA and DCF.

VII. Conclusion

The impact of transmission overheads on the throughput performance of IEEE 802.11 DCF is analyzed. We found that the network throughput degrades significantly due to DCF's high transmission overhead. To overcome these problems and to improve system performance, we have proposed a simple packet scheduling mechanism called BUMA. Results obtained have shown that BUMA protocol achieved significantly better throughput than DCF. This performance improvement is as a result of BUMA's channel access scheme that requires less overhead to send the same amount of payload than that of DCF.

We studied the performance of BUMA and DCF for a multi-user network scenario by an extensive simulation. Simulation results have shown that the BUMA achieved up to 45% higher throughput and 96% lower packet delay that that of DCF especially under medium-to-high loads. This is a very promising approach considering that it is an "all-win" design.

The models built using ns-2 simulator were validated using propagation measurements from wireless laptops and APs for an 802.11 network. A good match between simulation results and measurements validated our simulation models. We are currently implementing BUMA on a Linux operating system and a future paper will report this research results.

References

[1] Y. Xiao, "Concatenation and piggyback mechanisms for the IEEE 802.11 MAC," presented at the IEEE Wireless Communications and Networking Conference, March 21-25, 2004, pp. 1642-1647.

[2] K. Fall and K. Varadhan. *The ns manual. The VINT project*. Retrieved February 10, 2011, from http://www.isi.edu/nsnam/ns/doc/

[3] M. K. Denko and T. Jun, "Cross-layer design for cooperative caching in mobile ad hoc networks," presented at the 5th IEEE Consumer Communications and Networking Conference (CCNC '08), January 10-12, 2008, pp. 375-380.

[4] H. D. Trung, W. Benjapolakul, and P. M. Duc, "Performance evaluation and comparison of different ad hoc routing protocols," *Computer Communications*, vol. 30, no. 1, pp. 2478-2496, 2007.

[5] F. Kargl and E. Schoch, "Simulation of MANETs: a qualitative comparison between JiST/SWANS and ns-2," presented at the International Conference On Mobile Systems, Applications and Services, San Juan, Puerto Rico, June 11-14, 2007, pp. 41-46.

[6] M. David, D. Ken, and L. Doug, "Modeling the 802.11 distributed coordination function in nonsaturated heterogeneous conditions," *IEEE/ACM Transactions on Networking*, vol. 15, no. 1, pp. 159-172, 2007.

[7] K. Pawlikowski, H.-D. J. Jeong, and J.-S. R. Lee, "On credibility of simulation studies of telecommunication networks," *IEEE Communications Magazine*, vol. 40, no. 1, pp. 132-139, 2002.

[8] "IEEE 802.11b WG, Part II: wireless LAN medium access control (MAC) and physical layer (PHY) specifications: high-speed physical layer extension in the 2.4 GHz band, IEEE 802.11b Standard," New York, April 1999.

[9] "IEEE 802.11g WG. Amendment to IEEE Std 802.11, as amended by IEEE Stds 802.11a-1999, 802.11b-1999, 802.11b-1999/Cor 1-2001, and 802.11d-2001. IEEE 802.11g Standard," New York, 2003.

[10] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535-547, 2000.

[11] K.-P. Shih, W.-H. Liao, H.-C. Chen, and C.-M. Chou, "On avoiding RTS collisions for IEEE 802.11-based wireless ad hoc networks," *Computer Communications*, vol. 32, no. 1, pp. 69-77, 2009.

[12] T. K. Mak, K. P. Laberteaux, R. Sengupta, and M. Ergen, "Multichannel medium access control for dedicated short-range communications," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 1, pp. 349-366, 2009.

[13] T. Joshi, A. Mukherjee, Y. Younghwan, and D. P. Agrawal, "Airtime fairness for IEEE 802.11 multirate networks," *IEEE Transactions on Mobile Computing*, vol. 7, no. 4, pp. 513-527, 2008.

[14] F. Cali and M. Conti, "Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit," *IEEE/ACM Transactions on Networking*, vol. 8, no. 6, pp. 785-799, 2000.

[15] M. Heusse, F. Rousseau, G. Berger-Sabbatel, and A. Duda, "Performance anomaly of 802.11b," presented at the IEEE INFOCOM, March 30-April 3, 2003, pp. 836-843.

[16] N. I. Sarkar and K. W. Sowerby, "Buffer unit multiple access (BUMA) protocol: an enhancement to IEEE 802.11b DCF," presented at the

IEEE Global Telecommunications Conference (GLOBECOM '05), St. Louis, USA, November 28 - December 2, 2005, pp. 2584-2588.
[17] "IEEE 802.11 WG, IEEE Standard for wireless LAN: Medium access control (MAC) and physical layer (PHY) specifications, IEEE 802.11 Standard," New York, January 1997.

Nurul I Sarkar is a Senior Lecturer in the School of Computing and Mathematical Sciences at AUT University, New Zealand. He holds a PhD in Electrical and Electronic Engineering (Field of study: Wireless networks) from The University of Auckland. His first edited book entitled Tools for Teaching Computer Networking and Hardware Concepts has been published by IGI Global Publishing in 2006.

He has published more than 80 research papers in international refereed journals, conferences, and book chapters, including the IEEE Transactions on Education, the International Journal of Electrical Engineering Education, the International Journal of Information and Communication Technology Education, the International Journal of Business Data Communications and Networking, Measurement Science & Technology, and SIGCSE Bulletin.

Dr Sarkar is a member of various professional organisations and societies, iNurul served as TPC co-chair for mobile and wireless networking track (IEEE ATNAC 2010 and 2011) and wireless and communication track (IEEE TENCON'10). He was a local organising committee member for hosting Asia Pacific Computer Communications (APCC) Conference 2010 in Auckland. He served as TPC member for various leading networking conferences (e.g. IEEE Globecom, UbiCoNet, ISCC, ICCS, ICNC, and ICCIT) as well as track and session chairs for several national and international forums.