INTERNATIONAL JOURNAL OF INTELLIGENT CONTROL AND SYSTEMS
VOL. 10, NO. 1, MARCH 2005, 43-51

Performance Analysis Of Frame-Burst-based Medium Access Control Protocols Under Imperfect Wireless Channels

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***Abstract*— How to provide high throughput performance is a major challenge in the design of MAC protocol for next generation wireless local area networks (WLANs) and wireless personal area networks (WPANs). To achieve this goal, frame-burst-based CSMA/CA protocols have been proposed recently in both academia and industry. The main idea of the frame-burst-based protocol is to aggregate multiple upper-layer packets into a larger burst frame at the MAC layer; thus the MAC layer overhead can be substantially reduced. In our previous studies, we have demonstrated analytically that the frame-burst-based protocol can significantly improve the throughput performance of CSMA/CA protocol in the error-free channel condition. Since wireless channels are generally error-prone in practice, it is very important to study the performance of MAC protocols under such condition. In this paper, we address this issue and develop an analytical model to evaluate the unsaturated throughput performance of the frame-burst-based CSMA/CA protocol in imperfect wireless channel. Numerical results show that, our analytical model is highly accurate. More importantly, our results reveal that, given the traffic load and the bit error rate (BER) of channel, the best throughput performance can be achieved through appropriate setting of burst aggregation policy.**

***Index Term*— WLAN, high data rate, MAC, CSMA/CA, analytical model, throughput.**

1. Introduction

Wireless *local area networks* (WLANs) and wireless *personal area networks* (WPANs) are commonly regarded as the key components for the future Ubiquitous Computing Age [6]. In the past few years, WLANs and WPANs, especially IEEE 802.11 based WLANs [1], have been widely deployed and have attracted significant attention from both academia and industry. With the advances in wireless communication technologies such as *multi-input multi-output* (MIMO) [8] and *ultra-wide Band* (UWB) [13], the next generation WLANs and WPANs are capable of providing high data rate ($>$ 100 Mb/s) [9], [14] from the physical layer perspective. Consequently, how to efficiently utilize the high data rate provided by physical layer becomes a major challenge in the design of *medium access control* (MAC) protocols.

In both WLANs and WPANs, one of the most important MAC protocols is *carrier sense multiple access with collision avoidance* (CSMA/CA). Although CSMA/CA generally works well in a low data rate (less than 10 Mb/s) scenario[1], existing studies have shown that, in high data rate networks, the efficiency of CSMA/CA protocol will be significantly limited by various overheads, such as preamble, control messages, packet collision, backoff, and inter-frame-spacing. Moreover, many overheads cannot be avoided in practice. For instance, the duration of preamble for a new protocol must be the same as that of an old protocol to maintain a backward compatibility. Clearly, in such a case, the overhead problem will become more and more serious with the increase of channel data rate.

To reduce the overhead and to improve the throughput performance of CSMA/CA protocol, a number of schemes have been proposed recently in both academia [10], [20]–[22] and industry [15], [18]. A common feature of these approaches is to aggregate multiple upper-layer packets in a burst frame at the MAC layer and then transmit these packets in one frame instead of transmitting them one by one. In our previous study [10], we proposed a general framework to provide a comprehensive method for burst transmission control. In this paper, we will study the performance of a frame-burst-based MAC protocol within the framework. Particularly, we study the throughput performance of the protocol under different incoming traffic load in imperfect wireless channel, which has never been addressed in the literature.

The performance of CSMA/CA protocols, particularly IEEE 802.11, has been studied extensively in the literature [2]–[5], [7], [12], [16], [17], [19], [23], [24]. To simplify the analysis, most early studies, such as [2], [19], assumed that every node in the network always has packets ready to transmit, known as the *saturated* condition. Although these analysis can lead to insightful observations, a number of recent studies have been focusing on a more general, *unsaturated*, traffic condition.

In [3]–[5], [7], [24], the authors evaluated the unsaturated performance by analyzing the behavior of the MAC protocol only. Although these approaches have low computational complexity, they generally ignore the impact of MAC layer queue. The queueing behavior was first studied in [16], [17], in which a G/G/1 model is in use. However, due to computational complexity, this model is less accurate since it requires a number of approximations. Moreover, the model is not applicable when the traffic load is high since the queue size is assumed to be infinite. In [12], [23], the system under study is decomposed into a queueing subsystem and a service time subsystem. In addition, iterative algorithms are used in both of them to evaluate the performance of the whole system. In both models, the MAC layer queue is modeled as M/G/1/K. The difference between [12] and [23] is that the former used a simplified Markov-modulated general model to estimate the service time distribution, while the later derives the service time distribution directly through a transfer function approach.

Based on the transfer function approach introduced in [23], we have developed an analytical model to evaluate the unsaturated throughput performance for the frame-burst-based CSMA/CA protocol in [11], where we assumed an ideal

This work was supported in part by National Science Foundation Faculty Early Career Development Award under grant ANI-0093241 and the Office of Naval Research Young Investigator Award under grant N000140210464.

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[1] In this paper, we only consider the single-hop scenario, in which any two nodes in the network can directly communicate with each other.

channel condition, i.e., without any transmission error. In this paper, we further develop the analytical model to take into account the impact of imperfect wireless channel, which is more practical. Our simulation and numerical results show that, the proposed analytical model is rather accurate under various traffic and network conditions. Moreover, the new analytical model reveals the relationship between the channel bit error rate and the throughput performance of the frame-burst-based CSMA/CA protocol. Particularly, we show that an optimum burst assembly policy may exist, which can lead to the best throughput performance under a certain channel bit error rate and traffic load condition.

The rest of the paper is organized as follows. In Section 2, we describe our MAC protocol for high date rate ad hoc networks. In Section 3, we analyze the unsaturated performance of the MAC protocol. Simulation and numerical results will be provided in Section 4. Finally, Section 5 concludes the paper.

2. A Frame-burst-based CSMA/CA Scheme

In this section, we describe the frame-burst-based MAC scheme proposed in [10]. The main idea of this scheme is that a node can aggregate multiple upper-layer packets into a frame burst at the MAC layer and then transmit the frame burst according to CSMA/CA protocol. Compared to the traditional approach in which upper-layer packets will be delivered individually, the proposed scheme can significantly reduce the overhead, thus can improve the throughput performance of high data rate wireless networks dramatically.

It is important to note that a number of burst aggregation schemes have been proposed in both academia [20]–[22] and industry [15], [18]. However, the focus of these schemes is the detail of protocols, for example, the frame structure and handshake procedures. In contrast, [10] provides a more comprehensive framework to support frame burst transmission. Particularly, our framework includes five components:

- **Packet classifi cation policy** specifies the packet classification method according to the quality-of-service (QoS) requirement and destination of incoming packets. Note that packets will be queued in buffers after classification.
- **Buffer management policy** manages the buffer in a way that achieves QoS requirements and/or fairness among different flows.
- **Packet assembly policy** determines when and how to assemble a frame burst. This policy should take into account synchronization overhead, physical layer constraints, QoS, and fairness among different nodes.
- **Acknowledgment policy** defines the procedure of acknowledgment at the receiver side.
- **Packet error control policy** dictates what error control scheme to be used, since packet errors are unavoidable.

In the rest of this section, we first review the classic CSMA/CA protocol. We then provide a simple burst assembly policy that will be used in our analysis. Finally, we address the burst retransmission policy issue, which will be affected by the packet transmission errors.

2.1. A Classical CSMA/CA Protocol

In this paper, we consider a well-known CSMA/CA protocol, IEEE 802.11 distributed coordination function (DCF) [1]. To simplify the discussion, we assume that all packets in a frame burst have the same destination. Therefore, most existing functions of IEEE 802.11 DCF can be re-used. Below we briefly describe the binary exponential backoff scheme in DCF. Details of other functions in DCF can refer to [1].

Generally, in IEEE 802.11 DCF, a node with packet to send will randomly choose a backoff counter if the channel is busy. The backoff counter is uniformly chosen in the range of [0, CW-1], where CW is called contention window. The size of contention window is defined as follows. Initially, CW is set to the minimum value, denoted as CWmin. After every unsuccessful transmission, if the total number of retransmission is less than a predefined retry limit M, then the value of CW will be doubled until it reaches the maximum contention window size CWmax (=CWmin$\times 2^{M'}$). Now let W=CWmin, then the contention window size of the m-th transmission can be defined as

$$W_m = \begin{cases} 2^m W & 0 \leq m \leq M' \\ 2^{M'} W & M' \leq m \leq M \end{cases} . \quad (1)$$

The counter will be decreased by one if the channel is sensed idle for a certain time unit σ, the value of which depends on the physical layer specification. Retransmission will take place when the counter reaches zero. If a data frame is successfully received by the destination node, or if it is not successfully received after M times of retransmission, the data frame will be discarded at the MAC layer of the source node. In this paper, we define *departure* as the event of a data frame being removed from the MAC layer of the source node for the above two reasons.

2.2. Burst Assembly Policy

In the analysis, we consider a simple burst assembly policy as follows. In this scheme, we assume that there is only one class of traffic from upper layer. Therefore, packets from upper layer will be queued according to their destinations. Specifically, we need N packet queues in each node, where N is the number of nodes in the network. Among the queues, $N-1$ are used for buffering packets destined to other $N-1$ nodes respectively, and one queue is used for buffering broadcast packets. For each queue, we use tail-dropping when there is a buffer overflow.

A frame burst will be assembled if the total number of packets in a packet queue exceeds a threshold B_{min} and the transmission buffer is empty. This transmission buffer is used to store the single burst in service and is shared by all the queues. In addition, we assume that the total number of packets in a burst must be no more than a preset value B_{max}.

2.3. Packet Error Control Policy

In wireless networks, packet transmission errors due to varied channel conditions are unavoidable and unpredictable. Therefore, error control scheme is required to mitigate the impact. In IEEE 802.11 DCF, this task is achieved by the procedure of packet retransmission, which is basically a stop-and-wait Automatic Repeat Request (ARQ) protocol. In the frame-burst-based MAC protocol, the source node may retransmit only the packets that were not received correctly in one frame burst. However, such a scheme requires the modification of MAC protocol to identify the error status of a certain packet within a frame burst. It also requires the receiver to maintain received packets in buffer to keep the packet order. In short, from a practical point of view, there is a trade-off between efficiency and cost in the design of packet error control policy. In this paper, as the first step of our research, we consider a simple policy, in which a frame burst will be retransmitted if there is any bit error in the transmission.

3. Analytical Model

In this section, we develop an analytical model to evaluate the unsaturated throughput performance of the frame-burst-based MAC protocol in imperfect wireless channel conditions. Following [11], we first decompose the whole system into a queueing subsystem and a service time subsystem.

Since a burst will be retransmitted if the previous transmission attempt failed, the queueing model remains the same as that of [11], which is an M/G$^{[B_{min},B_{max}]}$/1/K queue. In this formulation, K is the capacity of the queue excluding packets in the burst buffer, and the superscript $[B_{min}, B_{max}]$ means that the total number of packets in a burst is an integer in the range of $[B_{min}, B_{max}]$.

The main difficulty of our analysis is how to take into consideration the impact of transmission errors, which will directly affect the formulation of the binary exponential backoff scheme and the burst service time distribution.

The rest of this section is organized as follows. In subsection 3.1 and 3.2, we provide the assumptions and notations used in our analysis. We then elaborate on the impact of transmission error in modeling of binary exponential backoff and the service time distribution, in subsection 3.3 and 3.4, respectively. The throughput analysis will be given in subsection 3.5. And finally, we describe the iterative algorithm for the analysis in subsection 3.6.

3.1. Assumptions

To conduct the analysis, we first make the following assumptions:

- There are N identical nodes in the network.
- At each node, packet arrivals are Poisson with rate λ (packets/sec), and all incoming packets to a node have the same destination. Therefore, the burst assembly policy can be simplified as follows:

  Suppose there are k packets in the queue just before a frame burst departure, then the number of packet in the next frame burst, denoted as B_k, is defined as

$$B_k = \begin{cases} B_{min} & 0 \le k \le B_{min} \\ k & B_{min} < k \le B_{max} \\ B_{max} & B_{max} \le k \le K. \end{cases} \quad (2)$$

- The size (in bytes) of incoming packets is an i.i.d random variable with an arbitrary distribution $f(n)$. We further define N_{min} and N_{max} be the minimum and maximum size of a packet in bytes.
- The queue of MAC layer has the capacity K (in packets), excluding the transmission buffer.
- The channel is not perfect in that every bit in a frame burst encounters error with a probability ϵ. To simplify the discussion we also assume that control packets and frame headers are error free.
- The burst service time is an integer multiple of a preset time unit τ (in seconds). This integer has an upper bound I_{max} as a server only tries to send one burst for finite number of times and each time the attempt has a finite duration.
- The probability that a burst transmission attempt fails, denoted as p, does not depend on the backoff stage of the node.
- The propagation delay is negligible.

3.2. The Notations

In this section, we provide the notations for the parameters we will use in the following sections:

- p_I denotes the probability that a node is idle at the beginning of a time segment[2], i.e. the node has no burst to transmit in the time segment.
- p_b ($B_{min} \le b \le B_{max}$) denotes the probability that a frame burst consists of b packets.
- p_t denotes the probability that a node will transmit in one time segment.
- p_k^d denotes the steady state probability that there are k packets left in the queue at the time instance just before a burst departures.
- q_{bi} denotes the steady state probability that the burst service time is $i\tau$, given that there are b packets in the burst.
- S denotes the MAC throughput per node in bits per second.

3.3. Binary Exponential Backoff

To analyze the exponential backoff scheme of the CSMA/CA protocol, we will use the Markov modeling technique introduced in [2], [19]. Particularly, we can first partition the continuous time axis into time segments, where two consecutive segments are delimited by the event of a value change in the backoff counter. We can then formulate a two-dimensional discrete time embedded Markov chain as that of [2], [19]. With the close form solution of the Markov chain, the first relation between p and p_t can be derived by Eq. (3).

The second relation comes from the physical meaning of p. Since a successful burst delivery only happens when there is neither collision nor bit error in a transmission attempt, we can calculate p through

$$p = 1 - (1 - p_c)(1 - p_e), \quad (4)$$

[2]In this paper, time segment is defined as the time duration in which the backoff counter of a node does not change. More detail explanation can be found in Section 3.3.

$$p_t = \begin{cases} \dfrac{2(1-2p)(1-p^{M+1})}{(1-2p)(1-p^{M+1}) + W(1-p)(1-(2p)^{M+1})} & M \le M' \\ \dfrac{2(1-2p)(1-p^{M+1})}{(1-2p)(1-p^{M+1}) + W(1-p)(1-(2p)^{M'+1}) + W2^{M'}p^{M'+1}(1-2p)(1-p^{M-M'})} & M > M' \end{cases} \tag{3}$$

where p_c is the collision probability and p_e is the average burst error probability. p_t and p_e can be expressed as

$$p_c = 1 - [1-(1-p_I)p_t]^{N-1} \tag{5}$$

and

$$p_e = \sum_{b=B_{min}}^{B_{max}} p_b \cdot p_e(b), \tag{6}$$

where we let $p_e(b)$ be the probability that the burst transmission is not successful due to bit error, given that there are b packets in the burst.

To calculate $p_e(b)$, we first define $f(b,n)$ as the probability distribution function of the size (in bytes) of a burst with b packets. Since the length of incoming packets is i.i.d. random variable, we can achieve $f(b,n)$ through an recursive algorithm

$$\begin{aligned} f(1,n) &= f(n) \\ f(2,n) &= f(n) \otimes f(1,n) \\ &\cdots \\ f(b,n) &= f(n) \otimes f(b-1,n), \end{aligned} \tag{7}$$

where $\otimes$ represents the convolution. Consequently, $p_e(b)$ can be calculated by

$$p_e(b) = 1 - \sum_{n=b\times N_{min}}^{b\times N_{max}} f(b,n) \times (1-\varepsilon)^{8n}. \tag{8}$$

3.4. Service Time Distribution

To derive the service time distribution, we use the technique introduced in [11]. First, we define $Q_b(z)$ as the probability-generating function (PGF) of q_{bi}, which is

$$Q_b(z) = \sum_i z^i \cdot q_{bi}. \tag{9}$$

Clearly, $Q_b(z)$ is the z-transform of q_{bi} and there is a one-to-one correspondence between $\{q_{bi}\}$ and $Q_b(z)$. Next, we let X_n be the duration of segment n and let X'_n be the duration within segment n, when the server is busy. We can then apply the transfer function approach, in which the MAC layer transmission process is characterized by a linear system, as shown in Fig. 1.

The parameters used in Fig. 1 are defined as the following

- $p(b)$ denotes the average probability that the transmission of a given burst with b packets is not successful in one time segment. Similar to Eq. (4), we have

$$p(b) = 1 - (1-p_c)(1-p_e(b)) \tag{10}$$

- $H(z)$ denotes the PGF of X'_n given that the current node has a packet in the transmission buffer but not transmitting.
- $C_b(z)$ denotes the PGF of X'_n given that a collision occurs when the current node is transmitting a burst with b packets.
- $S_b(z)$ denotes the PGF of X'_n given that the current node has successfully transmitted a burst with b packets.
- $H_m(z)$ denotes an interim function

$$H_m(z) = \frac{1}{W_m}\left[1 + H(z) + H^2(z) + \cdots + H^{W_m-1}(z)\right], \tag{11}$$

which is used to simplify the notation.

The formulation of $Q_b(z)$ can be directly derived from Fig. 1, as

$$\begin{aligned} Q_b(z) &= (1-p(b))S_b(z)\sum_{m=0}^{M}\left[(Y_b(z))^m \prod_{i=0}^{m} H_i(z)\right] \\ &\quad + (Y_b(z))^{M+1}\prod_{i=0}^{M} H_i(z), \end{aligned} \tag{12}$$

where

$$Y_b(z) = p_c C_b(z) + (p(b) - p_c)S_b(z). \tag{13}$$

In the remaining of this subsection, we will discuss how to calculate $S_b(z)$, $C_b(z)$, and $H(z)$ numerically.

To calculate $S_b(z)$, we can use

$$S_b(z) = \sum_{n=b\times N_{min}}^{b\times N_{max}} f(b,n) z^{\lfloor \frac{1}{\tau}\times(T_{so}+8n/R_d)\rfloor}, \tag{14}$$

where R_d is the physical layer data rate and T_{so} is the time overhead for a successful frame transmission. The calculation of T_{so} depends on the detailed protocol specification. For instance, T_{so} for the RTS/CTS access scheme can be found in [11].

To simplify the discussion, we provide the calculation of $C_b(z)$ and $H(z)$ only for the RTS/CTS scheme. For the RTS/CTS scheme, since collision can only occurs when two or more RTS packets collide, $C_b(z)$ can be derived as

$$C_b(z) = z^{\lfloor \frac{T_{co}}{\tau} \rfloor} \tag{15}$$

where T_{co} is the time overhead for collision.

To calculate $H(z)$, we can use

$$H(z) = (1-q_t)z^{\lfloor \frac{\sigma}{\tau} \rfloor} + q_s S(z) + (q_t - q_s)C(z), \tag{16}$$

where q_t denotes the probability that there is at least one transmission burst in $N-1$ neighbor nodes in segment n, q_s denotes the probability that there is only one burst transmission in $N-1$ neighbor nodes in slot n, $S(z)$ denotes the PGF of X'_n given that there is a successful transmission in time segment n,

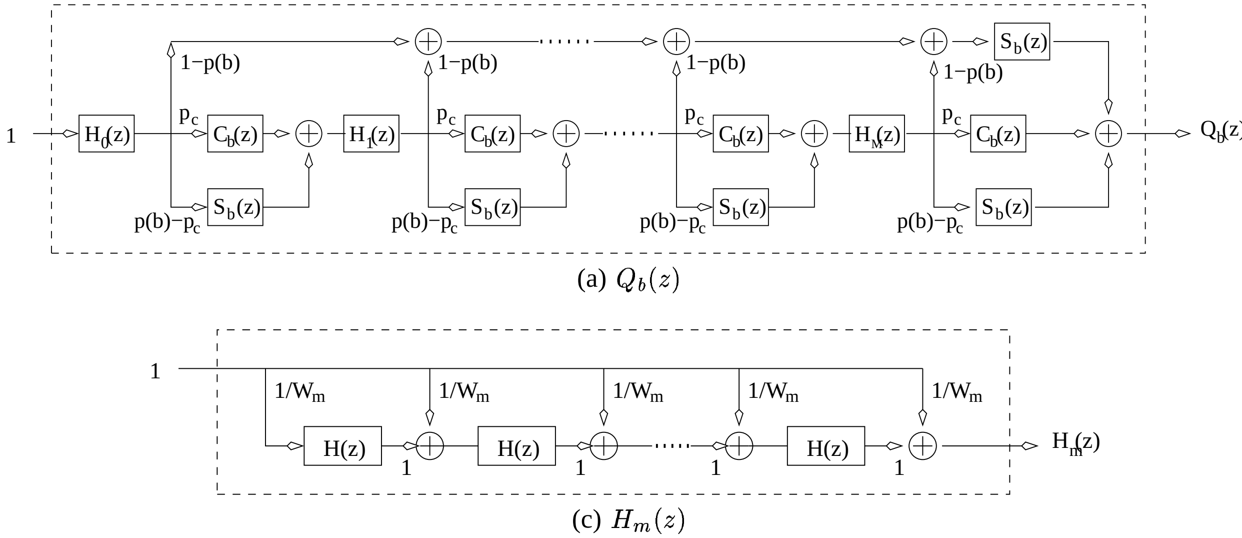


Fig. 1. Service system diagram.

and $C(z)$ denotes the PGF of X'_n given that there is a collision in segment n. These parameters can be calculated through

$$q_t = 1 - [1 - (1 - p_I)p_t]^{N-1} \quad (17)$$
$$q_s = (N-1)(1-p_I)p_t[1-(1-p_I)p_t]^{N-2} \quad (18)$$
$$S(z) = \sum_{b=B_{min}}^{B_{max}} p_b \times S_b(z) \quad (19)$$
$$C(z) = C_b(z). \quad (20)$$

3.5. Throughput Analysis

Now let $d_k(t)$ be the total number of burst departures, just before which there are k packets waiting in the queue; let $V(b)$ be the departure rate (in bursts / second) of bursts with b packets in the frame. Based on the burst assembly policy, we have

$$\begin{aligned} V(b) &= \lim_{t\to\infty} \frac{\sum_{\forall k:B_k=b} d_k(t)}{t} = \sum_{\forall k:B_k=b} \lim_{t\to\infty} \frac{d_k(t)}{t} \\ &= \frac{\sum_{\forall k:B_k=b} p_k^d}{T^s + \frac{1}{\lambda}\cdot \sum_{k=0}^{B_{min}-1}(B_{min}-k)p_k^d} \\ &= \frac{p_b}{T^s + \frac{1}{\lambda}\cdot \sum_{k=0}^{B_{min}-1}(B_{min}-k)p_k^d}. \end{aligned} \quad (21)$$

We can then calculate the expected size (in bits) of data that are successfully delivered in time duration t^*, given that these packets are all conveyed through bursts with b packets in each burst. Since each burst will be transmitted up to $M+1$ times, we have

$$S(b,t^*) = V(b) \times t^* \times b \times \overline{P} \times \left[1 - (p(b))^{M+1}\right], \quad (22)$$

where $\overline{P}$ is the average length of packet (in bits), which can be calculated through

$$\overline{P} = \sum_{n=Nmin}^{N_{max}} 8n \times f(n). \quad (23)$$

Finally, we can calculate the throughput (per node) of the frame-burst-based CSMA/CA protocol through

$$\begin{aligned} S &= \sum_{b=B_{min}}^{B_{max}} \frac{S(b,t^*)}{t^*} \\ &= \overline{P} \times \sum_{b=B_{min}}^{B_{max}} V(b) \times b \times \left[1-(p(b))^{M+1}\right]. \end{aligned} \quad (24)$$

3.6. The Iterative Algorithm

In this section, we provide the iterative algorithm to calculate the unsaturated throughput of a node:

Step 1: Initialize p_I and p_b to saturated condition, i.e., let $p_I = 0$, $p_{B_{max}} = 1$, and $p_b = 0$ for $b \neq B_{max}$.

Step 2: Calculate p and p_t according to an Markov model for exponential backoff.

Step 3: Calculate service time distribution q_{bi} through the transfer-function approach, using p and p_t.

Step 4: Calculate p_k^d by using the M/G$^{[B_{min},B_{max}]}$/1/K queueing model.

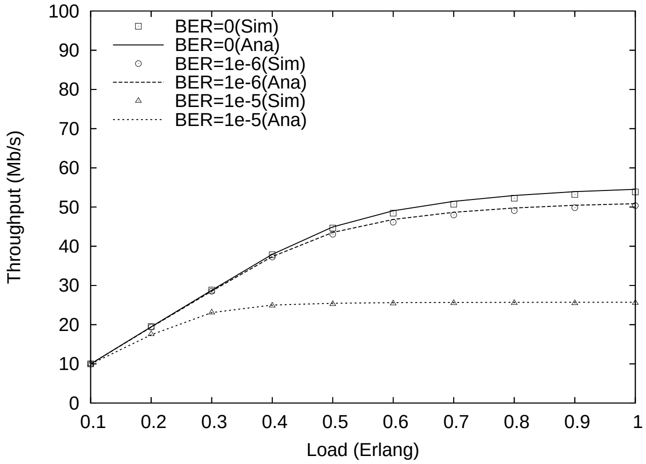
Step 5: Calculate new p_I and p_b based on p_k^d.

Step 6: Calculate the throughput S. Stop the algorithm if S converges; otherwise go to Step 2 with the new p_I and p_b values.

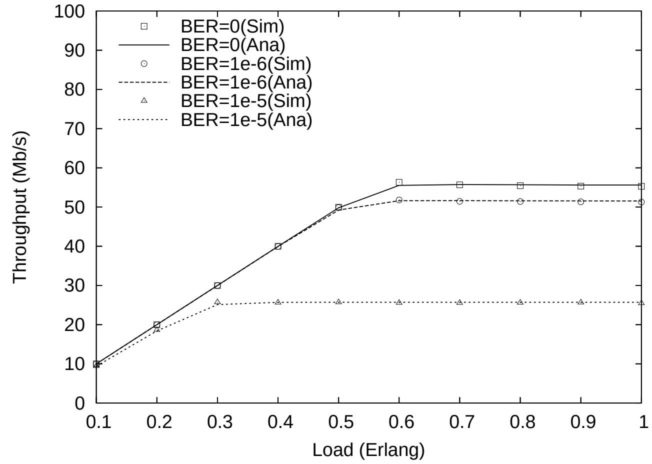
It is important to note that, although the convergence of the iterative algorithm has not been proved, the algorithm seems always converge in all our numerical calculations.

4. Simulation and Numerical Results

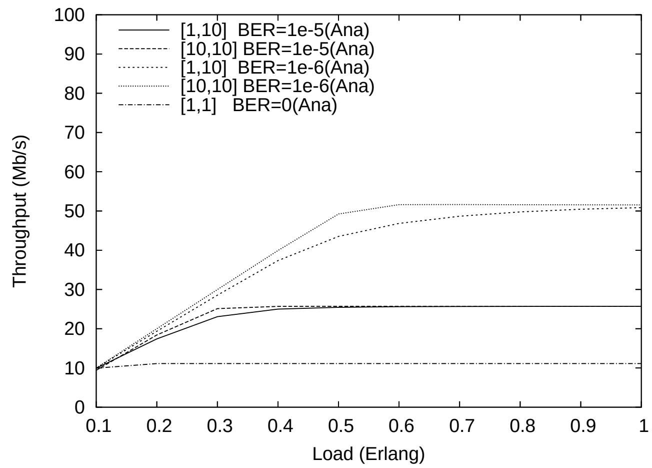
In this section, we evaluate the performance of the frame-burst-based MAC protocol under various traffic and channel



(a) $[B_{min}, B_{max}] = [1, 10]$



(b) $[B_{min}, B_{max}] = [10, 10]$



(c) Comparison

Fig. 2. Throughput performance vs. incoming traffi c data rate with different channel BER (Scenario (1), $N = 10$).

condition. Moreover, we compare the simulation results to the numerical results achieved through the proposed analytical method in Section 3.

The basic setting of our experiments is listed as the following:

- All nodes are located in a 10 m × 10 m area.
- The size of each packet follows the same distribution. Unless otherwise specified, we assume that the packet size is fixed at 1000 Bytes.
- Packet arrivals to each node are modeled by a Poisson process with the same rate λ (packets/s). Consequently, the incoming traffic data rate is $R_i = N\overline{P}\lambda$ (bits/s).
- We assume that the preamble overhead, denoted as T_{sync}, is identical for all messages.
- We assume that all messages are transmitted with the same channel data rate R. We then define the traffic load to the network as R_i/R Erlang.
- We assume that packet transmission error can only occur in payload, with a fixed bit error ratio.
- We assume that the RTS/CTS scheme is used with setting listed in Table I.

In addition, we conduct the experiments in the following

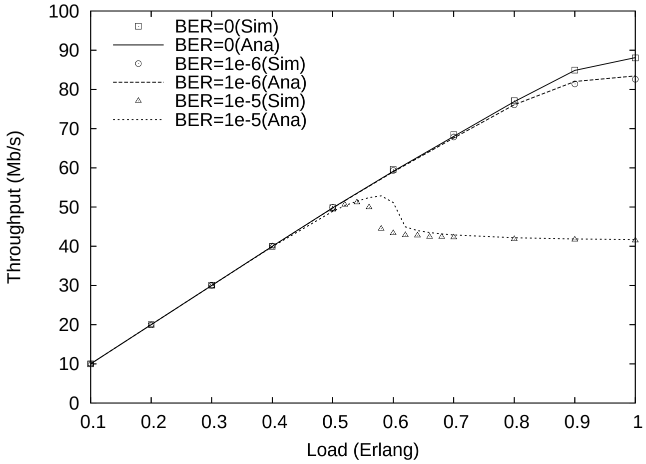
TABLE I
SETTING OF THE MAC PROTOCOL.

Minimum contention window size	8
Maximum contention window size	256
Long retry limit	4
Queue size	50

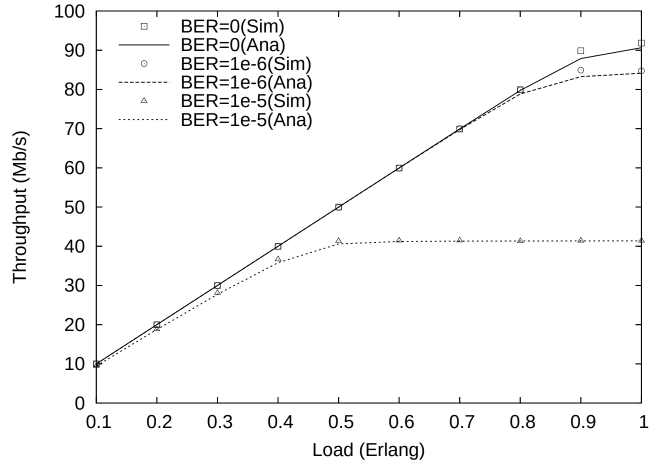
two scenarios:

1) IEEE 802.11n
   In this case, we assume that $\sigma = 20\mu s$, SIFS = $10\mu s$, DIFS = $50\mu s$, and $R = 100Mb/s$.
2) High data rate UWB
   In this case, we assume that $\sigma = 2\mu s$, SIFS = $1\mu s$, DIFS = $5\mu s$, and $R = 100Mb/s$.

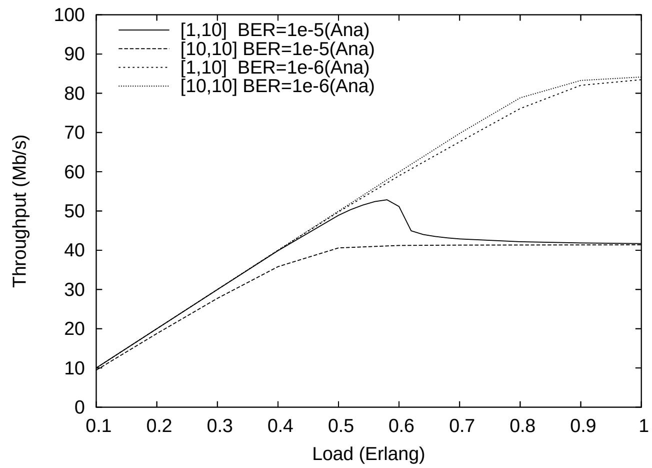
Figure 2 shows the throughput performance versus incoming traffic rate under different BER conditions in the first scenario and we let $N = 10$. In this experiment, we use three burst assembly setting: 1) $[B_{min}, B_{max}] = [1, 10]$; 2) $[B_{min}, B_{max}] = [10, 10]$, and 3) $[B_{min}, B_{max}] = [1, 1]$. From Fig. 2 (a) and (b), we can observe that our analytical model is highly accurate under different traffic and BER conditions. We notice that, compared to the benchmark case where BER



(a) $[B_{min}, B_{max}] = [1, 10]$



(b) $[B_{min}, B_{max}] = [10, 10]$



(c) Comparison

Fig. 3. Throughput performance vs. incoming traffic data rate with different channel BER (Scenario (2), $N = 10$).

is 0, the overall throughput performance decreases slightly if BER is 10^{-6} and if the traffic load is high. These results show that, the burst assembly policy and the simple retransmission policy can work fine if BER is 10^{-6}. One the other hand, if the BER is 10^{-5}, we can see that the protocol can still perform well if the load is very small, which suggests that more sophisticated retransmission mechanism must be utilized to improve the throughput performance in a high bit error channel condition.

We compare the performance of the three different assembly policies under various channel conditions in Fig. 2 (c). We can observe that, setting (2) can achieve the best performance in all traffic conditions. Moreover, the results show that the frame-burst-based MAC protocol can significantly outperform the original CSMA/CA protocol even in imperfect wireless channel. Specifically, we note that the throughput performance of setting (3) in an error-free channel is much smaller than that of the other two policies with BER as high as 10^{-5}.

In Fig. 3, we show the performance of the frame-burst-based protocol in the second scenario, where we keep all other setting the same as that of Fig. 2. Similarly, we can see that, compared to the benchmark case where BER is 0, the overall throughput performance decreases slightly if BER is 10^{-6} and only if the traffic load is higher than 0.8 Erlang. Interestingly, we found from Fig. 3 (a) that, if the BER is 10^{-5}, the maximum throughput is achieved when the load is about 0.55 Erlang, which is larger than the saturated throughput. Such results demonstrate that, our analytical model is much better than the saturated model, which can only be used to predict the throughput performance when the traffic load is close to 1.

From Fig. 3 (c) we can see that the performance of policy (2) is better than policy (1) when the BER is 10^{-6}. However, policy (1) performs better the policy (2) if the BER is 10^{-5} under medium traffic load (i.e., $0.4 - 0.7$ Erlang).

In Fig. 4 we demonstrate the impact of B_{max} on the performance of the protocol with different network traffic load and BER= 10^{-5} in the second scenario. We can see that, when the traffic load is 1 Erlang, the best throughput performance is achieved if B_{max} is 3; when the traffic load is 0.6 Erlang, the best throughput performance is achieved if B_{max} is 2; and when the traffic load is 0.5 Erlang, the throughput is nearly the same if $B_{max} > 1$, and is larger than that of $B_{max} = 1$. From Fig. 4 we can also observe that our analytical model

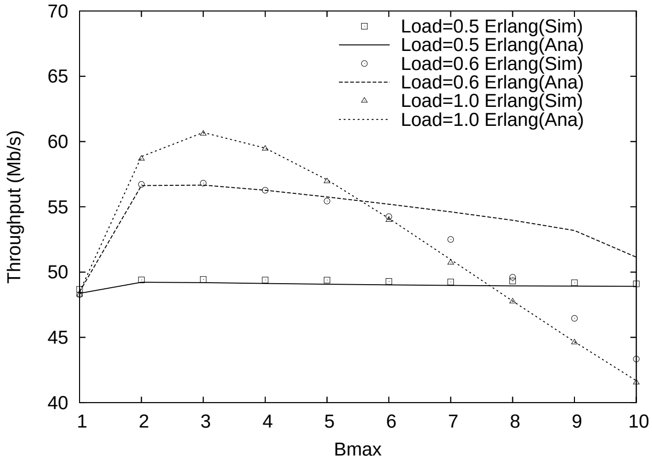


Fig. 4. Throughput performance vs. B_{max} (Scenario (2), $N = 10$, BER=10^{-5}).

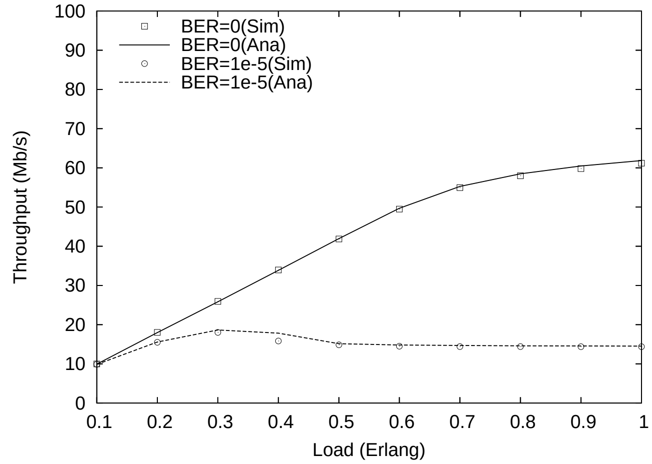


Fig. 6. Throughput performance vs. incoming traffic data rate with different channel BER (Scenario (1), $N = 20$, $[B_{min}, B_{max}] = [1, 20]$).

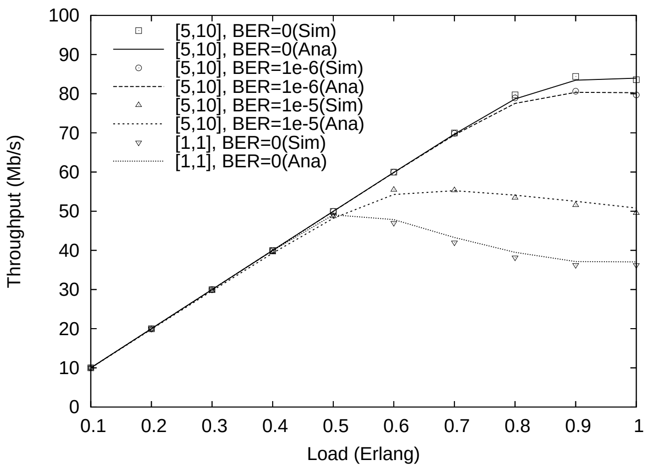


Fig. 5. Throughput performance vs. incoming traffic data rate with different channel BER (Scenario (2), $N = 50$).

is less accurate (over-estimates the throughput) if the load is 0.6 Erlang and when B_{max} is larger than 5. The reason of this phenomenon can be found in Fig. 3 (a), where we can observe that, with a slight increase of traffic load, the throughput decreases significantly from the maximum value.

Fig. 5 shows the performance of the protocol in the scenario when the total number of node in the network is $N = 50$. We can first observe that, for the traditional approach ($B_{min} = B_{max} = 1$), the throughput performance will decrease with the increase of load if the load is larger than 0.5 Erlang. Similar to previous results, we show that the performance of the frame-burst-based protocol is better than that of the traditional one even if the BER is 10^{-5}.

Finally, Fig. 6 shows the performance of the protocol when the size of incoming packets are not fixed. In particular, we assume that the length of incoming packets is uniformly chosen in $[500, 1500]$ Bytes. Comparing the simulation and analytical results, we can see that our analytical model is highly accurate under different traffic and channel conditions.

5. Conclusions

In this paper, we developed an accurate analytical model to evaluate the unsaturated throughput performance of a frame-burst-based CSMA/CA protocol in imperfect wireless channel. Simulation and numerical results show that, the proposed analytical model is highly accurate in most cases. More importantly, the results reveal that the best throughput performance can be achieved through appropriate setting of the burst aggregation policy.

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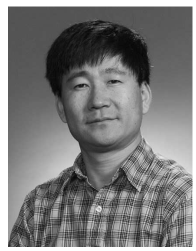

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