A Renewal Theory Based Analytical Model for the Contention Access Period of IEEE 802.15.4 MAC

Xinhua Ling, Yu Cheng, *Member, IEEE,* Jon W. Mark, *Life Fellow, IEEE,* and Xuemin (Sherman) Shen, *Senior Member, IEEE*

***Abstract*—In this paper, we propose a simple yet accurate analytical model for the slotted non-persistent carrier sense multiple access protocol with binary exponential backoff, as specified in the medium access control (MAC) protocol of the IEEE 802.15.4 standard for the contention access period. The model is based on a three-level renewal process, which leads to a general analytical framework applicable to the protocol variants of either single or double sensing, in a saturated or unsaturated case, under a general traffic arrival distribution and with various backoff policies. The analytical model can be used to obtain some important performance metrics, such as MAC throughput and average frame service time. The accuracy of the analytical model is demonstrated by extensive simulation results. The applicability of this model to the performance analysis of other slotted MAC protocols is also briefly discussed.**

***Index Terms*—Analytical model, CSMA/CA, IEEE 802.15.4, MAC, renewal theory, wireless networks.**

I. INTRODUCTION

THE FAST growth of public interest in wireless sensor networks and wireless personal area networks (WPAN) in recent years has led to the standardization of the IEEE 802.15.4 [1], which contains a new protocol stack targeting at low-power low-rate wireless networks. The standard has been quickly accepted by industry, and many products have appeared in the market since its ratification.

The IEEE 802.15.4 standard, especially its medium access control (MAC) protocol for the contention access period (CAP), also draws great interest from the academia. A salient difference between the CAP MAC specified in this standard and the classical slotted non-persistent carrier sense multiple access (CSMA) [2] is that a node can transmit only after two consecutive sensing of an idle channel in the former, while just one channel sensing is required in the latter. In addition, it differs from the well-known IEEE 802.11 [3] DCF MAC protocol for wireless local area networks (WLANs) in that the backoff counter (BC) of a node does not freeze when the channel is busy; instead, it keeps decreasing until reaching zero. Moreover, when the BC reaches zero, a node adopting DCF transmits immediately, while a node with CAP-MAC does so only after sensing two consecutive idle slots. Intuitively, the different protocol behavior of 802.15.4 will result in performance different from the two well-known MAC protocols.

Several simulation studies have been conducted [4]–[7] to understand the performance of the 802.15.4 protocol. In addition, efforts have also been made in analytically modeling the protocol, especially the *slotted non-persistent CSMA with binary-exponential-backoff (BEB)* MAC protocol for the contention access period defined in the standard [8]–[11]. While simulation studies, usually time consuming, may only address particular scenarios under specific conditions, analytical modeling enables one to gain a clearer insight into the characteristics of the protocol.

In this paper, a simple and yet accurate analytical model for the IEEE 802.15.4 MAC protocol is proposed. Instead of modeling the channel, we model the behavior of an individual node based on a novel concept of *three-level renewal process*, which can be solved by the fixed-point technique [12]. The new modeling approach significantly simplifies the mathematical analysis, where the important performance metrics of MAC throughput and average frame service time (also referred to as *access delay* in [13]) can be directly obtained. We also show that the proposed model is in fact a general analytical framework which enables us to analyze different protocol variants of either single or double sensing, in a saturated or unsaturated case, under a general traffic arrival distribution, and with various backoff policies. Extensive computer simulation results are presented to demonstrate the accuracy of the proposed analytical model.

The remainder of the paper is organized as follows. The 802.15.4 MAC protocol is briefly reviewed in Sec. II. The analytical model for saturated nodes is presented in Sec. III. In Sec. IV, we derive the normalized MAC throughput and the average frame service time. In Sec. V, we extend the analytical model to the case where nodes are unsaturated. Analytical results are compared with simulation results in Sec. VI to assess analytical accuracy; the impact of the key MAC parameters on the protocol performance is also discussed. Related work is given in Sec. VII, followed by concluding remarks in Sec. VIII.

II. THE IEEE 802.15.4 MAC PROTOCOL

In this section, we briefly review the MAC protocol specified in the IEEE 802.15.4 standard. More details of the

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X. Ling, J. W. Mark, and X. S. Shen are with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, N2L 3G1, Canada (e-mail: {x2ling, jwmark, xshen}@bbcr.uwaterloo.ca).

Y. Cheng is with the Department of Electrical and Computer Engineering, Illinois Institute of Technology, Chicago, IL 60616-3793, USA (e-mail: cheng@iit.edu).

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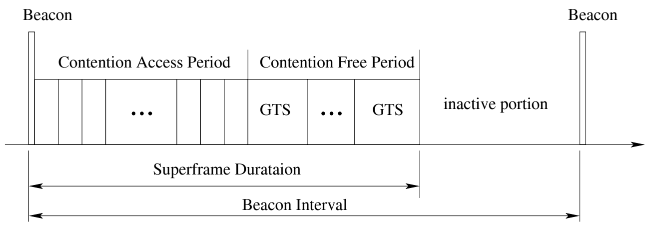

Fig. 1. IEEE 802.15.4 superframe structure in the beacon-enabled mode

protocol, such as specific parameter settings or physical layer related information, can be found in [1], [4].

The MAC layer in the IEEE 802.15.4 standard specifies two operating modes: an ad hoc non-beacon-enabled mode and a beacon-enabled mode. In the ad hoc mode, nodes in the network use a non-slotted CSMA with collision avoidance (CSMA/CA) mechanism to contend for channel access. If the channel is assessed to be idle, the transmission of a frame will begin immediately; otherwise the node will backoff and try to access the channel in a future slot. This mechanism has been extensively studied in the literature and its performance is well understood [2], [14]. In the beacon-enabled mode, a personal area network (PAN) coordinator transmits a beacon periodically to form the so-called "superframe" time structure, as shown in Fig. 1. A superframe consists of a beacon that enables the beacon-enabled mode, contention access period (CAP), contention free period (CFP), and an optional inactive portion in which all the nodes may enter a sleep mode to reduce power consumption. The CAP and CFP together form the active portion of the superframe, during which all communication among the nodes should take place. In the CFP, the network coordinator alone controls entirely the contention-free channel access by assigning guaranteed time slots (GTS) to those nodes with their GTS requests granted. According to the default values specified in the standard [1], the active portion of each superframe contains 48 backoff slots, 15 of which are occupied by the CFP. The assignment of the GTS to those nodes is determined by the scheduling scheme adopted by the network coordinator, which is open in the standard. Therefore, depending on the specific scheduling scheme used, the performance analysis of CFP is actually the same as that of the well-studied centralized scheduling schemes in cellular systems.

In the CAP, a non-persistent slotted CSMA/CA with binary exponential backoff multiple access protocol, termed CAP-MAC in the sequel, is defined in the standard. Three variables need to be maintained for each frame before it is successfully transmitted. They are respectively the number of random back-off stages experienced (NB), the current backoff exponent (BE), and the contention window (CW)[1]. According to this protocol, a node with a frame waiting for transmission at the MAC buffer is required to backoff a random number of slots first, with CW set to two. At the end of this backoff stage, the node will do the first channel clear assessment (CCA). If the channel is sensed idle, CW is decremented by one and the node will do the second CCA in the next slot. Only when both CCAs indicate an idle channel (thus CW reaches zero), will the node start the transmission in the next slot; otherwise, it will enter the next backoff stage and reset CW to two.

The number of backoff slots in stage $NB, 0 \leq NB \leq NB_{\max}$, is drawn from a uniform distribution over $[0, 2^{\mathrm{BE}_{NB}} - 1]$, where $BE_0 = macMinBE$ is the initial and minimum backoff exponent for each frame. $BE_{NB+1} = BE_{NB} + 1$ is upper-bounded by *aMaxBE* which is the default maximum value of backoff exponent, and $NB_{\max}$ is the maximum number of backoff stages allowed for a frame. If all the $NB_{\max}$ backoff stages end up with a busy channel indicated by the associated CCAs, a *Channel Access Failure* event will be reported to the upper layer; the node may then start the above procedure again for the next frame. The standard specifies the following default parameter values: $macMinBE = 3, aMaxBE = 5$ and $NB_{\max} = 5$. Their impact on the protocol performance will be discussed in Sec. VI. During the backoff procedure, if the node succeeds in accessing the channel, it will reset the three parameters NB, BE and CW to the default values for initial transmission of the next frame.

III. The Analytical Model

In this section, we first describe the network considered, then present the 3-level renewal process, which is the foundation of the proposed analytical model for the CAP-MAC. We then develop the model by first considering the single channel sensing (SS) case, to illustrate the essence of our model. We further extend the model to the double channel sensing (DS) case specified in the standard. Notice that the only difference between the SS and the DS is that the former just requires one successful CCA before the node can start to transmit[2]. In the analysis, it is assumed that for each node, the probability τ to start channel sensing in a randomly chosen slot is constant, regardless of the number of retransmission trials it has experienced. This assumption is widely adopted for the study of IEEE 802.15.4 [9]–[11], which is the counterpart of the assumption regarding the channel access probability taken in the IEEE 802.11 MAC protocol modeling [15], [16]. Two important first-order MAC performance metrics, normalized throughput and average frame service time, are the primary targeting results of the proposed model. Hence, we have used average values wherever possible, as in [15], [17].

A. System Model

A single-hop wireless network consisting of N functionally identical nodes is considered. Specifically, all the nodes are within the same transmission range of one another so there are no hidden terminals in the network. In addition, all the nodes are synchronized and they can correctly sense the channel status during the CCA slots. An ideal wireless channel without transmission error is assumed so that all transmitted frames may be lost only due to collisions caused by simultaneous transmissions from multiple nodes. However, non-ideal channels that may cause unsuccessful reception of

[1]The term *contention window* is the number of slots that the channel has to be sensed idle by a node before its transmission of a frame, which is completely different from the contention window defined in IEEE 802.11.

[2]Some issues of SS will be addressed in Sec. VI-B2

frames due to transmission error can also be embedded in our analysis, following the approach presented in [18], [19]. All MAC frames are assumed to have the same fixed length (with transmission time of L slots), which is also a widely adopted assumption in MAC protocol analysis [2], [13], [14] and can be easily achieved in practice by the commonly used link layer functions, such as fragmentation or concatenation of the upper layer packets. In addition, link layer acknowledgement is not considered.

In this paper, we focus on the contention access period only to illustrate the protocol performance by the proposed analytical model. In such a simplified MAC, the inactive portion and the contention free period in the active portion will not be considered in the superframe time structure. In other words, a node will always contend for channel access according to the protocol for CAP as described in Sec. II, whenever it has a frame to transmit. Therefore, the superframe contains equal-size time slots with fixed length, which is normalized to unit time in the sequel for presentation simplicity. In fact, since the contention access related activities such as backoff counter decrement occurs only in the CAPs and freeze in the CFPs and inactive portion of the superframes, the impact of these two periods on the MAC performance can be taken into our proposed model as having a constant time cost (equal to the aggregate length of the CFP and the inactive portion of a superframe) associated to every A slots, where A is the length of each CAP in units of slots. A similar approach is used in [9], but for generating low duty cycle constant rate traffic as a special case of unsaturated nodes.

B. The 3-level Renewal Process

From the description of the 802.15.4 protocol given in Sec. II, the link layer activities (channel sensing and frame transmissions) of any node over a given time interval is a renewal process [20], since the node resets its backoff parameters to the default initial value after each transmission trial (regardless of the result) or when it senses a busy channel at the end of the last backoff stage. Over a larger time scale, the end of each transmission trial is also a renewal point of the frame service process. If the time scale is even larger, the renewal point can also be set at the end of each successful transmission. Such a three-level renewal process is illustrated[3] in Fig. 2, which is the key concept that inspires the proposed analytical model.

In Fig. 2, a level-1 renewal cycle is defined as the period between two adjacent time instants where the tagged node starts a stage 0 backoff. In this context, the number of sensing attempts R conducted by the tagged node can be viewed as a reward associated with the level-1 renewal cycle of length X. A level-1 renewal cycle can be of either type X_1 or X_2, as shown in Fig. 2. Type X_1 is a cycle that includes no transmission from the tagged node due to M consecutive failures in sensing the channel idle, which is marked by the symbol "×" in the figure. Type X_2 is a cycle that contains a period of frame transmission from the tagged node immediately after sensing an idle channel (marked as

[3]For simplicity, the CCA slots (i.e., the sensing slots) are not shown in the figure, but they will be considered in the analysis.

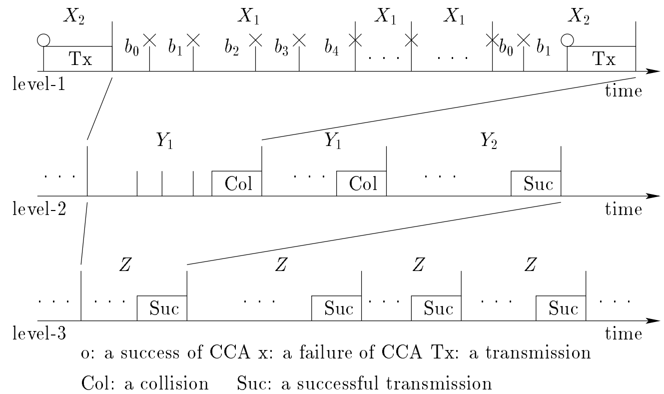

Fig. 2. Illustration of the concept of 3-level renewal process, M=5

"o"). Note that the transmission in an X_2 cycle may be a successful transmission or a collision.

A level-2 renewal cycle Y is from the end of an X_2 level-1 cycle to the end of the next X_2 cycle. As shown in Fig. 2, there can be j $(j \geq 0)$ X_1 cycles before the X_2 cycle. Depending on the result of transmission in the X_2-cycle, a level-2 cycle can be of either type Y_1, in which the transmission results in a collision, or type Y_2, in which the transmission succeeds.

Finally, a level-3 renewal cycle Z is from the end of a Y_2 level-2 cycle to the end of the next Y_2 cycle. Similarly, there can be $k, k \geq 0$, Y_1 cycles before the Y_2 cycle. Therefore, the successful transmission of a frame in the Z cycle can be viewed as the reward for the level-3 renewal cycle. The throughput of the tagged node can thus be obtained as the average reward in a Z cycle.

C. The Single-Sensing Case (One CCA)

According to the renewal reward theorem [20], the sensing attempt rate for the tagged node is given by $\overline{R}/\overline{X}$, where $\overline{(\cdot)}$ denotes the mean of the corresponding random variable. Assume a homogeneous network, where the behavior of all the nodes is statistically the same, and the failure probability α is the same for all the channel sensing activities from all the nodes. With a given α, the average number of sensing attempts for one node in a level-1 renewal cycle is

$$\begin{aligned}\overline{R} &= (1-\alpha) + 2\alpha(1-\alpha) + 3\alpha^2(1-\alpha) + \cdots \\ &\quad + (M-1)\alpha^{M-2}(1-\alpha) + M\alpha^{M-1} \\ &= \sum_{m=0}^{M-1} \alpha^m, \end{aligned} \tag{1}$$

and the average length of a level-1 renewal cycle is

$$\begin{aligned}\overline{X} &= (1-\alpha)(b_0+1+L) + \alpha(1-\alpha)(b_0+b_1+2+L) + \cdots \\ &\quad + \alpha^{M-1}(1-\alpha)(\sum_{m=0}^{M-1}(b_m+1)+L) + \alpha^M \sum_{m=0}^{M-1}(b_m+1) \\ &= \sum_{m=0}^{M-1} \alpha^m (b_m+1) + (1-\alpha^M)L, \end{aligned} \tag{2}$$

where L is the duration of a frame transmission in units of slots, and $b_m, 0 \leq m \leq M$, is the average number of slots in backoff stage m. Note that at the end of each backoff stage, there is always one slot used for sensing the channel. In addition, with a probability of α^M, the tagged node encounters M contiguous sensing failures and thus ends up the current renewal cycle without a transmission period incurred. Therefore, a period of L is included in the level-1 renewal cycle with probability $(1-\alpha^M)$, which is reflected by the last term in (2). The sensing probability τ can be obtained as

$$\tau = \frac{\overline{R}}{\overline{X}} = \frac{\sum_{m=0}^{M-1} \alpha^m}{\sum_{m=0}^{M-1} \alpha^m (b_m + 1) + (1 - \alpha^M) L}. \quad (3)$$

Next we derive the sensing failure probability α. When the tagged node starts to sense the channel, the channel state is either idle with probability P_i or busy with probability $P_b = 1 - P_i$. To obtain P_i, consider the channel status for two consecutive slots. By the Law of Total Probability in classical probability theory, we have $P_i = P_{(i,i)} P_i + P_{(b,i)}(1 - P_i)$, which yields

$$P_i = \frac{P_{(b,i)}}{1 + P_{(b,i)} - P_{(i,i)}}, \quad (4)$$

where $P_{(b,i)}$ $\left(P_{(i,i)}\right)$ is the conditional probability that the next channel state is idle given that the current channel state is busy (idle). Since a transmission lasts for L slots, a busy slot will end with probability $1/L$ at a randomly selected slot, which yields $P_{(b,i)} = \frac{1}{L}$. On the other hand, considering the constant sensing probability assumption, the channel will remain in the idle state when it is idle in the current slot only if none of the nodes starts to sense in the current slot, i.e., $P_{(i,i)} = (1-\tau)^N$. Substituting $P_{(b,i)}$ and $P_{(i,i)}$ into (4), we obtain

$$P_i = \frac{1}{1 + L(1 - (1 - \tau)^N)}.$$

Thus, the sensing failure probability α, defined as the probability of finding a busy channel when the tagged node is sensing the channel in a slot, is given by

$$\alpha = 1 - P_i = \frac{L(1 - (1 - \tau)^N)}{1 + L(1 - (1 - \tau)^N)}. \quad (5)$$

With given L and N, the set of fixed-point equations (3) and (5) can be solved numerically (e.g., using the contraction mapping approach [21]) to obtain α and τ.

Notice that it is important to properly determine the *fixed point*. To model the MAC protocol, the criterion for selecting the fixed point is that the MAC behavior of each node can be independently modeled around the parameter associated with the fixed point; the equations describing different nodes are coupled by the fixed point. In our analytical model, the probability to start sensing the channel, τ, is selected as the fixed point. It is difficult (if not impossible) to give a theoretical proof that τ strictly meets the fixed-point selection criterion, but it can be intuitively justified. In the MAC protocol, each node observes the shared common channel, and independently determines its backoff behavior according to the MAC protocol specification. The probability τ associated with a certain node is exclusively determined by the node's backoff procedure; therefore, the probabilities τ associated with different nodes are independent from each other due to the independent backoff procedures[4]. In the homogeneous network, all the nodes are configured with the same backoff parameters, and therefore they have the same probability τ. It is noteworthy that if an improper fixed point without the required property is selected, the analytical model will lead to inaccurate performance results.

D. The Double-Sensing Case (Two CCAs)

Consider the double-sensing channel access mechanism specified in the standard. Similar to the single sensing case, the analysis can be done with appropriate changes in the equations regarding α and τ. In this subsection, the superscript $'$ is added to all the relevant variables for the double-sensing case.

Let p_1 denote the probability of sensing a busy channel in the first CCA, and p_2 the probability of sensing a busy channel in the second CCA given that the channel is idle in the first CCA. Let α' denote the probability of sensing failure, which is defined as sensing a busy channel in either of the two CCA events. At the end of each backoff stage, the tagged node will either enter the next backoff stage with probability α' or start a transmission with probability $1 - \alpha'$. Therefore,

$$\alpha' = p_1 + (1 - p_1) p_2. \quad (6)$$

In addition, for each backoff stage, a node must spend one slot for the first CCA, and spend another slot for the second CCA with probability $1 - p_1$. Hence, the average number of slots spent for channel sensing in each backoff stage ending up without a transmission is

$$c = 1 + (1 - p_1) = 2 - p_1.$$

In the situation that the node succeeds in starting a transmission at the end of a backoff stage, the two successful CCA events will occupy two slots. In summary, the average length of a level-1 renewal cycle for the double-sensing case is

$$\begin{aligned}\overline{X'} &= (1 - \alpha')(b_0 + 2 + L) + \alpha'(1 - \alpha')(b_0 + c + b_1 + 2 + L) \\ &\quad + \cdots + (\alpha')^{M-1}(1 - \alpha')(\sum_{m=0}^{M-1} b_m + (M - 1)c + 2 + L) \\ &\quad + (\alpha')^M \sum_{m=0}^{M-1} (b_m + c) \\ &= \sum_{m=0}^{M-1} (\alpha')^m b_m + c \sum_{m=1}^{M} (\alpha')^m + (1 - (\alpha')^M)(2 + L). \end{aligned} \quad (7)$$

Denote τ' the counterpart of τ in the double-sensing case. We have

$$\tau' = \frac{\overline{R'}}{\overline{X'}} = \frac{\sum_{m=0}^{M-1} (\alpha')^m}{\overline{X'}}, \quad (8)$$

where α is replaced with α' in (1) to obtain $\overline{R'}$ as the average number of sensing attempts in the double-sensing case.

To compute τ', we need to know α', p_1 and p_2, which can be derived as follows. Let $P'_{(i,b)}$ denote the probability that

[4]According to our intuitive approach to examine the independence property of a parameter used for MAC modeling, the *channel access probability* used in the 802.11 DCF modeling meets the fixed-point parameter selection. In fact, we have implicitly applied such a fixed-point modeling for 802.11 DCF in [22].

the channel turns busy in slot $k+1$ given that it is idle in slot k, for an arbitrary slot index k. This can only occur when the channel in slot $k-1$ is idle and at least one node starts to sense the channel at that time. Hence,

$$P'_{(i,b)} = [1-(1-\tau')^N]P'_{(i,i)}. \quad (9)$$

Also, since the channel is either idle or busy in any slot, we have

$$P'_{(i,b)} = 1 - P'_{(i,i)}. \quad (10)$$

Combining (9) and (10) and letting $t = 1-(1-\tau')^N$, we obtain

$$P'_{(i,i)} = \frac{1}{1+t}. \quad (11)$$

Notice that the derivation of (4) does not rely on any specific assumption of the channel sensing mechanism, so the relationship among the relevant probabilities is also valid for the DS case. Substituting (11) into (the DS version of) (4), and noting that $P'_{(b,i)} = 1/L$, we have $P'_i = \frac{1+t}{1+(L+1)t}$. Then, the channel sensing failure probabilities for the two sensing attempts can be obtained as:

$$p_1 = 1 - P'_i = \frac{Lt}{1+(L+1)t}, \quad (12)$$

$$p_2 = P'_{(i,b)} = \frac{t}{1+t}. \quad (13)$$

Substituting the above two equations into (6), we obtain

$$\alpha' = \frac{L(1-(1-\tau')^N)}{1+L(1-(1-\tau')^N)}. \quad (14)$$

Notice that α' for the DS case has a relationship to τ' exactly same as that of α to τ in the SS case. However, τ' as a function of α' is different from τ as a function of α, due to the time cost of the second CCA slot in the DS case. This difference causes the lower throughput of the DS mechanism compared to the SS, as will be shown in Sec. VI.

IV. MAC Performance Analysis

In this section, we study the MAC throughput of an individual node and that of the whole network, and the average MAC service time for an individual frame. We consider the single-sensing case first, then the double-sensing case.

A. The SS Case

As shown in Fig. 2, for every level-1 renewal cycle X, it contains a transmission of L slots (i.e., it is a type X_2 cycle) with probability $P_{\text{tx}} = (1-\alpha^M)$. Thus, the number of level-1 cycles contained in a level-2 cycle Y follows a geometric distribution with parameter P_{tx}. Hence, a level-2 cycle Y contains an average number of $1/P_{tx}$ level-1 cycles with an average length of $\overline{X}$ given by (2), i.e., the average length of a level-2 cycle is

$$\overline{Y} = \frac{\overline{X}}{P_{\text{tx}}}. \quad (15)$$

Notice that the conditional probability that a transmission from the tagged node is successful is

$$P_{\text{suc}} = (1-\tau)^{N-1}, \quad (16)$$

because none of the other $N-1$ nodes should start to sense the channel in the same slot as the tagged node does. Similar to the case in a Y cycle, the number of level-2 cycles contained in a level-3 cycle Z is a geometrically distributed random variable. Thus a level-3 cycle Z contains an average number of $1/P_{suc}$ level-2 cycles with average length of $\overline{Y}$, i.e., the average length of a level-3 cycle is

$$\overline{Z} = \frac{\overline{Y}}{P_{\text{suc}}}. \quad (17)$$

Combining (2) and (15) – (17), we can rewrite $\overline{Z}$ as follows:

$$\overline{Z} = \frac{1}{\tau(1-\tau)^{N-1}(1-\alpha)}. \quad (18)$$

1) Average Frame Service Time T_s: The average frame service time, T_s, defined as the average duration from the instant a frame becomes the head-of-line at the MAC buffer to the end of its successful transmission, is simply $\overline{Z}$ in (18).

2) MAC Throughput: Observing that there is only one successful transmission in a Z cycle, the throughput of an individual node is

$$\eta_s = \frac{L}{\overline{Z}} = L\tau(1-\tau)^{N-1}(1-\alpha). \quad (19)$$

For the homogeneous network, the throughput is

$$\eta = N\eta_s. \quad (20)$$

B. The DS Case

Since no assumption specific to the SS case is made in the above analysis, similarly, we can obtain the two performance metrics for the DS case. The average frame service time is

$$\overline{Z'} = \frac{1}{\tau'(1-\tau')^{N-1}(1-\alpha')}, \quad (21)$$

the MAC throughput of an individual node is

$$\eta'_s = L\tau'(1-\tau')^{N-1}(1-\alpha'), \quad (22)$$

and the network throughput is $\eta' = N\eta'_s$, where τ' and α' in the above equations are given in (8) and (14), respectively. Notice that the network throughput η' is consistent with (29) in [9], which was obtained with a much more complex approach.

V. Extension to Unsaturated Nodes

The analysis so far has been for saturated nodes that always have frames waiting for transmission in the MAC buffer. In practice, this corresponds to the case when some delay-insensitive data applications (such as bulk file transfer through FTP) running on the nodes. With multimedia applications that usually generate bursty traffic, a node may work in the unsaturated situation in which the MAC buffer may be empty from time to time. The proposed analytical model can also be extended to the unsaturated nodes. In the sequel, the subscript "u" will be added to relevant variables to indicate the unsaturated analysis. For presentation succinctness, we only present the unsaturated analysis for the single-sensing case.

Consider a generally distributed traffic with average frame inter-arrival time $1/\lambda$ slots at the MAC layer buffer of a node. Denote $1/\mu$ the average frame service time in slots. A node

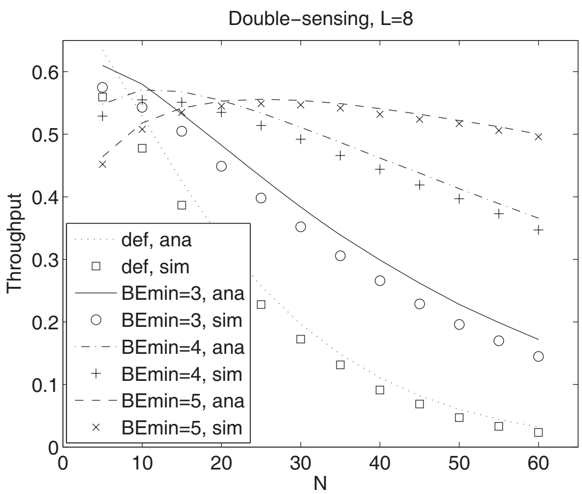

Fig. 3. Saturation throughput

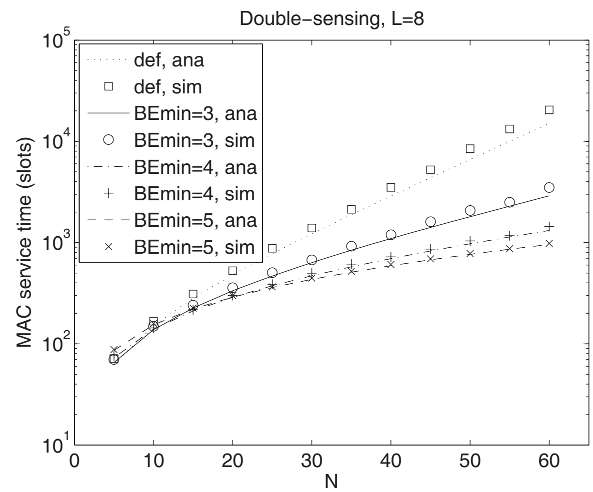

Fig. 4. Average frame service time in saturated case

will not attempt to sense the channel when its MAC buffer is empty, i.e., the node will contend to access the channel only when it has a frame in the buffer waiting for transmission (i.e., it is *busy*), which occurs with probability $\rho = \lambda/\mu$. The sensing probability τ_u for a busy node remains in the same format as in (3) except α is now α_u. Thus, τ_u is given by

$$\tau_u = \frac{\sum_{m=0}^{M-1} \alpha_u^m}{\sum_{m=0}^{M-1} \alpha_u^m (b_m + 1) + (1 - \alpha_u^M) L}. \tag{23}$$

Consider the conditional probability that the channel will remain in the idle state in slot $k+1$ given that it is idle in slot k. Such an event will occur only when neither the tagged station nor any of the $n, 0 \le n \le N-1$, busy nodes starts to sense in slot k. Hence, we have

$$P_{(i,i)_u} = (1 - \tau_u)(1 - \rho\tau_u)^{N-1}. \tag{24}$$

Following the approach in Sec. III-C, α_u can be obtained as

$$\alpha_u = \frac{L(1 - P_{(i,i)_u})}{1 + L(1 - P_{(i,i)_u})}, \tag{25}$$

and

$$\overline{Z_u} = \frac{1}{\tau_u P_{(i,i)_u} (1 - \alpha_u)}, \tag{26}$$

$$\rho = \left[\lambda \overline{Z_u}\right]_1, \tag{27}$$

where $[x]_1$ is the smaller of x or one, which is necessary because ρ can reach its upper bound of one if the frame service time is longer than the average frame inter-arrival time, which corresponds to the saturated case analyzed previously. In that case, (23) and (25) will reduce to (3) and (5), respectively. In addition, we have used in (27) the fact that $1/\mu$ is exactly $\overline{Z_u}$, as explained in Sec. IV-A1.

With given λ, N and L, τ_u, $\alpha_u, \overline{Z_u}$ and ρ can be obtained from equations (23)–(27). Similar to Sec. IV-A1, the throughput and average frame service time in the unsaturated case can be obtained from $\overline{Z_u}$.

VI. Simulation Results

In this section, we present simulation results and compare them with the analytical ones to demonstrate the accuracy of the proposed analytical model.

A. Performance of Default Parameters and Potential Improvements

We study the performance of the MAC protocol with default parameter values given in the standard, i.e., the minimum backoff exponent $BE_{min} = 3$, the maximum backoff exponent $BE_{max} = 5$, and the maximum allowed backoff stage for a frame $NB_{max} = 5$. The saturation throughput and average frame service time versus the number of nodes N in the networks with the above default settings are shown in Figs. 3 and 4, respectively, marked as "def" in the figures. The frame length is $L = 8$. It can be seen that the throughput decreases sharply with the number of nodes while the average frame service time shows an opposite trend. This is because with small values of $BE_{min} = 3$ (corresponding to $b_0 = 3.5$) and $BE_{max} = 5$, the backoff slots are uniformly distributed over a relatively small range of $[0, 31]$, which causes the probability of simultaneous channel sensing conducted by multiple nodes increases quickly with N. In contrast, the probability of finding the channel idle in the sensing slots decreases quickly when N increases. Therefore, a large portion of time is spent in backoff and thus the network throughput downgrades with significantly increased frame service time. To overcome this issue, a straightforward solution is to remove the upper limit of maximum backoff exponent (or set it to a large number, e.g., 10 as in IEEE 802.11). That is, every time a node enters a new backoff stage, it simply increases the backoff exponent by one. In this way, the selection range of backoff slots is enlarged so that the probability of simultaneous channel sensing increases slower with N than it does in the default settings. The performance of this slightly different variant of the protocol is shown in the figures as "BEmin=3". We can see that the performance is about the same when N is small ($N < 20$). However, the performance gain becomes obvious when N is large. The network throughput is almost doubled for $N = 30$ and it is ten-folded for $N = 60$. Meanwhile, the average frame service time is always shorter than that in the default setting, and the gap between them increases with N, e.g., T_{serv} for $N = 60$ decreases to just $1/3$ of that with the default settings.

For larger BE_{min} (4 and 5), their performance is also shown in Figs. 3 and 4 as "BEmin=4" and "BEmin=5",

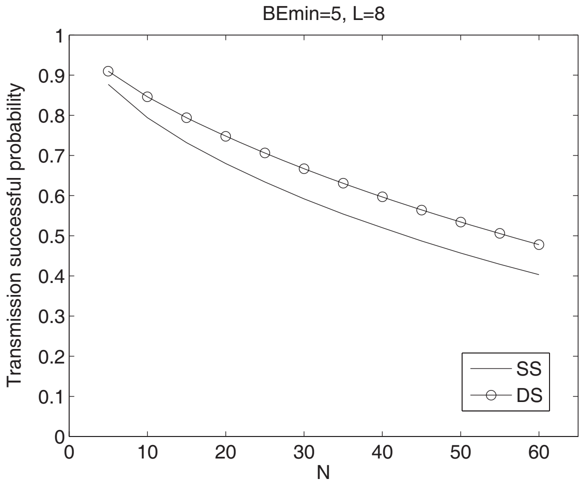

Fig. 5. Transmission successful probabilities in SS and DS cases

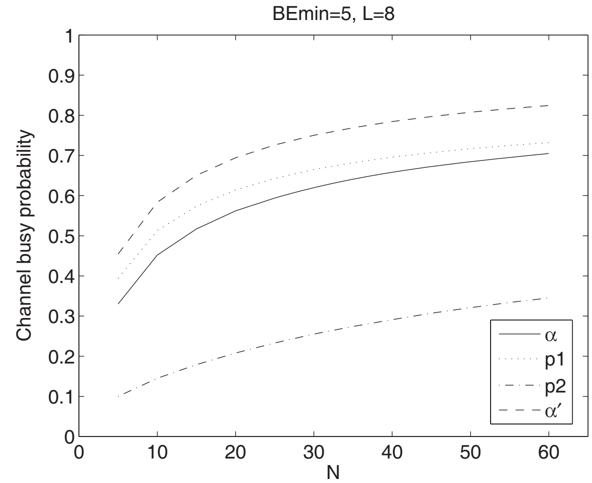

Fig. 6. Channel busy probabilities in the CCAs in SS and DS cases

respectively. It is interesting to observe that the saturation network throughput first increases with N when N is small (less than 15 for "BEmin=4" and 25 for "BEmin=5"), then start to decrease with N, but much slower than in the "BEmin=3" and the default settings cases. This is because when N is small, nodes can access the channel to transmit frames relatively easily with relatively small collision probability. For a small N, a larger BE_{min} means the nodes spend more time in backoff for each frame transmission, resulting in a larger portion of channel idle time and lower network throughput. As N increases, more nodes contribute to the network throughput increase by more successful frame transmissions and more overlapped backoff time until this is offset by the increasing collision probability, upon which the maximum network throughput is reached. After that optimal point, further increasing N will cause a busier channel with less opportunity for nodes to transmit and, even worse, higher collision probability for transmissions, leading to decreased network throughput. A larger BE_{min} gives a larger range for the selection of the number of backoff slots, which mitigates the above two adverse effects and makes the degradation of network throughput slower. For the same reason, T_{serv} for larger BE_{min} cases is slightly longer when N is small, but becomes much shorter with large N, as shown in Fig. 4.

B. Single Sensing vs. Double Sensing

1) Performance Comparison: In developing the analytical model in Sec. III, we have considered both the single sensing and double sensing mechanisms. Two expressions with the same form, (5) and (14), have been obtained for the channel sensing failure probabilities α (α') as a function of the sensing probability τ (τ'), respectively. However, the difference in channel sensing requirements leads to the two different expressions for the relationship between the two probabilities, which can be seen from (3) and (8). In the following, we study the impact of this difference on the performance of the two mechanisms.

The probabilities of success for a frame transmission (P_{suc}) in the SS and DS cases are compared in Fig. 5. With the same parameter (e.g., N, L and BE_{min}) values, P_{suc} of the DS is higher than that of the SS, which may suggest that the

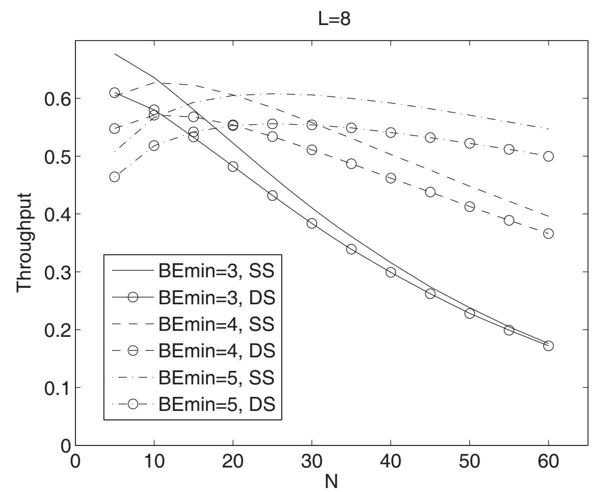

Fig. 7. Saturation throughput comparison between SS and DS modes

DS mechanism is preferable over the SS. However, as shown in Fig. 6, just the probability p_1 of sensing a busy channel in the first CCA slot in the DS case alone is always larger than that in the SS, which means a node gets less chance to transmit in the DS than in the SS during the same given period of time. Therefore, the DS mechanism is in an obvious disadvantage position, considering possible further the adverse effect of the probability p_2 of sensing a busy channel in the second CCA slot. The net effect of the above two contradicting factors is a lower network throughput of DS, which is clearly shown in Fig. 7. It can be seen that with the same parameters, network throughput of the SS mode is always about 10% higher than that of the DS mode, which conforms with the results presented in [10], [11]. In addition, the performance gain of larger BE_{min} still exists in the SS case due to the similar reasons given in Sec. VI-A.

Fig. 8 shows the average frame service time for the SS case. The relationships among the results for different parameter settings are similar to those in Fig. 4. It should be mentioned that according to the general relationship between network throughput and average frame service time, T_s of the SS case is always shorter than that of the DS case.

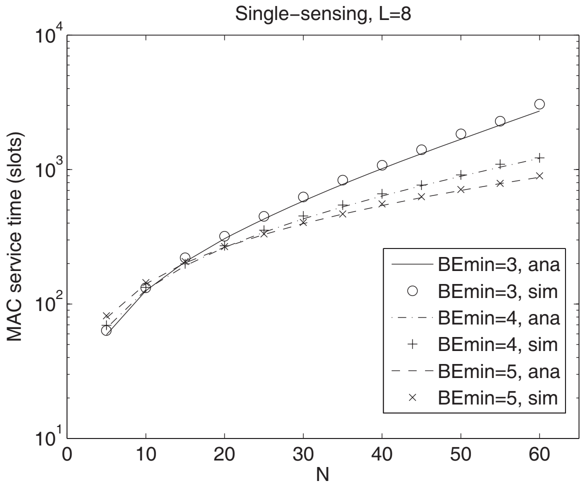

Fig. 8. Average frame service time in the SS case

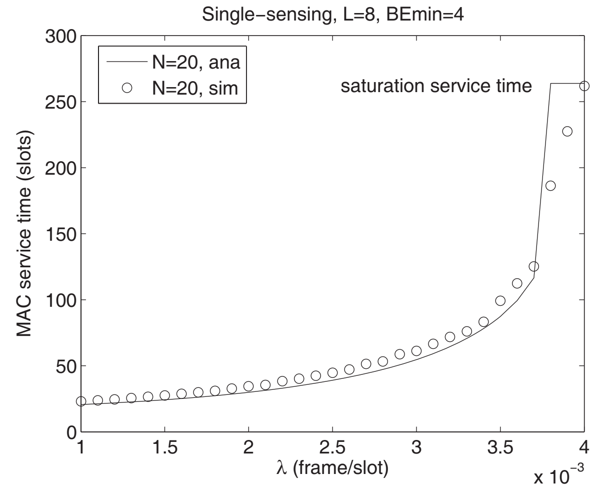

Fig. 9. Average frame service time in unsaturated case

2) Issues in the ACK mode: The SS policy has been proposed in [10], [11] to improve the throughput of the IEEE 802.15.4 MAC protocol. As the SS outperforms the DS when other parameters are the same, it is natural to ask why the DS, instead of the SS, is chosen for the standard. In fact, the DS mechanism is designed mainly for the ACK mode, in which a short acknowledgement (ACK) frame is transmitted by the receiver of a data frame after an inter frame space (IFS). Since nodes backoff without monitoring the channel, they may sense the channel during an IFS in the ACK mode, find an idle channel, transmit in the next slot and thus collide with the ACK frame. Hence, the SS mechanism can be used only when the IFSs do not cover slot boundaries, which requires that 1) the IFS be shorter than the slot time, 2) the frame transmission periods end slightly after slot boundaries, and 3) the ACK frame transmission starts in the same slot where the preceding frame transmission ends. In the standard, however, the slot time is longer than the IFS used in the ACK mode. Consequently, if two consecutive CCAs are performed, the second CCA will fail even if the first one is successful when it lies in an IFS. Therefore, the DS mechanism can help to prevent a new transmission from interrupting an on-going ACK mode frame exchanging in a CAP-MAC based network while the SS mechanism cannot.

C. Unsaturated Nodes

To demonstrate the effectiveness of the model for the unsaturated case, Fig. 9 shows the average frame service time versus the frame arrival rate for $N = 20$. Poisson traffic is used in the simulation to compare with the analytical results. T_s increases quite slowly with low to medium load, and it soars when the load becomes high until it reaches a saturation level which depends only on N. Similar sharp increase of average frame service time in high traffic load region has also been observed in the study of IEEE 802.11 DCF, e.g., in [22], [23]. It can be seen that the analytical results approximate the simulation ones very well.

D. Discussion

Although we only study the binary-exponential-backoff policy combined with the slotted CSMA/CA protocol, the analytical model should be applicable to other popular backoff policies such as uniform and geometric backoff policies [13]. It can also deal with any other type of backoff policies (e.g., multiplicative increase instead of exponential increase, bounded or un-bounded), as long as the backoff procedure resets to its initial status for each new frame transmission.

VII. Related Work

The performance of MAC protocols is usually analyzed by developing stochastic models, often with various assumptions and approximations. In the literature, there are mainly three techniques commonly used in this area [24]. The traditional *S-G* technique [2], [14] was widely used in the 1970's-80's to analyze the throughput-delay performance of both slotted and non-slotted multiple access protocols such as ALOHA and CSMA. It assumes an infinite number of nodes collectively generate traffic equivalent to an independent Poisson source with an aggregate mean packet generating rate of S frames per slot, and the aggregated new transmissions and retransmissions is approximated as a Poisson process with rate of G frames per slot. The scenario considered is mainly of theoretical interest in the sense that a practical system has just a finite number of users, each of which usually has a buffer size larger than one, rather than that assumed in the S-G analysis. The second technique is Markov analysis. A Markovian model of the system is developed and its state transition probabilities need to be found. The state space of the Markovian model increases with both the complexity of the protocol studied and the number of users in the system, which hinders its usage in system with a large user population. Finally, equilibrium point analysis (EPA) is a fluid-type approximation analysis usually applied to systems in steady state [25]–[27]. It assumes that the system always works at its equilibrium point so that the number of users in any working mode is always fixed. To solve the system, it requires a set of nonlinear equations, the number of which equals the number of the working modes (e.g., different backoff stages) in the system.

For the IEEE 802.15.4 MAC protocol considered in this paper, there are several recent analytical works appeared in the literature. A Markov chain based analytical model is proposed in [8] to analyze the access delay of uplink transmissions in an IEEE 802.15.4 beacon enabled PAN of nodes with finite size buffer. Many details of the protocol are taken into consideration in the model. With the assumption of Poisson arrivals to each node and the use of M/G/1/K queueing model, the probability generating functions (PGF) of the access delay and packet queue size at the nodes are derived. With the assumption that each node's probability to start sensing the channel is constant, the Markov model proposed in [9] gives good throughput accuracy in the saturated case, where all the nodes always have frames in their MAC buffers waiting for transmission. A more complicated three-dimensional Markov chain is proposed in [10], also for the saturated case only. Another Markov chain based model is presented in [11], and both throughput and power efficiency are studied. It replaces the uniform distribution with a geometric distribution in the selection of a random number of slots in each backoff stage, primarily for analytical tractability. Also, the model limits itself only to a Bernoulli frame arrival process for the unsaturated case. Both [10] and [11] advocate changing the initialization of CW to one, i.e., using single sensing instead of double sensing for the collision avoidance purpose. In all the above models, a common issue is the complexity involved in deciding the transition probability matrix for the multi-dimensional Markov chain, especially when the number of states is large. In addition, they can only deal with limited types of traffic distributions for unsaturated nodes.

Simulation-based studies of the IEEE 802.15.4 protocol have also been reported in the literature. In [4], comprehensive simulations using *ns2* are conducted to study the delay performance and some other aspects of the protocol stack. In addition, an excellent overview of the IEEE 802.15.4 standard and its applications is also provided. The energy efficiency of the protocol in a dense wireless mircosensor network is studied in [5]. A small size star-topology network is considered in [6], and some throughput-energy-delay tradeoffs of the protocol have been revealed. The application of IEEE 802.15.4 to medical environment (e.g., hospitals) is the subject of an *OPNET* based simulation in [7]. Interesting topics such as scalability issues and the impact of interference from co-existing WLANs are studied. The only performance evaluation that is based on real hardware experiments is reported in [28].

VIII. Conclusions

We have presented a simple yet accurate analytical model for the contention access period of the IEEE 802.15.4 MAC protocol. We have considered single sensing and double sensing, under a saturated or unsaturated node condition. The accuracy of the analysis has been validated by extensive simulation results.

The proposed model is a very general analytical framework. It can be used to analyze other slotted MAC protocols using the three-level renewal process. The corresponding fixed-point equations can be obtained by properly adjusting the parameters to capture the salient features of the backoff procedure and channel access policy. Our on-going work is to analyze the popular WLAN protocol IEEE 802.11 DCF with the renewal process based modeling, and compare its performance with that of the IEEE 802.15.4 MAC protocol. The modeling approach can also be extended to analyze networks with heterogeneous nodes, such as nodes with different backoff parameters and traffic loads [29]. Fairness issue is a challenging one in such networks (similar to the case of DCF [30], [31]), compared to the homogeneous network studied in this paper, which is also our on-going work.

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Xinhua Ling (S’03) received the B.Eng. degree in Radio Engineering from Southeast University, Nanjing, China, in 1993, the M.Eng. degree in Electrical Engineering from the National University of Singapore, Singapore, in 2001, and the Ph.D. degree in Electrical and Computer Engineering from the University of Waterloo, ON, Canada, in 2007.

He is currently a Post-Doctoral Fellow at the University of Waterloo. From 1993 to 1998, he was an engineer with the Beijing Institute of Radio Measurement, China. From 2001 to 2002, he was a Senior R&D Engineer with the Centre for Wireless Communications (currently the Institute for Infocomm Research), Singapore, developing the protocol stack for UE in the UMTS system. His general research interests are in the areas of cellular, WLAN, WPAN, mesh and ad hoc networks and wireless/wireline interworking, particularly in protocols design and performance analysis, and cross-layer design for Quality-of-Service support.

Yu Cheng (S’01-M’04) received the B.E. and M.E. degrees in Electrical Engineering from Tsinghua University, Beijing, China, in 1995 and 1998, respectively, and the Ph.D. degree in Electrical and Computer Engineering from the University of Waterloo, Waterloo, Ontario, Canada, in 2003.

From September 2004 to July 2006, he was a postdoctoral research fellow in the Department of Electrical and Computer Engineering, University of Toronto, Ontario, Canada. Since August 2006, he has been with the Department of Electrical and Computer Engineering, Illinois Institute of Technology, Chicago, USA, as an Assistant Professor. His research interests include service and application oriented networking, autonomic network management, Internet measurement and performance analysis, wireless networks, and wireless/wireline interworking.

Dr. Cheng received a Postdoctoral Fellowship Award from the Natural Sciences and Engineering Research Council of Canada (NSERC) in 2004, and a Best Paper Award from the International Conference on Heterogeneous Networking for Quality, Reliability, Security and Robustness (QShine’07), Vancouver, British Columbia, August, 2007.

Jon W. Mark (M’62-SM’80-F’88-LF’03) received the B.A.Sc degree from the University of Toronto in 1962, and the M.Eng and Ph.D. degrees in 1968 and 1970 from McMaster University, Canada, all in electrical engineering.

He was an engineer and then a senior engineer at Westinghouse Canada Ltd., Hamilton, Ontario, Canada from 1962 to 1970, where he conducted research in sonar signal processing and submarine detection. Upon receiving the Ph.D. degree, he joined the Department of Electrical Engineering (now Electrical and Computer Engineering) at the University of Waterloo where he is currently a Distinguished Professor Emeritus. He was promoted to full Professor in 1978, and served as Department Chairman from July 1984 to June 1990. In 1996, he established the Centre for Wireless Communications (CWC) at the University of Waterloo and has since been serving as the founding Director. Dr. Mark was on sabbatical leave at the IBM Thomas Watson Research Center, Yorktown Heights, NY, as a Visiting Research Scientist (1976-77); at AT&T Bell Laboratories, Murray Hill, NJ, as a Resident Consultant (1982-83); at the Laboratoire MASI, Université Pierre et Marie Curie, Paris, France, as an Invited Professor (1990-91); and at the Department of Electrical Engineering, National University of Singapore, as a Visiting Professor (1994-95). His current research interests are in wireless communications and wireless/wireline interworking, particularly in the areas of resource management, mobility management, cross-layer design, and end-to-end information delivery with QoS provisioning.

A co-author of the text *Wireless Communications and Networking*, Prentice-Hall, 2003, Dr. Mark is a Life Fellow of the IEEE. He has served as a member of a number of editorial boards, including *IEEE Transactions on Communications*, *ACM/Baltzer Wireless Networks*, *Telecommunication Systems*, etc. He was a member of the Inter-Society Steering Committee of the *IEEE/ACM Transactions on Networking* from 1992-2003, and a member of the IEEE COMSOC Awards Committee during the period 1995-1998.

Xuemin (Sherman) Shen (M’97-SM’02) received the B.Sc.(1982) degree from Dalian Maritime University (China) and the M.Sc. (1987) and Ph.D. degrees (1990) from Rutgers University, New Jersey (USA), all in electrical engineering.

He is a Professor and University Research Chair and the Associate Chair for Graduate Studies, Department of Electrical and Computer Engineering, University of Waterloo, Canada. His research focuses on mobility and resource management in interconnected wireless/wired networks, UWB wireless communications, wireless security, and ad hoc/sensor networks.

Dr. Shen serves as the Technical Program Committee Chair for IEEE Globecom’07, General Co-Chair for Chinacom’07 and QShine’06, the Founding Chair for IEEE Communications Society Technical Committee on P2P Communications and Networking. He also serves as a Founding Area Editor for *IEEE Transactions on Wireless Communications*; Editor-in-Chief for *Peer-to-Peer Networking and Application*; Associate Editor for *IEEE Transactions on Vehicular Technology*; *ACM Wireless Networks*; and *Wiley Wireless Communications and Mobile Computing*, etc. He has also served as Guest Editor for *IEEE Journal on Selected Areas in Comunications*, *IEEE Wireless Communications*, and *IEEE Communications Magazine*. Dr. Shen received the Excellent Graduate Supervision Award in 2006, and the Outstanding Performance Award in 2004 from the University of Waterloo, the Premier’s Research Excellence Award (PREA) in 2003 from the Province of Ontario, Canada, and the Distinguished Performance Award in 2002 from the Faculty of Engineering, University of Waterloo. Dr. Shen is a registered Professional Engineer of Ontario, Canada.