Modeling Energy Consumption in Error-Prone IEEE 802.11-Based Wireless Ad-Hoc Networks

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Abstract. In the IEEE 802.11 MAC layer protocol, there are different trade-off points between the number of nodes competing for the medium and the network capacity provided to them. There is also a trade-off between the wireless channel condition during the transmission period and the energy consumption of the nodes. Current approaches at modeling energy consumption in 802.11-based networks do not consider the influence of the channel condition on all types of frames (control and data) in the WLAN. Nor do they consider the effect on the different MAC and PHY schemes that can occur in 802.11 networks. In this paper, we investigate energy consumption corresponding to the number of competing nodes in IEEE 802.11's MAC and PHY layers in error-prone wireless channel conditions, and present a new energy consumption model. Analysis of the power consumed by each type of MAC and PHY over different bit error rates shows that the parameters in these layers play a critical role in determining the overall energy consumption of the ad-hoc network. The goal of this research is not only to compare the energy consumption using exact formulae in saturated IEEE 802.11-based DCF networks under varying numbers of competing nodes, but also, as the results show, to demonstrate that channel errors have a significant impact on the energy consumption.

Keywords: IEEE 802.11, DCF, Ad-Hoc Energy consumption, error-prone.

1 Introduction

Ad-hoc wireless networks are currently receiving a significant amount of interest. Some of this interest may be attributed to the distributed nature of IEEE 802.11's DCF, which allows for instant deployment and routing of packets around nodes in multi-hop ad-hoc wireless networks. However, in the IEEE 802.11 DCF, the wireless channel needs to be shared efficiently among contending nodes, and considerable research efforts are being dedicated to improving the energy consumption in these networks. In [1] the power consumption of the wireless network interface card was measured when used by different end-user devices. In [2] an analytical model to predict energy consumption in saturated IEEE 802.11 single-hop networks under ideal channel conditions is presented. This work focused on the energy consumption in a condition which assumes each node actively contends for channel access while at the same time is a potential receiver of some other node's transmission (i.e. the network

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is saturated). A framework for conserving energy across routes in multi-hop and ad-hoc wireless networks is proposed in [3]. This approach adjusts the radio transmission power and the rebroadcast time of RREQ packets, using a rebroadcast mechanism for estimating the end-to-end energy consumption of a multi-hop network. These works have focused on energy consumption without any channel contention.

Recently, several researchers have begun to focus on the saturation throughput of DCF in error-prone channels [4-7]. To the best of our knowledge, most existing research only considers the error probability of transmission errors on data frames, and do not consider the influence of the channel state on the energy consumption. In [4], an improved analytical model is proposed that calculates IEEE 802.11a's DCF performance taking into account retransmitted packets and transmission errors. However, all the currently proposed performance models [4-6] ignore the influence of the physical layer and assume that the collision probability is same in all circumstances. The different types of frames transmitted by the different modulation schemes can result in different frame error rates. Furthermore, in a noisy wireless environment which is typically encountered in practice, all frames sent will have different error probabilities depending on the received signal strength. In [7], the performance model addresses the error probability of ACK frames. However, it only considers the error probability in the DCF basic access method.

On the other hand, some related work has been done on the analysis of energy consumption in DCF [2, 8, 9]. These models do not consider the transmission errors encountered in real wireless environments. In [10] and [11] the energy consumption models presented do consider the effect of transmission errors, however, the performance models address the effect of errors in data frames only (i.e. signaling and control frames are not considered). Furthermore, in [2, 10, 11], the impact of the EIFS interval has not been considered when a transmission failure occurs.

Therefore, in this paper, we first evaluate several critical PHY/MAC layer design components and their impact in an error-prone channel condition, and then we propose a novel model for energy consumption of an 802.11-based Ad-Hoc network in an error-prone wireless environment. In particular, we consider the impact of the noisy wireless channel and the number of competing nodes using both basic access and RTS/CTS exchange methods in IEEE 802.11-based DCF networks [12-15]. Results show that the transmitter produces much higher energy consumption when the channel is very noisy (e.g., when BER $\geq 10^{-5}$). The contribution of this research is to serve as an indication of the achievable reduction in energy consumption by using a cross-layer framework design for Ad-Hoc networks. A specific topology control, rate adaptation and routing strategy that takes advantage of this research will be reported in future research.

The rest of the paper is organized as follows. Section 2 gives an overview of the IEEE 802.11-based system. Section 3 presents the analytic model under different channel states for both basic access and RTS/CTS exchange methods in an error-prone wireless environment. Then we obtain the energy consumption model under the error-prone channel in section 4. Section 5 describes the simulation results and compares the energy consumption between 802.11a and g in DCF networks. Finally, we conclude the paper in Section 6.

2 System Overview

The IEEE 802.11 MAC [12] sub-layer provides a fairly controlled access to the shared wireless medium through two different access mechanisms: the basic access mechanism, called the distributed coordination function (DCF), and a centrally controlled access mechanism, called the point coordination function (PCF). In this paper, we focus on the energy consumption of IEEE 802.11 based networks using DCF.

2.1 IEEE 802.11a/b/g Physical Layer

The IEEE 802.11Physical (PHY) layer is an interface between the Medium Access Control (MAC) layer and the wireless medium, which transmits and receives data frames over the shared wireless medium. The exchange of frames between the MAC and PHY is under the control of the physical layer convergence procedure (PLCP) sub-layer. The PLCP protocol data units (PPDU) format of the IEEE 802.11 PHY includes PLCP preamble, PLCP header, PHY Sub-layer Service Data Units (PSDU), tail bits, and pad bits.

In the IEEE 802.11a/b/g PHY characteristics, we denote the PLCP preamble field, with duration of t*PLCP*Preamble. The PLCP header, with duration of t*PLCP*Header. In IEEE 802.11a and g, the OFDM symbol interval denoted by T_m is 4μs. For IEEE 802.11b, we assume that T_m =1. A summary of each frame type is given by equations (1)-(4) for both exchange methods (i.e. basic access and RTS/CTS). Note that, the FCS (frame check sequence) field in each MAC frame is a 32 bit cyclic redundancy code (CRC).

$$T_{r,m,data}(l) = tPLCP\mathrm{Pr}eamble + tPLCPHeader + \frac{(MPDUHeader/FCS + l)\cdot 8}{D_{bps}(r)}\cdot T_m \tag{1}$$

$$T_{r,m,ack} = tPLCP\mathrm{Pr}eamble + tPLCPHeader + \frac{ACKHeader/\,FCS\cdot 8}{S_{bps}(r)}\cdot T_m \tag{2}$$

$$T_{r,m,CTS} = tPLCP\mathrm{Pr}eamble + tPLCPHeader + \frac{RTSHeader/\,FCS\cdot 8}{S_{bps}(r)}\cdot T_m \tag{3}$$

$$T_{r,m,RTS} = tPLCP\mathrm{Pr}eamble + tPLCPHeader + \frac{CTSHeader/\,FCS\cdot 8}{S_{bps}(r)}\cdot T_m \tag{4}$$

$T_{r,m,data}(l)$ is the data transmission duration when a node transmits a data frame with l payload octets over a PHY scheme m using transmission rate r. $T_{r,m,ack}$, $T_{r,m,CTS}$ and $T_{r,m,RTS}$ denote the transmission times of Acknowledgement (ACK), Clear-to-send (CTS) and Ready-to-send (RTS) frames respectively, again for the selected transmission rate r and PHY scheme m. In IEEE 802.11 a/g, the basic rate set (BSS) is 6Mbps, 12 Mbps and 24 Mbps. Each station should support these rates and control information should be sent at these rates. We assume that all rates for IEEE 802.11 a/b/g can be used and $D_{bps}(r)$ and $S_{bps}(r)$ are the transmission rates of the data and control frames respectively.

2.2 The CSMA/CA Mechanism in DCF

The IEEE 802.11 MAC protocol's DCF, is based on carrier sense multiple access with collision avoidance (CSMA/CA). In operation a random backoff interval is uniformly chosen in the range (0, *W*). The value *W* is called the contention window, which is an integer with range $CW_{m,min}$ (i.e. minimum contention window for PHY scheme *m*) to $CW_{m,max}$ (i.e. maximum contention window for PHY scheme *m*). A backoff counter is decremented while the medium is sensed idle, frozen when a transmission is detected on the channel, and reactivated when the channel is sensed idle again for more than a DIFS. The wireless node transmits when the backoff counter reaches zero. After each unsuccessful transmission, the contention window is doubled; up to a maximum backoff size $CW_{m,max}$. Since the backoff is uniformly distributed over 0,1,…,$CW_{m,min}$-1 for the first attempt, the backoff window size is ($CW_{m,mim}$-1)/2 on average. For a RTS/CTS exchange method, the short retry counter (SRC) is large than the maximum retry counter. The default values for LRC and SRC are 4 and 7 respectively. *k'* denotes the maximum retry counter, thus,

$$2^{k'} \cdot (CW_{m,\min} + 1) = (CW_{m,\max} + 1) \quad (5)$$

$W_m(k)$ is the average contention window for any selected PHY scheme *m* in a node *A*. After *k* consecutive unsuccessful transmission attempts this is given by

$$W_m(k) = \begin{cases} \dfrac{2^k \cdot (CW_{m,\min} + 1) - 1}{2} & 0 \le k \le k' \\ \dfrac{CW_{m,\max}}{2} & .k > k' \end{cases} \quad (6)$$

$T_{m,backoff}(k)$ is the average backoff interval in μsec for the PHY scheme *m*.

$$T_{m,backoff}(k) = W_m(k) * \sigma_m \quad (7)$$

k is the number of retransmission attempts. σ_m is the time duration of a slot in PHY scheme *m*.

3 Analysis of IEEE 802.11 a/b/g in an Error-Prone Channel

For an error-prone channel, unsuccessful transmission occurs not only when more than one node simultaneously transmits packets (contention), but also when poor channel conditions corrupt the packet. Since DCF has basic access and RTSCTS exchange methods, we assume packet errors occur from both data and ACK packets for basic access method and RTS, CTS, data and ACK packets for the RTS/CTS exchange method. For accurate analysis, we assume each node incurs a different packet error probability for its received packets. The packet error probability depends on the frame error rate (FER) when the packets are received.

The collision probability $P_{r,m,coll}$ is the probability that in a time slot at least one of the *n*-1 remaining nodes transmits. This is given by:

$$P_{r,m,coll} = 1 - (1 - \tau_m)^{n-1} \quad (8)$$

Where τ_m is the probability that a node transmits in a generic slot time.

$$\tau_m = \begin{cases} \dfrac{(1-P_{r,m,coll}^{k+1})\cdot 2\cdot(1-2\cdot P_{r,m,coll})}{W_m\cdot(1-(2\cdot P_{r,m,coll})^{k+1})\cdot(1-P_{r,m,coll})+(1-2\cdot P_{r,m,coll})(1-P_{r,m,coll}^{k+1})} & \text{k} \le \text{k'} \\ \dfrac{(1-P_{r,m,coll}^{k+1})\cdot 2\cdot(1-2\cdot P_{r,m,coll})}{\left(\begin{matrix} W_m\cdot(1-(2\cdot P_{r,m,coll})^{k'+1})\cdot(1-P_{r,m,coll})+(1-2\cdot P_{r,m,coll})\cdot(1-P_{r,m,coll}^{k+1})+ \\ W_m\cdot 2^{k'}\cdot P_{r,m,coll}^{k'+1}\cdot(1-2\cdot P_{r,m,coll})\cdot(1-P_{r,m,coll}^{k-k'}) \end{matrix}\right)} & \text{k} > \text{k'} \end{cases} \tag{9}$$

Where $CW_{m,min}$ is the minimum backoff window size in m PHY scheme. After each unsuccessful transmission, the backoff window is doubled, up to a maximum backoff size. From equations (8) and (9), we define $P_{r,m,tr}$ as the probability in a slot time, of at least one or more transmissions. n active nodes contend to access the medium and each node has transmission probability τ_m.

$$P_{r,m,tr} = 1-(1-\tau_m)^n \tag{10}$$

The probability of successful transmission $P_{r,m,s}$ is given by:

$$P_{r,m,s} = \frac{n\cdot\tau_m\cdot(1-\tau_m)^{n-1}}{P_{r,m,tr}} = \frac{n\cdot\tau_m\cdot(1-\tau_m)^{n-1}}{1-(1-\tau_m)^n} \tag{11}$$

In basic access method, The transmission error probability ($P_{r,m,error}$) stands for the frame error rate (FER) of a MAC data frame or an ACK frame for a given node. We assume that the two events "data frame corrupted" and "ACK frame corrupted" are independent, and obtain:

$$p_{r,m,error} = 1-(1-p_{r,m,data\_error})\cdot(1-p_{r,m,ack\_error}) \tag{12}$$

Where $P_{r,m,data\_error}$ and P_{r,m,ack_error} are FERs of data frames and ACK frames for the selected transmission rate r and PHY scheme m respectively.

The $P_{r,m,error}$ for RTS/CTS exchange method is:

$$\begin{aligned} p_{r,m,error} &= 1-(1-p_{r,m,RTS\_error})\cdot(1-p_{r,m,CTS\_error})\cdot \\ &(1-p_{r,m,data\_error})\cdot(1-p_{r,m,ack\_error}) \end{aligned} \tag{13}$$

Where P_{r,m,RTS_error}, P_{r,m,CTS_error}, $P_{r,m,data\_error}$ and P_{r,m,ack_error} are FERs of RTS frames, CTS frames, data frames and ACK frames for selected transmission rate r and PHY scheme m respectively.

The bit errors are uniformly distributed over the whole frame, the P_{r,m,RTS_error}, P_{r,m,CTS_error}, $P_{r,m,data\_error}$ and P_{r,m,ack_error} can then be calculated as:

$$\begin{cases} p_{r,m,data\_error} = 1-\left(1-BER_{m,data}\right)^{N_{data}} \\ p_{r,m,ack\_error} = 1-\left(1-BER_{m,ack}\right)^{N_{ack}} \end{cases} \begin{cases} p_{r,m,RTS\_error} = 1-\left(1-BER_{m,RTS}\right)^{N_{RTS}} \\ p_{r,m,CTS\_error} = 1-\left(1-BER_{m,CTS}\right)^{N_{CTS}} \end{cases} \tag{14}$$

Where N_{RTS}, N_{CTS}, N_{data} and N_{ack} are the length (bits) of the RTS, CTS, data and ACK frames and the $BER_{m,data}$ and $BER_{m,ack}$ are the bit error rates of the data and ACK frames respectively. The bit error rate is based on the selected PHY scheme, which is determined by SNR, modulation scheme and code scheme or transmission rate. Thus, we can obtain the received FER by measuring the SNR from a PLCP Protocol Data Unit (PPDU) packet in transmission rate r in PHY scheme m. The bit error rate (BER) can then be estimated by measuring the bit-energy-to-noise ratio [16].

$p'_{r,m,s}$ denotes the successful transmission probability for a single station in an error-prone channel condition, which is defined as the probability that only one of n nodes is successfully transmitting and there are no corrupted packets. The probability of one node successfully transmitting in error-prone channel for the basic access method is:

$$P'_{r,m,s} = P_{r,m,s} \cdot (1 - P_{r,m,error}) \tag{15}$$

From equation (12), thus we could denote the probability for one node successfully transmitting in error-prone channel as shown in following,

$$P'_{r,m,s} = P_{r,m,s} \cdot (1 - P_{r,m,data\_error}) \cdot (1 - P_{r,m,ack\_error}) \tag{16}$$

Let $P_{r,m,dataframe\_error}$ stands for the probability that a transmission error occurs on a data frame in a time slot; this occurs when one and only one station transmits in a time slot and the data frame is corrupted because of transmission errors. $P_{r,m,ackframe\_error}$ denotes the probability that a data frame transmission is successful but the corresponding ACK frame is corrupted due to transmission errors.

Thus, $P_{r,m,dataframe\_error}$ and $P_{r,m,ackframe\_error}$ can be expressed using the following equations:

$$P_{r,m,dataframe\_error} = P_{r,m,s} \cdot P_{r,m,data\_error} \tag{17}$$

$$P_{r,m,ackframe\_error} = P_{r,m,s} \cdot (1 - P_{r,m,data\_error}) \cdot P_{r,m,ack\_error} \tag{18}$$

Otherwise, from equation (13), the $P'_{r,m,s}$ for the RTS/CTS exchange method is:

$$\begin{aligned}
&P'_{r,m,s} = P_{r,m,s} \cdot (1 - p_{r,m,RTS_error}) \cdot (1 - p_{r,m,CTS_error}) \cdot (1 - p_{r,m,data_error}) \cdot \\
&(1 - P_{r,m,ack_error}) \\
&P_{r,m,RTSframe_error} = P_{r,m,s} \cdot P_{r,m,RTS_error} \\
&P_{r,m,CTSframe_error} = P_{r,m,s} \cdot (1 - P_{r,m,RTS_error}) \cdot P_{r,m,CTS_error} \\
&P_{r,m,dataframe_error} = P_{r,m,s} \cdot (1 - P_{r,m,RTS_error}) \cdot (1 - P_{r,m,CTS_error}) \cdot P_{r,m,data_error} \\
&P_{r,m,ackframe_error} = P_{r,m,s} \cdot (1 - P_{r,m,RTS_error}) \cdot (1 - P_{r,m,CTS_error}) \cdot \\
&(1 - P_{r,m,data_error}) \cdot P_{r,m,ack_error}
\end{aligned} \tag{19}$$

$P_{r,m,RTSframe\_error}$, $P_{r,m,CTSframe\_error}$, $P_{r,m,dataframe\_error}$ and $P_{r,m,ackframe\_error}$ are the respective probability of a transmission error occurring in a RTS, CTS, data or ACK frame.

4 Energy Consumption of IEEE 802.11/ a/b/g in an Error-Prone Channel

In the IEEE 802.11 DCF, two power management mechanisms are supported: active and power saving mechanism (PSM). In this paper, we only consider the active mechanism, in which a node may be in one of three different radio modes, namely, transmit, receive, and idle modes. The main parameters of our energy model are:

- $P_{r,m,tx}$: the energy required for the transmission rate r and PHY scheme m to transmit data to the destination (mJ/sec).

- $P_{r,m,rx}$: the energy required for the transmission rate r and PHY scheme m to receive data from source (mJ/sec).
- $P_{r,m,sense}$: the energy required for a PHY scheme m to sense that the radio signal (mJ/sec) is idle.

The timing of successful two-way and four-way frame exchanges is shown in Table 1 and 2. Alternatively, if an RTS (ACK) frame is not received, for example because of an erroneous reception of the preceding CTS (Data) frame, the transmitter will contend for the medium to re-transmit the frame after a CTS (ACK) timeout.

Table 1. Channel states for the basic access method under DCF

No.	Scenario	T	Duration
1	Idle	$T_{r,m,idle}$	σ_m
2	Success	$T_{r,m,s}(l)$	$T_{r,m,data}(l)+T_{r,m,SIFS}+T_{r,m,ack}+T_{r,m,DIFS}+2*\delta_m$
3	Collision	$T_{r,m,c}(l)$	$T_{r,m,data}(l)+T_{r,m,EIFS}+\delta_m$
4	Data corruption	$T_{r,m,data\_error}(l)$	$T_{r,m,data}(l)+T_{r,m,EIFS}+\delta_m$
5	ACK corruption	$T_{r,m,ack\_error}(l)$	$T_{r,m,data}(l)+T_{r,m,ACK\_timeout}+T_{r,m,DIFS}+2*\delta_m$

Table 2. Channel states for the RTS/CTS exchange method under DCF

No.	Scenario	T	Duration
1	Idle	$T_{r,m,idle}$	σ_m
2	Success	$T_{r,m,s}(l)$	$T_{r,m,RTS}+T_{r,m,CTS}+T_{r,m,data}(l)+T_{r,m,ack}$ $+T_{r,m,DIFS}+3*T_{r,m,SIFS}+4*\delta_m$
3	Collision	$T_{r,m,c}(l)$	$T_{r,m,RTS}+T_{r,m,EIFS}+\delta_m$
4	RTS corruption	$T_{r,m,RTS\_error}(l)$	$T_{r,m,RTS}+T_{r,m,EIFS}+\delta_m$
5	CTS corruption	$T_{r,m,CTS\_error}(l)$	$T_{r,m,RTS}+T_{r,m,CTS\_timeout}+T_{r,m,DIFS}+2*\delta_m$
6	Data corruption	$T_{r,m,data\_error}(l)$	$T_{r,m,RTS}+T_{r,m,CTS}+T_{r,m,data}(l)+T_{r,m,EIFS}$ $+2*T_{r,m,SIFS}(m)+3*\delta_m$
7	ACK corruption	$T_{r,m,ack\_error}(l)$	$T_{r,m,RTS}+T_{r,m,CTS}+T_{r,m,data}(l)+T_{r,m,ack\_timeout}$ $+T_{r,m,DIFS}+2*T_{r,m,SIFS}(m)+4*\delta_m$

$T_{r,m,EIFS}$ is derived from the SIFS and the DIFS and the length of time it takes to transmit an ACK (CTS) Control frame at control signal transmission rate by the following equation:

$$T_{m,EIFS} = T_{r,m,SIFS} + T_{r,m,ack} + T_{r,m,DIFS} \tag{20}$$

$$T_{r,m,ack\_timeout} = T_{r,m,SIFS} + T_{r,m,ack} \tag{21}$$

$$T_{r,m,CTS\_timeout} = T_{r,m,SIFS} + T_{r,m,CTS} \tag{22}$$

We assume that, under a heavy traffic load (i.e. saturation), n competing nodes always have packets to transmit. On average, node A incurs collisions $N_{m,collision}$ times before a successful transmission. $P_{r,m,collision}$ is the collision probability. Thus, (1-$P_{r,m,collision}$) is the probability of probability of successful transmission. Therefore, the average number of retransmissions before a successful transmission is 1/(1-$P_{r,m,collision}$). The number of collisions is

$$N_{m,collision} = \frac{1}{1-(P_{r,m,collision} + (1-P_{r,m,collision}) \cdot P_{r,m,error})} - 1 \quad (23)$$

Let $E_{m,collision}(l)$ is the energy consumption in collision period in node A.
In the basic access method, the $E_{m,collision}(l)$ is,

$$E_{r,m,collision}(l) = N_{m,collision} \cdot (T_{r,m,data}(l) \cdot P_{r,m,tx} + (T_{r,m,EIFS} + \delta_m) \cdot P_{r,m,sense}) \quad (24)$$

The $E_{m,collision}(l)$ for the RTS/CTS exchange method is

$$E_{r,m,collision}(l) = N_{m,collision} \cdot (T_{r,m,RTS} \cdot P_{r,m,tx} + (T_{r,m,EIFS} + \delta_m) \cdot P_{r,m,sense}) \quad (25)$$

During the backoff period of node A, it will overhear transmissions from other nodes. The average number overheard in A is denoted as $N_{m,overheard}$.

$$N_{m,overheard} = W_m(k) \cdot P_{r,m,tr} \quad (26)$$

Among the $N_{m,overheard}$ transmissions, the probability of a successful transmission is $P_{r,m,s}$, and (1-$P_{r,m,s}$) is the probability of unsuccessful transmission. $E_{r,m,overheard}(l)$ denotes the energy consumption for transmissions overheard in node A.
In the basic access method this is,

$$E_{r,m,overheard}(l) = N_{m,overheard} \cdot P_{r,m,rx} \cdot \begin{pmatrix} P'_{r,m,s} \cdot P_{r,m,tr} \cdot T_{r,m,s}(l) + P_{r,m,tr} \cdot (1-p'_{r,m,s}) \cdot T_{r,m,c}(l) + \\ P_{r,m,dataframe\_error} \cdot T_{r,m,data\_error}(l) + P_{r,m,ackframe\_error} \cdot T_{r,m,ack\_error}(l) \end{pmatrix} \quad (27)$$

For the RTS/CTS exchange method this is,

$$E_{r,m,overheard}(l) = N_{m,overheard} \cdot P_{r,m,rx} \cdot \begin{pmatrix} P'_{r,m,s} \cdot P_{r,m,tr} \cdot T_{r,m,s}(l) + P_{r,m,tr} \cdot (1-p'_{r,m,s}) \cdot T_{r,m,c}(l) + \\ P_{r,m,RTSframe\_error} \cdot T_{r,m,RTS\_error}(l) + P_{r,m,CTSframe\_error} \cdot T_{r,m,CTS\_error}(l) + \\ P_{r,m,dataframe\_error} \cdot T_{r,m,data\_error}(l) + P_{r,m,ackframe\_error} \cdot T_{r,m,ack\_error}(l) \end{pmatrix} \quad (28)$$

We assume that a node will remain in the sensing mode if it doesn't transmit, node A will therefore remain in the sensing mode during all the backoff periods, and it will backoff for $N_{m,backoff}$ times. Thus,

$$N_{m,backoff} = \frac{1}{1-(P_{r,m,collision} + (1-P_{r,m,collision}) \cdot P_{r,m,error})} \quad (29)$$

Let $E_{r,m,backoff}$ is the energy consumption in the backoff period in node A.

$$E_{r,m,backoff} = N_{m,backoff} \cdot T_{m,backoff}(k) \cdot P_{r,m,sense} \quad (30)$$

We assume that $E_{r,m}(l)$ is the overall energy consumption of a successful data frame transmission, with length packet l ,over the selected transmission r rate and PHY scheme m.

$$E_{r,m}(l) = E_{r,m,backoff} + E_{r,m,overheard}(l) + E_{r,m,collision}(l) + E_{r,m,error}(l) + E_{r,m,transmission}(l) \tag{31}$$

$E_{r,m,backoff}$ is the energy consumption during a backoff period in a transmitter. $E_{r,m,collision}(l)$ is the energy consumption in a transmitter during a packet collision. The average number overheard in A is denoted as $N_{m,overheard}$. $E_{r,m,transmission}(l)$ is the total energy consumption during a successful transmission when there is no collision or packet errors. Thus, the $E_{r,m,transmission}(l)$ and $E_{r,m,error}(l)$ in Basic access method are,

$$\begin{aligned}
E_{r,m,transmission} &= T_{r,m,data}(l)\cdot P_{r,m,tx} + T_{r,m,ack}\cdot P_{r,m,rx} + (T_{r,m,SIFS} + T_{r,m,DIFS} + 2\cdot\delta_m)\cdot P_{r,m,sense} \\
E_{r,m,error} &= N_{r,m,dataframe_error}\cdot\begin{pmatrix} T_{r,m,data}(l)\cdot P_{r,m,tx} + \\ (T_{r,m,EIFS} + \delta_m)\cdot P_{r,m,sense}\end{pmatrix} + \\
&N_{r,m,ackframe_error}\cdot\begin{pmatrix} T_{r,m,data}(l)\cdot P_{r,m,tx} + \\ (T_{r,m,ACK_timeout} + T_{r,m,DIFS} + 2\cdot\delta_m)\cdot P_{r,m,sense}\end{pmatrix}
\end{aligned} \tag{32}$$

For the RTS/CTS exchange method this is,

$$\begin{aligned}
E_{r,m,transmission} &= (T_{r,m,RTS} + T_{r,m,data}(l))\cdot P_{r,m,tx} + \\
&(T_{r,m,CTS} + T_{r,m,ack})\cdot P_{r,m,rx} + (T_{r,m,DIFS} + 3\cdot T_{r,m,SIFS} + 4\cdot\delta_m)\cdot P_{r,m,sense} \\
E_{r,m,error} &= N_{r,m,RTSframe_error}\cdot\left(T_{r,m,RTS}\cdot P_{r,m,tx} + (T_{r,m,EIFS} + \delta_m)\cdot P_{r,m,sense}\right) + \\
&N_{r,m,CTSframe_error}\cdot\begin{pmatrix} T_{r,m,RTS}\cdot P_{r,m,tx} + (T_{r,m,CTS_timeout} + \\ T_{r,m,DIFS} + 2\cdot\delta_m)\cdot P_{r,m,sense}\end{pmatrix} + \\
&N_{r,m,dataframe_error}\cdot\begin{pmatrix} (T_{r,m,RTS} + T_{r,m,data}(l))\cdot P_{r,m,tx} + T_{r,m,CTS}\cdot P_{r,m,rx} + \\ (T_{r,m,EIFS} + 2\cdot T_{r,m,SIFS} + 3\cdot\delta_m)\cdot P_{r,m,sense}\end{pmatrix} + \\
&N_{r,m,ackframe_error}\cdot\begin{pmatrix} (T_{r,m,RTS} + T_{r,m,data}(l))\cdot P_{r,m,tx} + T_{r,m,CTS}\cdot P_{r,m,rx} + \\ (T_{r,m,ack_timeout} + T_{r,m,DIFS} + 2\cdot T_{r,m,SIFS} + 4\cdot\delta_m)\cdot \\ P_{r,m,sense}\end{pmatrix}
\end{aligned} \tag{33}$$

$N_{r,m,RTSframe\_error}$, $N_{r,m,CTSframe\_error}$, $N_{r,m,dataframe\_error}$ and $N_{r,m,ackframe\_error}$ are the number of transmissions error occurring in RTS, CTS, data and ACK frames respectively.

$$\begin{cases} N_{r,m,dataframe\_error} = \dfrac{1}{1-P_{r,m,dataframe\_error}} \\ N_{r,m,ackframe\_error} = \dfrac{1}{1-P_{r,m,ackframe\_error}} \end{cases} \begin{cases} N_{r,m,RTSframe\_error} = \dfrac{1}{1-P_{r,m,RTSframe\_error}} \\ N_{r,m,CTSframe\_error} = \dfrac{1}{1-P_{r,m,CTSframe\_error}} \end{cases} \tag{34}$$

Therefore, the energy consumption per bit $G_{r,m}(l)$ can be computed as:

$$G_{r,m}(l) = \frac{E_{r,m}(l)}{l\cdot 8} \tag{35}$$

5 Simulation Results and Discussion

A simulation environment was developed using the Qualnet simulation Lab [17]. Although extensive simulations have been conducted, in this paper, we only present a summary of those results that focus on energy consumption in IEEE 802.11-based networks. In the model, a range of randomly distributed errors were introduced into the channel. The specific BER values were chosen as they are the values used by commercial wireless adapters for rate adaptation (e.g. Orinoco) [18].

Table 3. The energy consumption and MAC parameters used in simulation. [19]

	Transmit	Receive	Standby	$CW_{m,min}$	$CW_{m,max}$	$aSlotTime$ (σ_m)
802.11a	554 mA	318 mA	203 mA	16 slots	1024 slots	9 µs
802.11b	539 mA	327 mA	203 mA	32 slots	1024 slots	20 µs
802.11g	530 mA	282 mA	203 mA	32 slots	1024 slots	20 µs

To observe the energy consumption in a relatively heavy loaded network, we set up a simulation scenario with 30 active nodes during the channel competition. The transmission bit rate is 6 Mbps in both the basic access and RTS/CTS exchange methods for the 802.11a and g. Each active node transmits 2304 bytes of traffic in their data frames.

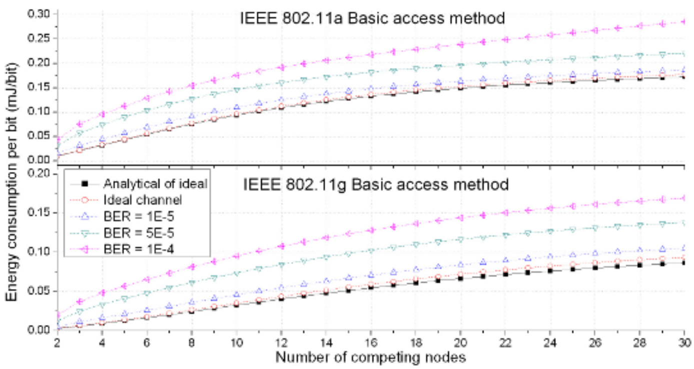

Fig. 1. Energy consumption per bit of basic access method for 802.11a/g

Figures 1 and 2 show the energy consumption per bit (mJ/bit) when transmitting using the basic access and RTS/CTS exchange methods. The results consider 802.11a/OFDM and 802.11g/ERP-OFDM PHYs with different bit error rates. Analytical results for an ideal channel are also shown to agree well with the simulations. The results show that energy consumption is primarily influenced by the selected MAC and PHY layers. The 802.11a with basic access method is most sensitive to channel interference; and 802.11g consumes less energy than 802.11a at the same data rate for both methods. The RTS/CTS exchange method has lower energy consumption than the basic access method in both 802.11a and g. This is

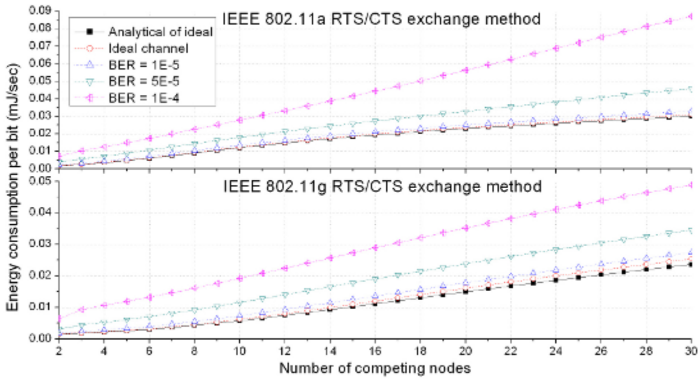

Fig. 2. Energy consumption per bit of RTS/CTS exchange method for 802.11a/g

because, when the number of competing nodes is increased, the congestion is also increased; the cost of packet retransmissions is also lower in the RTS/CTS exchange method than in the basic access method. Furthermore, for an ideal channel, the results also show that a MAC sub-layer with a larger minimum contention window size (e.g. 802.11g has a lager $CW_{m,min}$ of 31 slots than 802.11a of 15 slots in MAC sub-layer protocol) will reduce the energy consumption under saturation conditions for both exchange methods.

Another interesting result in this study is the energy consumption under the varying bit error rates. The results show that the transmitter produces much higher energy consumption when the channel is very noisy (e.g., when BER$\geq 10^{-5}$). The bulk of frames are dropped due to transmission errors. This is because the larger frame size has a higher probability of transmission error when the channel condition is noisy. Therefore there will be more data frames corrupted by the channel thus the higher cost of energy consumption per bit. There will be less RTS/CTS packets corrupted as they are smaller sized than the data frames; hence the results show that although the RTS/CTS method consumes less energy than the basic access method, it does appear to be more sensitive when used in an 802.11a network operating in noisy conditions.

6 Conclusions

This paper presents a new approach for predicting energy consumption in IEEE 802.11-based DCF networks with multiple modulation and PHY layers. The energy consumption model developed may be applied to both congested and error-prone wireless channels. Analysis shows that the selected MAC and PHY layers have the primary influence on the energy consumption. The simulation results are observed to match very well with the analytical results, which show that the condition of the wireless channel and the level of congestion both increase the energy consumption. Moreover, this study shows that the energy consumption of the RTS/CTS exchange method is less than that of the basic access method. This paper describes research that aims to model energy consumption in IEEE-based DCF networks under an error-prone channel condition. An interesting area of future research will be to extend the approach into a cross-layer architecture to provide further rate adaptation to optimize network capacity and reduce energy consumption in 802.11-based Multi-hop wireless networks.

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