Power consumption analysis of data transmission in IEEE 802.11 multi-hop networks

Wataru Toorisaka†, Go Hasegawa‡, and Masayuki Murata†
† Graduate School of Information Science and Technology, Osaka University
1-5 Yamadaoka, Suita-shi, Osaka, 565-0871 Japan
Email: {t-wataru,murata}@ist.osaka-u.ac.jp
‡ Cybermedia Center, Osaka University
1-32 Machikaneyama-cho, Toyonaka-shi, Osaka, 560-0043 Japan
Email: hasegawa@cmc.osaka-u.ac.jp

***Abstract*—The issue of power consumption in wireless networks is becoming increasingly important due to the rapid development of various wireless devices such as sensors, smartphones, and tablet PCs. The IEEE 802.11 wireless LAN standard defines multiple data transmission protocols, each of which has various characteristics such as power consumption, data rate, modulation method, and transmission distance. Therefore, it is important to choose the optimal data rate in terms of power consumption as well as throughput, especially when considering data transmission over multi-hop networks. In this paper, we present a mathematical analysis of power consumption in data transmission over IEEE 802.11-based wireless multi-hop networks to investigate the effect of data rate selection on power consumption. The analysis results show that there are some situations where a low data rate should intentionally be selected in order to minimize power consumption. Our analysis indicates that power consumption can be decreased by up to 13% when the symbol error rate is comparatively small.**

***Index Terms*—IEEE 802.11, wireless multi-hop networks, power consumption, modulation method**

I. Introduction

Internet access via wireless networks has become very popular due to the rapid development of the wireless devices. These devices are mostly battery-driven, and wireless communication accounts for around 10% to 50% of their total power consumption [1-3]. Therefore, decreasing the power consumption in wireless communication is an important issue, especially when considering wireless multi-hop networks such as sensor networks and wireless mesh networks in which energy efficiency is essential. In this paper, we focus on the power consumption in wireless multi-hop networks based on IEEE 802.11 wireless LAN (WLAN), which is the most popular for implementing wireless multi-hop networks.

The IEEE 802.11 WLAN standard has multiple data rates that can be used, each of which has various characteristics such as modulation method, maximum transmission distance, and power consumption. Many rate adaptation algorithms have been proposed in the literature, such as automatic rate fallback (ARF) [4], receiver-based auto rate (RBAR) [5], and adaptive ARF (AARF) [6]. In ARF and AARF, each sender attempts to use a higher transmission rate after a fixed number of successful transmissions at a given rate and switches back to a lower rate after some consecutive failures. RBAR requires to

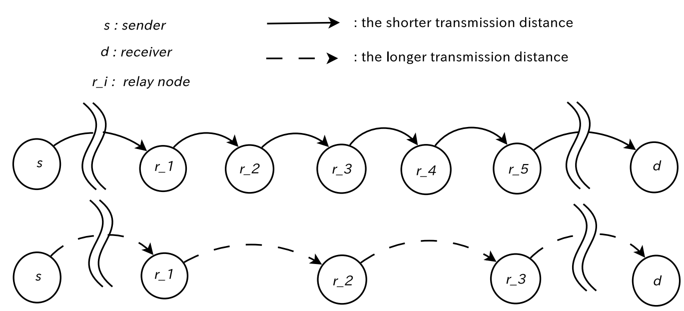


Fig. 1. Effect of transmission distance.

change some MAC control frames and include a new header field. However, these algorithms are designed for maximizing the throughput of applications and they do not focus on energy efficiency. In addition, these existing algorithms do not consider multi-hop networks. On the other hand, the authors in [7-10] present the mathematical analysis on the power consumption in data transmission over WLAN. However, those analyses do not take multi-hop networks into account.

In wireless communication, in general, when a node lowers its transmission power, the transmission distance becomes shorter, resulting in a reduction in power consumption. However, when considering wireless multi-hop network, a shorter transmission distance may increase the total power consumption, since the shorter transmission distance requires greater node density and increases the hop count between a sender and a receiver, as shown in Figure 1. Using a higher data rate can decrease the air time of a packet, which may in turn decrease power consumption. However, a higher data rate generally has a shorter maximum transmission distance, and thus may increase the hop count for data transmission. Note that such an increase in hop count would lower energy efficiency, since the number of packet transmissions would rise.

In addition, some data rates in IEEE 802.11 WLAN employ different modulation methods, which may affect energy efficiency. In general, a modulation method used at a higher data rate can transmit more bits per transmitted symbol, but

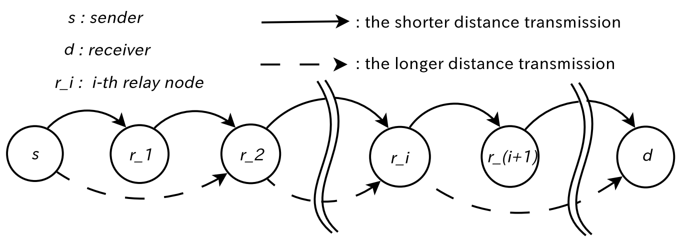


Fig. 2. Network model

may result in a higher symbol error rate in a poor wireless environment due to noise and interference. A higher symbol error rate would then increase frame losses and retransmissions, lowering energy efficiency.

The complicated situations described above warrant special attention when considering the energy efficiency of wireless multi-hop networks. Therefore, in this paper, we present a mathematical analysis of power consumption in data transmission over IEEE 802.11-based wireless multi-hop networks. In particular, we consider the detailed behavior of the carrier sense multiple access with collision avoidance (CSMA/CA) method, and the complicated trade-off relationships described above. We show numerical examples of the analysis based on the specifications of an existing WLAN interface device and clarify the effect of data rate on energy efficiency in wireless multi-hop networks. In particular, we show that there are some situations where a low data rate should be intentionally selected in order to minimize power consumption.

The rest of this paper is organized as follows. In Section II, we describe our mathematical analysis of power consumption in data transmission over IEEE 802.11 wireless multi-hop networks. In Section III, we show numerical examples of the analysis and discuss the effect of data rate selection on energy efficiency. Finally, in Section IV, we give our conclusions and discuss directions of future research.

II. Mathematical Analysis

In the analysis, we assume a CSMA/CA MAC with RTS/CTS. There are multiple data rates that can be used in IEEE 802.11 WLAN standard, each of which is different in terms of transmission power, transmission distance, and modulation method. Therefore, the distance of one hop has a large impact on energy efficiency when data are transmitted over a multi-hop network.

Figure 2 shows the network model for the analysis. The network has a linear topology, where data are transmitted from a sender (node s) to a receiver (node d), which are separated by distance L. r_i $(i = 1, 2, ...)$ is a relay node located between the sender and receiver. For simplicity, we do not consider the effects of radio wave interference and overhearing on power consumption. The number of hops between the sender and receiver is determined when we choose the distance for one-hop transmission. In other words, when the one-hop transmission distance is D, the number of hops between the sender and receiver becomes $\lceil L/D \rceil$. This corresponds to the situation where we have an infinite number of relay nodes between the sender and receiver and we can select some of them to be used according to the transmission distance, as shown in Figure 2. Under this assumption we can explicitly evaluate the effect of data rate and its characteristics on the energy efficiency of multi-hop networks.

In Section II-A, we explain the detailed behavior of CSMA/CA in IEEE 802.11 WLAN. In Section II-B, we describe the power consumption of one-hop transmission of a single data frame between two relay nodes, and in Section II-C, we analyze multi-hop transmission of a total data whose size is S_{DATA} in Section II-C.

A. Frame exchange with CSMA/CA with RTS/CTS

Let us first look at one-hop data transmission. Figure 3 illustrates the frame exchange in the data transmission from r_i to r_{i+1} by CSMA/CA with request to send/clear to send (RTS/CTS). Figure 3(a) shows the case where no frame loss occurs, and Figure 3(b) shows the case where successive frame losses occur.

As shown in Figure 3(a), when a transmission demand occurs at r_i, it transmits an RTS command frame to r_{i+1} after a distributed coordination function (DCF) interframe space (DIFS) and a random backoff (BO_1). Then, r_{i+1} waits for a short interframe space (SIFS) and transmits a CTS command frame to r_i. When r_i receives the CTS command frame, it begins to transmit a data frame after an SIFS. After r_{i+1} finishes receiving the data frame, it transmits an acknowledgment (ACK) frame to r_i after an SIFS. When r_i receives the ACK frame from r_{i+1}, the transmission of one data frame is completed.

In Figure 3(b), when r_{i+1} fails to receive a data frame from r_i, it does not transmit an ACK frame to r_i. In this case, r_i waits a retransmission time out (RTO) and retransmits the data frame after a DIFS and a random backoff (BO_2). This cycle continues until the data frame successfully reaches r_{i+1} . Note that BO_j in Figure 3(b) is the random backoff for the $(j-1)$ th retransmission of the data frame. In the analysis, we assume that RTS, CTS, and ACK frames are never lost in the entire data transmission process.

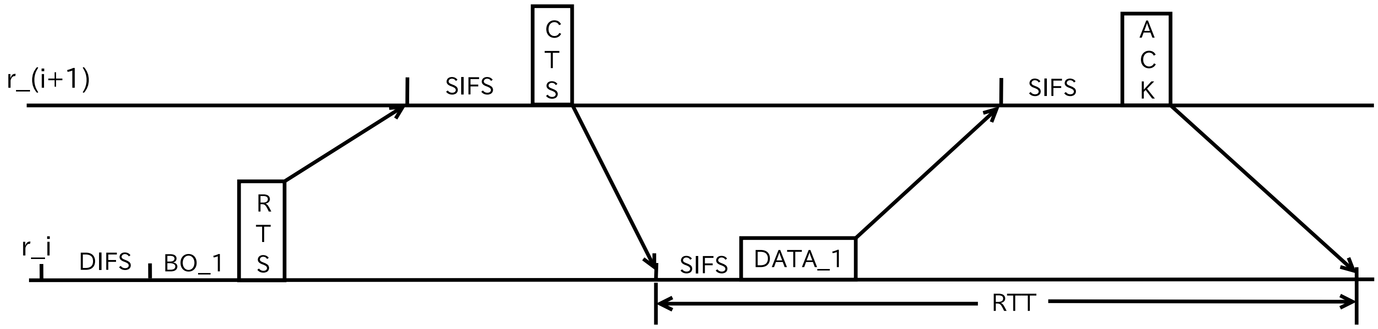
B. Power consumption in one-hop data transmission

Based on the behavior shown in Section II-A, we calculate the power consumption in one-hop transmission of a single data frame. We denote the total size of the data to be transmitted as S_{DATA} and the size of one data frame as S_f. Then, the number of data frames to be transmitted, n_f, is calculated as

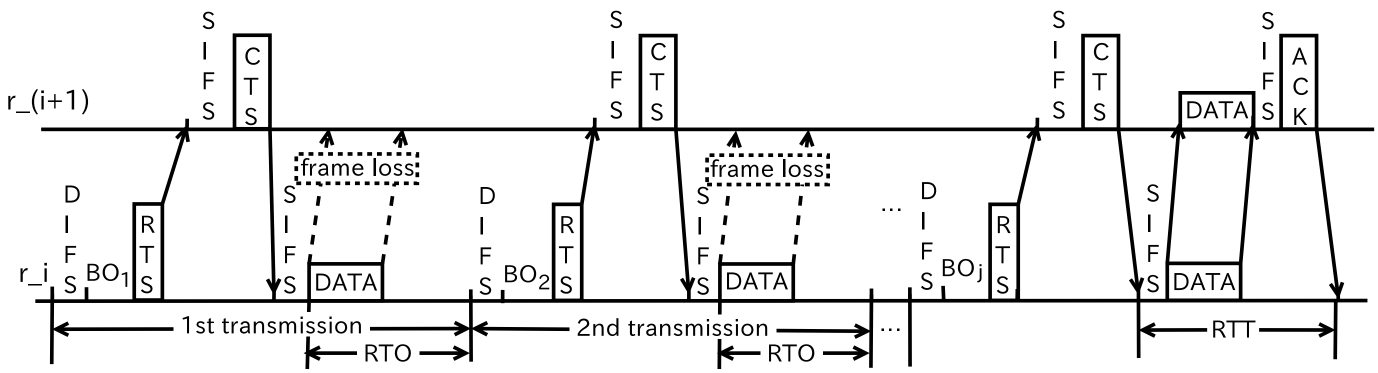
$$n_f = \left\lceil \frac{S_{DATA}}{S_f} \right\rceil . \quad (1)$$

The modulation method used for a data rate is defined to modulate l bit(s) per transmitted symbol. Then, the number of symbols in a data frame is

$$n_s = \left\lceil \frac{S_f}{l} \right\rceil . \quad (2)$$



(a) Case of no frame loss



(b) Case of successive flame losses

Fig. 3. Frame exchange based on IEEE 802.11 with RTS/CTS

The value of l is different in each modulation method. For example, $l = 1$ in binary phase shift keying (BPSK) and $l = 2$ in quadrature phase shift keying (QPSK). Note that a single symbol error corresponds to multiple bit errors when $l > 1$. In the numerical evaluations in Section III, we treat the symbol error rate as the probability that a transmitted symbol is not received successfully. We then assume that a loss of a data frame occurs due to one or more bit errors when the frame is transmitted from r_i to r_{i+1}. By denoting the symbol loss rate as p_s, the probability with which a data frame fails to be transmitted successfully, is

$$p_f = 1 - (1 - p_s)^{n_s}. \tag{3}$$

The average number of transmissions until r_{i+1} successfully receives the data frame, denoted by e, is given by

$$e = \lim_{x\to\infty} \sum_{i=1}^{x} i p_f^{i-1}(1 - p_f). \tag{4}$$

This Equation (4) is solved as follows:

$$\begin{aligned}
(1-p_f)e &= \lim_{x\to\infty}\left(\sum_{i=1}^{x} i p_f^{i-1}(1-p_f) - \sum_{i=1}^{x} i p_f^{i}(1-p_f)\right),\\
e &= \lim_{x\to\infty}\left(\sum_{i=1}^{x} i p_f^{i-1} - \sum_{i=2}^{x+1}(i-1)p_f^{i-1}\right),\\
&= \lim_{x\to\infty}\left\{\left(1+\sum_{i=2}^{x} i p_f^{i-1}\right) - \left(\sum_{i=2}^{x} i p_f^{i} + (x+1)p_f^{x} - \sum_{i=2}^{x+1} p_f^{i-1}\right)\right\},\\
&= \lim_{x\to\infty}\left(1+\sum_{i=2}^{x} p_f^{i-1} + p_f - (x+1)p_f^{x}\right),\\
&= \lim_{x\to\infty}\left(\sum_{i=1}^{x} p_f^{i-1} - x p_f^{x}\right),\\
&= \frac{1}{1-p_f}.
\end{aligned} \tag{5}$$

Next, we examine the backoff time (BO_j in Figure 3(b)). The backoff time is a waiting period before a data frame is transmitted to prevent collisions between multiple transmitting nodes. The length of the backoff time is determined at random within the range $[0, CW]$ multiplied by slot time, denoted by T_{slot}. The value of CW varies according to the number of successive retransmissions. The value of CW for the backoff time at the j th retransmission, CW_j, is calculated as

$$CW_j = \min\left(2^{j-1}CW_{min}, CW_{max}\right), \quad (1 \le j). \tag{6}$$

Then the length of backoff time on j th retransmission is obtained as $CW_j \cdot T_{slot}$. For the sake of simplicity, we assume that CW_{max} is given as follows:

$$CW_{max} = 2^m CW_{min}. \tag{7}$$

where m in an integer value. Then, we can compute the average value of the sum of the backoff times for the transmission of one data frame, T_{BO}, from Equations (5) and (7):

$$\begin{aligned} T_{BO} &= \lim_{x\to\infty} \left(\sum_{j=1}^{m} \left\{ \frac{2^{j-1}CW_{min}T_{slot}}{2} \cdot p_f^{j-1}(1-p_f) \right\} \right. \\ &\quad \left. + \sum_{j=m+1}^{x} \left\{ \frac{CW_{max}T_{slot}}{2} \cdot p_f^{j-1}(1-p_f) \right\} \right). \end{aligned} \tag{8}$$

In what follows, the first term in Equation (8) is denoted as Q_1 and the second term is denoted as Q_2. These terms are calculated as

$$\begin{aligned} Q_1 &= \lim_{x\to\infty} \frac{1}{2} \sum_{j=1}^{m} \left\{ (2p_f)^{j-1} CW_{min}T_{slot}(1-p_f) \right\}, \\ &= \frac{1}{2} \sum_{j=1}^{m} \left\{ (2p_f)^{j-1} CW_{min}T_{slot}(1-p_f) \right\}, \\ &= \frac{CW_{min}T_{slot}(1-p_f)}{2} \sum_{j=1}^{m} (2p_f)^{j-1}, \\ &= \begin{cases} \frac{CW_{min}T_{slot}(1-p_f)}{2} \cdot \frac{(2p_f)^m - 1}{2p_f - 1} & (\frac{1}{2} < p_f < 1) \\ \frac{mCW_{min}T_{slot}(1-p_f)}{4} & (p_f = \frac{1}{2}) \\ \frac{CW_{min}T_{slot}(1-p_f)}{2} \cdot \frac{1-(2p_f)^m}{1-2p_f} & (0 < p_f < \frac{1}{2}), \end{cases} \end{aligned} \tag{9}$$

$$\begin{aligned} Q_2 &= 2^{m-1} CW_{min}T_{slot}(1-p_f) \sum_{j=m+1}^{x} p_f^{j-1}, \\ &= 2^{m-1} CW_{min}T_{slot}(1-p_f) \left(\sum_{j=1}^{x} p_f^{j-1} - \sum_{j=1}^{m} p_f^{i-1} \right), \\ &= 2^{m-1} CW_{min}T_{slot}(1-p_f) \left(\frac{1-p_f^x}{1-p_f} - \frac{1-p_f^m}{1-p_f} \right), \\ &= 2^{m-1} CW_{min}T_{slot}(p_f^m - p_f^x), \\ &\to 2^{m-1} p_f^m CW_{min}T_{slot} \quad (x \to \infty). \end{aligned} \tag{10}$$

Consequently, from Equations (8)- (10), T_{BO} is given by

$$T_{BO} = Q_1 + 2^{m-1} p_f^m CW_{min}T_{slot}. \tag{11}$$

We now calculate the power consumed for the transmission of a data frame. We denote the period for bit transmission, bit reception, and the idle time of the sender (node r_i in Figure 2) as T^s_{send}, T^s_{recv}, and T^s_{idle}, respectively. Similarly, for the receiver (node r_{i+1} in Figure 2), we use the variables T^r_{send}, T^r_{recv}, and T^r_{idle}. In reference to Figure 2, these variables can be used to formulate the following equations:

$$\begin{aligned} T^s_{send} &= T^r_{recv}, \\ &= \frac{1}{d^{(k)}(1-p_f)} (S_{RTS} + S_{DATA} + S_{head}), \end{aligned} \tag{12}$$

$$\begin{aligned} T^s_{recv} &= T^r_{send}, \\ &= \frac{1}{d^{(k)}} \left(\frac{S_{CTS}}{1-p_f} + S_{ACK} \right), \end{aligned} \tag{13}$$

$$\begin{aligned} T^s_{idle} &= T^r_{idle}, \\ &= \frac{1}{1-p_f} \{ T_{DIFS} + (1-p_f)T_{BO} \\ &\quad + (3-2p_f)T_{SIFS} \\ &\quad + p_f \left(T_{RTO} - \frac{S_{DATA} + S_{head}}{d^{(k)}} \right) \}. \end{aligned} \tag{14}$$

T_{SIFS} and T_{DIFS} are respectively an SIFS and a DIFS. T_{RTO} is the time of RTO. S_{RTS}, S_{CTS}, and S_{ACK} are respectively the size of an RTS frame, a CTS frame, and an ACK frame. S_{head} is the sum of the physical layer convergence protocol (PLCP) preamble and the PLCP header added at the physical layer. $d^{(k)}$ is the data rate to be used. We assume that the number of available data rates in IEEE 802.11 WLAN is K. The power consumption in one-hop transmission with the data rate of $d^{(k)}$ is

$$\begin{aligned} E_1^{(k)} &= P_i \times (T^s_{idle} + T^r_{idle}) + P_t \times (T^s_{send} + T^r_{send}) \\ &\quad + P_r \times (T^s_{recv} + T^r_{recv}), \\ &= 2P_s \times T^s_{idle} + (P_t + P_r)(T^s_{send} + T^s_{recv}). \end{aligned} \tag{15}$$

P_t and P_r are the power needed in bit transmission and reception per unit time, respectively. P_i is the power consumed in the idle period.

C. Power consumption in multi-hop data transmission

We now calculate the power consumed in the entire data transmission process over the multi-hop network depicted in Figure 2. The transmission power and transmission distance of the k th data rate are denoted as $P_t^{(k)}$ and $r^{(k)}$, respectively. We also introduce the maximum transmission power and the maximum transmission distance at the k th data rate, denoted by $\hat{P}_t^{(k)}$ and $\hat{r}^{(k)}$, respectively. We assume that when a data frame is transmitted at less than the maximum power, the relation between the transmission power and transmission distance is expressed as

$$P_t^{(k)} = \hat{P}_t^{(k)} \cdot \left(\frac{r^{(k)}}{\hat{r}^{(k)}} \right)^{\alpha}, \tag{16}$$

where α is the parameter that describes the attenuation [11, 12]. The above equation can be transformed for $r^{(k)}$ as follows.

$$r^{(k)} = \hat{r}^{(k)} \cdot \left(\frac{P_t^{(k)}}{\hat{P}_t^{(k)}} \right)^{\frac{1}{\alpha}}. \tag{17}$$

Since the distance between the sender and receiver is L, the hop count is given by

$$h^{(k)} = \left\lceil \frac{L}{r^{(k)}} \right\rceil. \tag{18}$$

TABLE I
PARAMETER SETTINGS

item	size
S_{ACK}	40 [bytes]
S_{RTS}	40 [bytes]
S_{CTS}	40 [bytes]
S_f	1000 [bytes]
S_{header}	24 [bytes]

(a) Frame size and physical-layer overhead

item	length
T_{DIFS}	34 [μs]
T_{SIFS}	16 [μs]
T_{slot}	9 [μs]
T_{RTO}	5 RTT

(b) IEEE 802.11 parameters

TABLE II
TRANSMISSION DISTANCE AND POWER OF CISCO AIRONET IEEE 802.11/A/B/G WIRELESS CARDBUS ADAPTER

data rate [Mbps]	1	6	11	18	54
maximum transmission distance [m]	610	396	304	183	76
maximum transmission power [mW]	100	100	100	50	20

Finally, the power consumption for the transmission of S_{DATA} data over the multi-hop network $E_M^{(k)}$ is given as follows:

$$E_M^{(k)} = n_f \cdot E_1^{(k)} \cdot h^{(k)}. \quad (19)$$

III. NUMERICAL EVALUATION

A. Parameter settings

We set the distance L between the sender and receiver to 1000 [m] and the total data size S_{DATA} is set to 100 [Kbytes]. As the parameters for determining the backoff time in Equation (11), we set $m = 10$ and $CW_{min} = 15$. The parameter α in Equation (17) is set to 2. Frame sizes and physical-layer overhead are listed in Table II(a), and IEEE 802.11 parameters are shown in Table II(b). T_{RTO} is set at five times the round trip time (RTT), according to the implementation of FreeBSD [13]. RTT, which is shown in Figure 2, is calculated based on frame size and data rate by ignoring the propagation delay between relay nodes. We utilize the specifications shown in Table II for a Cisco Aironet IEEE 802.11a/b/g Wireless CardBus adapter [14] for the maximum transmission distance and corresponding power of each data rate.

B. Numerical results and discussions

Figure 4 shows the power consumption for various data rates as a function of symbol error rate when we set the transmission power to 20 [mW]. Here, we assume that the symbol error rate remains unchanged when we change the data rate. We can see from this figure that power consumption can be decreased simply by using a higher data rate. This is because the main contribution to reducing power consumption is from the decreased air time of a packet.

When we consider the transmission power configuration, the situation changes notably. In Figure 5, we plot the relationships between symbol error rates when we use a 6 [Mbps] data rate and when we use a 11 [Mbps] data rate, for certain transmission powers where the power consumption at the two data rates become equal. For example, observing the plot for

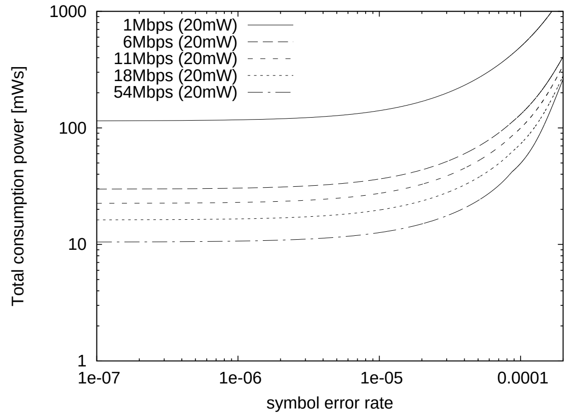


Fig. 4. Power consumption at various data rates

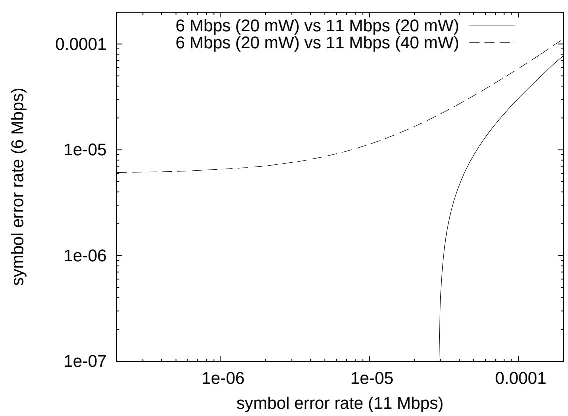


Fig. 5. Symbol error rates at two data rates that give equal power consumption

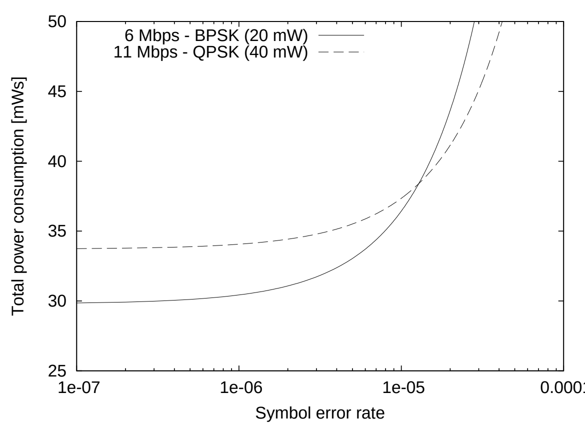


Fig. 6. Power consumption comparison between 6 [Mbps] (BPSK) and 11 [Mbps] (QPSK)

6 [Mbps] (20 [mW]) versus 11 [Mbps] (40 [mW]), using 11 [Mbps] has smaller power consumption in the upper-left region of the plot and 6 [Mbps] has an advantage in the lower-right region of the plot.

One possible way to decrease the symbol error rate at a higher data rate is to increase the transmission power. By comparing the two curves in the graph, we can observe that when the transmission power is increased at the 11 [Mbps] data rate from 20 [mW] to 40 [mW], the region where the 11 [Mbps] data rate has smaller power consumption decreases considerably. This means that we should carefully choose the data rate and transmission power according to the symbol error rate which is observed during the data transmission.

Finally, we show another example where we utilize a static relation between two modulation methods. Here we assume that QPSK consumes twice as much power as BPSK in order to obtain a given symbol error rate [15]. In other words, when we decrease the symbol error rate at higher data rates we should significantly increase the transmission power. With consideration these characteristics, BPSK at 6 [Mbps] and 20 [mW] transmission power is compared with QPSK at 11 [Mbps] and 40 [mW] transmission power in Figure 6. Here, when the symbol error rate is approximately 10^{-6} or lower, the lower data rate gives smaller power consumption, which is an opposite result to that in Figure 4. The reduction in power consumption reaches about 13% when the 6 [Mbps] data rate is chosen. This means that increasing transmission power to decrease the symbol error rate results in increased power consumption for total data transmission, although we can expect a longer transmission distance and smaller hop count with larger transmission power.

From the above results, we conclude that we should consider various factors that affect the power consumption of data transmission over wireless multi-hop networks.

IV. Conclusion

In this paper, we presented a mathematical analysis of power consumption in data transmission over IEEE 802.11-based wireless multi-hop networks to investigate the effects of data rate selection on energy efficiency. The analysis revealed that power consumption can be decreased by up to 13% when the symbol error rate is comparatively small.

For future work, we plan to consider other modulation methods such as quadrature amplitude modulation to provide further insight into energy efficiency at high data rates. Another plan for future research is to enhance the accuracy of the analysis, by including the effects of losses of ACK, RTS, and CTS frames, data frame collision, interference, and overhearing.

Acknowledgment

This work was supported in part by the Ministry of Internal Affairs and Communications (MIC), Japan, under the Promotion program for Reducing global Environmental loaD through ICT innovation (PREDICT).

References

[1] A. Communications, "Power Consumption and Energy Efficiency Comparisons of WLAN Products," tech. rep., Atheros, May 2003.

[2] V. Raghunathan, T. Pering, R. Want, A. Nguyen, and P. Jensen, "Experience with a low power wireless mobile computing platform," in *Proceedings of ISLPED 2004*, pp. 363–368, Aug 2004.

[3] Y. Agarwal, "Dynamic power management using on demand paging for networked embedded systems," in *Proceedings of the ASP-DAC 2005*, pp. 755–759, Jul 2005.

[4] A. Kamerman and L. Monteban, "WaveLAN-II: a high-performance wireless LAN for the unlicensed band," *Bell Labs Technical Journal*, vol. 2, pp. 118–133, summer 1997.

[5] G. Holland, N. Vaidya, and P. Bahl, "A rate-adaptive MAC protocol for multi-hop wireless networks," in *Proceedings of the 7th annual international conference on Mobile computing and networking*, pp. 236–250, Jul 2001.

[6] M. Lacage, M. H. Manshaei, and T. Turletti, "IEEE 802.11 rate adaptation: A practical approach," in *Proceedings of MSWiM 2004*, pp. 126–134, Oct 2004.

[7] G. Kuriakose, S. Harsha, A. Kumar, and V. Sharma, "Analytical models for capacity estimation of IEEE 802.11 WLANs using DCF for internet applications," *Wireless Networks*, vol. 15, pp. 259–277, Feb 2009.

[8] V. Baiamonte and C.-F. Chiasserini, "Saving energy during channel contention in 802.11 WLANs," *Mobile Networks*, vol. 11, pp. 287–296, Apr 2006.

[9] M. Ergen and P. Varaiya, "Decomposition of energy consumption in IEEE 802.11," in *Proceedings of ICC 2007*, pp. 403–408, Jun 2007.

[10] M. Hashimoto, G. Hasegawa, and M. Murata, "Modeling and analysis of power consumption in TCP data transmission over a wireless LAN environment," *the IEICE techreport*, vol. 110, pp. 1–6, Dec 2010.

[11] W. R. Heizelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proceedings of HICSS 2000*, pp. 3005–3014, Jan 2000.

[12] R. Bhatia and M. Kodialam, "On power efficient communication over multi-hop wireless networks: joint routing, scheduling and power control," in *Proceedings of INFOCOM 2004*, pp. 1457–1466, Mar 2004.

[13] Gary R. Wright and W. Richard Stevens, *TCP/IP Illustrated, Vol.2:The Implementation*. Addison-Wesley Professional, 1998.

[14] Cisco Aironet 802.11a/b/g wireless CardBus adapter. available at http://www.cisco.com/web/JP/product/hs/wireless/adapter/prodlit/cecbs_ds.html.

[15] Ishii Satoshi, *The wireless communication and the digital modulation and demodulation technique*. CQ publisher, 2005.