Master's Thesis

Title

Power Consumption Analysis of Data Transmission over IEEE 802.11 Multi-hop Networks

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Abstract

Internet access via wireless networks has become popular due to the rapid development of various wireless devices such as smartphones and tablet PCs. Since these devices consume a lot of electric power in data transmission over wireless networks, we need to reduce the power consumption in data transmission by such devices. In this thesis, we focus on wireless multi-hop networks based on IEEE 802.11 wireless LAN, which is often used for implementing wireless multi-hop networks.

The IEEE 802.11 WLAN standard defines multiple data rates, each of which has various characteristics such as power consumption, data rate, modulation method, and transmission distance. It is important to choose the optimal data rate to reduce the power consumption, as well as improving data transmission performance. Furthermore, when considering data transmission over multi-hop networks, we need to take more factors into consideration since the data rate and transmission power affects the hop count between a sender and a destination, and resulting power consumption. In other words, we should choose an optimal data rate and transmission power by considering complicated trade-off relationships for achieving high-performance and energy efficient data transmission over wireless multi-hop networks.

Therefore, in this thesis, we investigate the effect of data rate selection on power consumption in data transmission over IEEE 802.11-based wireless multi-hop networks. For this purpose, we give a detailed mathematical analysis of power consumption in multi-hop wireless data transmission. In the analysis, we consider detailed behaviors of the Carrier Sense Multiple Access with Collision Avoidance and the impact of interference from nodes out of the intended frame exchanges. In addition, we consider the various characteristics of IEEE 802.11 WLAN such as transmission power, data rate and transmission distance. We show numerical examples of the analysis results based on the specification of an existing IEEE 802.11 wireless LAN interface device and clarify the effect of data rate selection on energy efficiency. We also present that it is possible to decrease power consumption by intentionally choosing lower data rate when the nodes suffer the frequent interference.

Keywords

IEEE 802.11
CSMA/CA
wireless multi-hop networks
rate adaptation
power consumption

Contents

1 Introduction **6**

2 Related works **8**

3 Frame exchange sequences in IEEE 802.11 WLAN **9**

3.1 Frame exchange sequence using CSMA/CA with RTS/CTS frame 9

3.2 Impact of interference on frame exchange sequence 9

4 Power consumption analysis of data transmission **13**

4.1 Assumptions 13

4.2 Analysis of single-hop data transmission 13

4.2.1 Probability of interference occurrence 13

4.2.2 Additional time cased by interference occurrence 17

4.2.3 Power consumption 19

4.3 Analysis of multi-hop data transmission 20

5 Numerical evaluation **23**

5.1 Parameter settings 23

5.2 Numerical results and discussions 23

6 Conclusion and future work **33**

7 Acknowledgements **34**

Reference **35**

List of Figures

1 Frame exchange in CSMA/CA with RTS/CTS 11

2 Effect of interference on frame exchange 12

3 Network model for the analysis of single-hop transmission 14

4 Additional time cased by interference occurrence 16

5 Network model for the analysis of multi-hop transmission 22

6 Effect of retry limit on average transmission time for the single-hop transmission 25

7 Probability of successful data transmission with various retry limit 26

8 Transmission, reception, and idle times for r_a and r_b 28

9 Average power consumption in single-hop data transmission 29

10 Power consumption in multi-hop data transmission 31

11 Minimum hop count and maximum transmission distance with various data rates 32

List of Tables

1 Parameter settings 24
2 Maximum transmission distance and power of Cisco Aironet IEEE 802.11/a/b/g Wireless CardBus adapter [1] 24

1 Introduction

Internet access via wireless networks has become more popular due to the rapid development of wireless devices such as smartphones and tablet PCs. These devices are mostly battery-driven and wireless communication accounts for around 10-50 % of their total power consumption [2-4]. Therefore, decreasing the power consumption in wireless communication is an important issue, especially when considering wireless multi-hop networks such as sensor networks, ad hoc networks and wireless mesh networks in which energy efficiency is one of most important performance metric. In this thesis, we focus on the power consumption in wireless multi-hop networks based on IEEE 802.11 wireless LAN (WLAN), which is often used for implementing wireless multi-hop networks. The IEEE 802.11 WLAN standard has multiple data rates, each of which has various characteristics such as power consumption, modulation method, and maximum transmission distance. Rate adaptation (RA) techniques choose the data rate for achieving high network performance. Many RA algorithms have been proposed [5-9]. These algorithms are designed mainly for maximizing the throughput of applications and they do not focus on energy efficiency. In addition, these algorithms do not consider multi-hop networks. On the other hand, the authors in [10-15] present the mathematical analysis on the power consumption in data transmission over WLAN. However, those analyses do not take into account multi-hop networks. [16-19] consider the multi-hop networks but these do not mainly consider the power consumption but the network throughput. [20, 21] focus on the power consumption over wireless multi-hop networks, but they do not consider the effect of data rate selection.

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 networks, a shorter transmission distance may increase the total power consumption since the shorter transmission distance requires dense node distribution and increases the hop count between a sender and a destination. Using higher data rates can decrease the air time of a packet, which may in turn decrease the power consumption. However, higher data rates generally have a shorter maximum transmission distance, and thus may increase the hop count for data transmission. In contrast, a longer transmission distance decreases the hop count for data transmission but it requires more transmission power for single-hop transmission.

IEEE 802.11 WLAN employs carrier sense multiple access with collision avoidance (CSMA/CA).

Especially when request-to-send/clear-to-send (RTS/CTS) mechanism is utilized, the frame exchange sequence becomes complicated to estimate the power consumption. Furthermore, when considering the effect of interference from unintended nodes, the sequence becomes longer. However, to determine the optimal data rate for power consumption, we need to consider the above-mentioned complicated trade-off relationships as well as the effect of interference.

Therefore, in this thesis, we investigate the effect of data rate selection on power consumption in data transmission over IEEE 802.11-based wireless multi-hop networks. For this purpose, we give a detailed mathematical analysis of power consumption in multi-hop wireless data transmission. In the analysis, we consider the detailed behavior of the CSMA/CA and the impact of interference from unintended nodes. In addition, we also consider the various characteristics of IEEE 802.11 WLAN such as power consumption, data rate and transmission distance. We show numerical examples of the analysis results based on the specification of an existing IEEE 802.11 WLAN interface device and clarify the effect of data rate selection on energy efficiency in wireless multi-hop networks.

The rest of this thesis is organized as follows. In Section 2, we introduce related works on the data rate selection methods and performance analysis in IEEE 802.11 -based networks. We describe the details in the frame exchanges in IEEE 802.11 WLAN with and without the effect of interference from unintended client nodes in Section 3. In Section 4, we describe the mathematical analysis for power consumption in data transmission over IEEE 802.11-based multi-hop networks. In Section 5, we show numerical evaluations of the analysis results based on the specification of an existing WLAN interface device. Finally, in Section 6, we give our conclusions and discuss directions of future research.

2 Related works

There are many existing researches on control methods on IEEE 802.11 WLAN and IEEE 802.11-based multi-hop networks. For example, rate adaptation (RA) techniques choose the data rate for achieving a high network performance. Some papers have proposed many types of RA algorithms for single-hop transmission over WLAN. [5-9]. However, most of them only considered to improve the network or application throughput and do not consider the power consumption. In [22-27], the rate adaptation algorithm for IEEE 802.11-based multi-hop networks. However, they do not take the power consumption into account.

The analytical models and mathematical calculation for the perdormance of single-hop WLAN are presented in [10-15]. [28-30] conducted the simulations and experiments for evaluating the power consumption in multi-hop WLAN networks. [20] proposed three power management protocols which are directly applicable to IEEE 802.11-based mobile ad hoc networks (MANETs). [21] also considers to utilize the IEEE 802.11 power-saving (PS) mode for MANETs. They both utilize the PS mode in WLAN and propose to enhance the effectiveness of the PS mode in IEEE 802.11-based MANETs.

There are a few researches on reducing the power consumption for multi-hop WLAN by selecting the data rate in WLAN. In [31], a novel intelligent transmit power control (TPC) mechanism, called MiSer, is proposed, which is combined with RA algorithm. The proposed method can further reduce power consumption compared to the case where RA is applied without TPC. The authors in [32] consider the energy efficiency in IEEE 802.11-based multi-hop networks and propose the RA algorithm that each node determines the optimal rate for itself and cooperate with the neighboring nodes whether its rate is feasible.

These works mean that the rate adaptation can be applied to IEEE 802.11-based multi-hop networks for reducing the power consumption. However, they are not based on the mathematical analysis on the detailed behavior of the CSMA/CA.

3 Frame exchange sequences in IEEE 802.11 WLAN

In this section, we briefly introduce the frame exchange sequences for data transmission over IEEE 802.11 WLAN, required for the analysis in the next section. We first show the sequence without interference from unintended nodes, and explain how the interference affects the sequence.

3.1 Frame exchange sequence using CSMA/CA with RTS/CTS frame

Figure 1 illustrates the frame exchange sequence between two WLAN nodes, denoted by r_a (lower line) and r_b (upper line), using CSMA/CA with RTS/CTS when neither frame loss nor interference from other nodes occurs. The sequence starts at the left edge and progresses toward the right edge. In the figure, DIFS, SIFS and BO mean time durations for a distributed coordination function (DCF) interframe space, a short interframe space and a random backoff, respectively. RTS, CTS, DATA and ACK mean an RTS frame, a CTS frame, a data frame and an acknowledgement frame, respectively.

When a demand for a data frame transmission occurs at r_a, it transmits an RTS command frame to r_b after a DIFS and a BO. If r_b is not busy, it successfully receives the RTS frame. r_b then waits for an SIFS and transmits a CTS command frame to r_a. When r_a successfully receives the CTS frame, it begins to transmit a data frame after an SIFS. After r_b finishes receiving the data frame, it sends an ACK frame back to r_a after an SIFS. When r_a receives the ACK frame from r_b, the transmission of one data frame is completed.

3.2 Impact of interference on frame exchange sequence

The impact of interference on the frame exchange sequence varies depending on when the node (r_a or r_b) receives the interference signal from unintended nodes. In what follows, we call the nodes sending interference signals to r_a and r_b as interference nodes.

Here we assume that the radio wave can propagate equally to any directions, meaning that when a node r can transmit a frame to another node r', r' can successfully transmit a frame to r. Based on this bi-directional transmission assumption, we consider the possibility of interference among nodes as follows. When an RTS frame is sent from r_a, whose intended destination is r_b, it may be overheard by surrounding nodes. Then the surrounding nodes do not transmit any frames during the time called as network allocation vector (NAV) which is equivalent to the time recorded in the RTS frame. It means that the surrounding nodes cannot interfere the following frame exchange between r_a and r_b. Similarly, when the surrounding nodes overhear CTS frame which r_b transmits to r_a, they do not transmit any frames during the following frame exchanges between r_a and r_b. Therefore, assuming that the hidden node problem can be avoided by RTS/CTS mechanisms, the frame exchange between r_a and r_b is interfered only before the exchange of RTS and CTS frames finishes, and it is interfered only by RTS/CTS frames that surrounding nodes transmit.

Considering above-mentioned discussion, we consider three cases of the interference that affect the frame exchange between r_a and r_b. We depict the detailed sequences of the three cases in Figures 2(a), 2(b), and 2(c), respectively. In these figures, “interference” means the interference signal from interference nodes. On the first case in Figure 2(a), we show the case where r_a receives the interference signal when r_a transmits an RTS frame. This corresponds to the situation where the backoff timer expires while r_a receives the interference signal. Since r_a cannot transmit the RTS frame, it retries the transmission of an RTS frame after DIFS and random backoff.

Figure 2(b) for the second case shows the case where r_a successfully sends an RTS frame to r_b, but r_b cannot receive it since the interference signal is heard simultaneously. In this case, since r_b cannot transmit a CTS frame to r_a, r_a does not receive the CTS frame within the expected time. Therefore, r_a restarts the frame exchange from transmitting an RTS frame.

In Figure 2(c) for the third case, we show the case where r_a receives the interference signal when the CTS frame arrives. In this case, since r_a does not receive the CTS frame successfully, it restarts the frame exchange from the beginning.

In the next section, we show the analysis results of the power consumption in multi-hop data transmission considering the effect of interference described above.

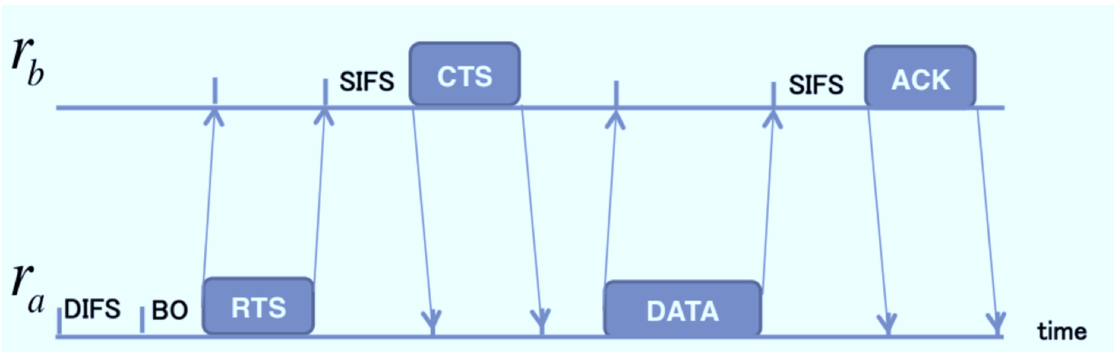
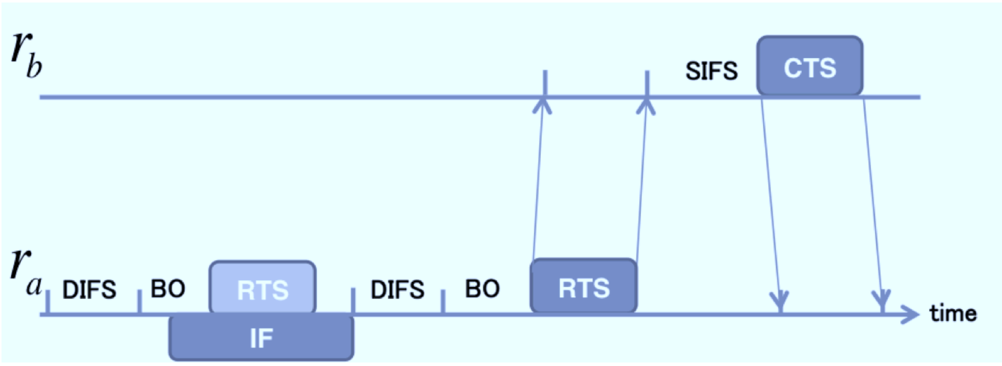
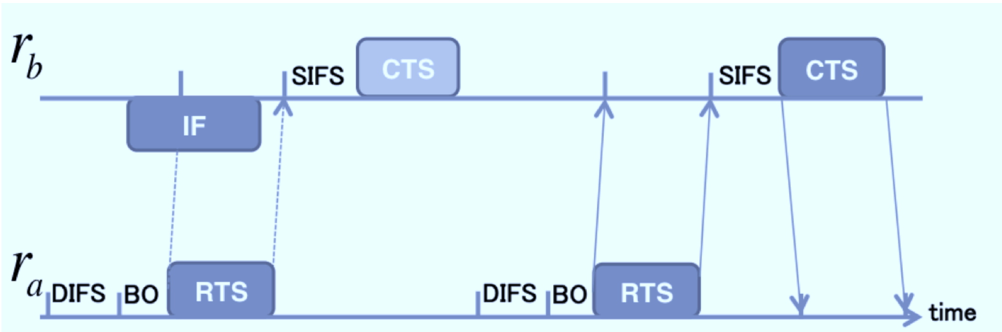


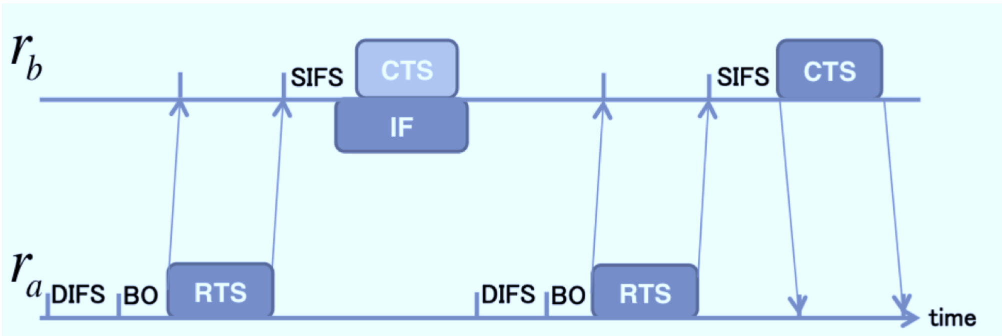
Figure 1: Frame exchange in CSMA/CA with RTS/CTS



(a) Interference when r_a transmits the RTS frame



(b) Interference while r_b receives the RTS frame



(c) Interference when r_b transmits the CTS frame

Figure 2: Effect of interference on frame exchange

4 Power consumption analysis of data transmission

In this section, we describe the analysis of power consumption in multi-hop data transmission over IEEE 802.11 WLAN. In Section 4.1, we summarize the assumptions in the analysis. We then show the power consumption analysis in single-hop data transmission in Section 4.2. Finally, we extend the analysis for applying to multi-hop transmission in Section 4.3.

4.1 Assumptions

Figure 3 shows the network model for a single-hop transmission from r_a to r_b, which considers the existence of interference nodes denoted by r. Here, we summarize the assumptions of the analysis. Data transmission between nodes is conducted by CSMA/CA with RTS/CTS. The frame transmissions by interference nodes occur independently. It also means that we do not consider the interactions among interference nodes. The interference signal from each interference node arrives at r_a and r_b following the Poisson arrival process. The distribution of interference signal length from each interference node follows the general distribution. Based on the above assumptions, the arrival process of the interference signals from each interference node can be modelled by M/G/∞ queueing system.

4.2 Analysis of single-hop data transmission

4.2.1 Probability of interference occurrence

In Figure 4(a), we show the case where r_a fails to transmit an RTS frame, which corresponds to the first case in Section 3.2. We assume that interference signal from each node to r_a follows the Poisson process whose arrival rate is λ_a and the interference signal length from each node to r_a follows the general distribution whose average is $1/\mu_a$. Then, since r_a can transmit the RTS frame when no interference signal is received just when the backoff duration ends, the probability is equal to the probability at which no customer exists in M/G/∞ queueing system whose arrival rate is λ_a and service rate is μ_a. Therefore, the probability at which r_a fails to transmit an RTS frame, denoted by $p_{t(\mathrm{RTS})}$, is

$$p_{t(\mathrm{RTS})} = 1 - e^{-\rho_a} \quad (1)$$

where $\rho_a = \lambda_a/\mu_a$.

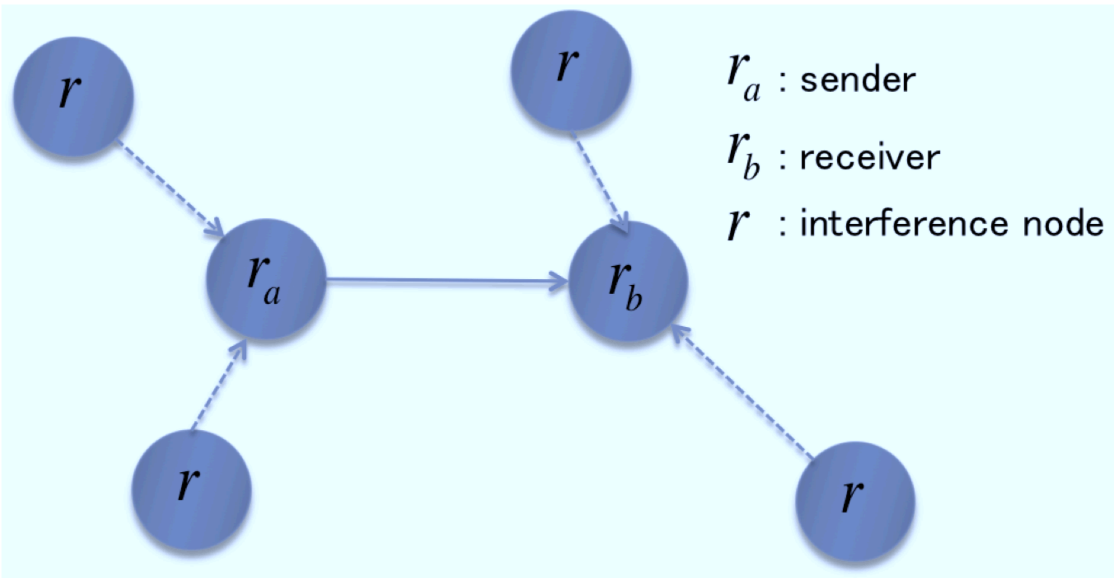


Figure 3: Network model for the analysis of single-hop transmission

Next, we show the second case where r_a successfully sends an RTS frame to r_b, but r_b cannot receive it because of the reception of the interference signal from each node, which is depicted in Figure 4(b). r_b fails to finish receiving the RTS frame from r_a if the interference signal arrives at r_b while it receives the RTS frame. We assume that interference signal from each node to r_b follows the Poisson process whose arrival rate is λ_b and the interference signal length from each node to r_b follows the general distribution whose average is $1/\mu_b$. Then, since r_b can receive the RTS frame when no interference signal is received while r_b receives the RTS frame, whose length is denoted by T_{RTS}, the probability is equal to the probability at which no customer exists for a period of T_{RTS} in M/G/∞ queueing system whose arrival rate is λ_b and service rate is μ_b. Therefore, the probability at which r_b fails to receive an RTS frame, denoted by $p_{r(\mathrm{RTS})}$, is

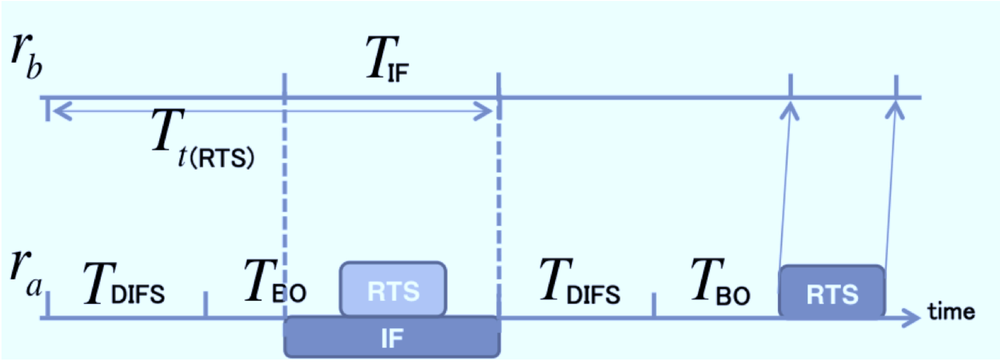
$$\begin{aligned} p_{r(\mathrm{RTS})} &= 1 - e^{-\lambda_b T_{\mathrm{RTS}}} \cdot e^{-\rho_b} \\ &= 1 - e^{-(\lambda_b T_{\mathrm{RTS}} + \rho_b)} \end{aligned} \tag{2}$$

where $\rho_b = \lambda b/\mu_b$.

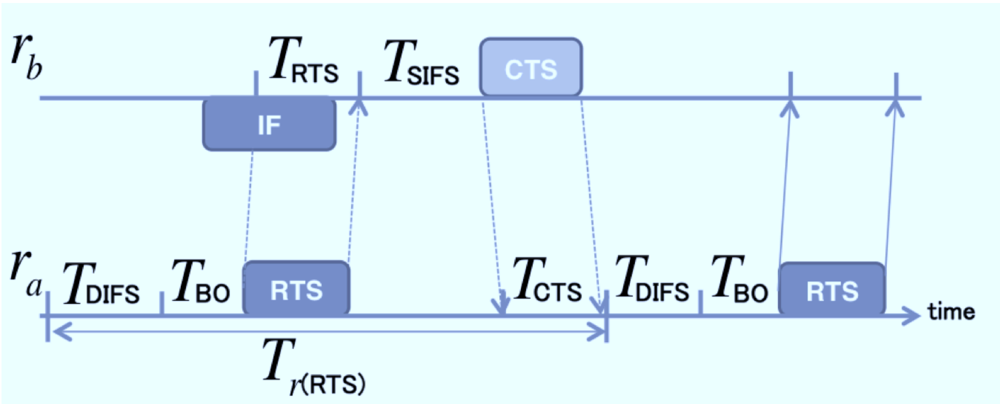
Finally, we show the third case, in which r_b successfully receives an RTS frame from r_b, but r_b cannot transmit a CTS frame. r_b fails to transmit the CTS frame to r_a if the interference signal is overheard when SIFS after receiving the RTS frame finishes. We assume that the ratio of nodes which cannot communicate with r_a but can communicate with r_b is α. Since r_b can transmit the CTS frame when no interference signal is received just when the SIFS duration ends, the probability is equal to the probability at which no customer exists in M/G/∞ queueing system whose arrival rate is $\alpha\lambda_b$ and service rate is μ_b. Therefore, the probability at which r_b fails to transmit a CTS frame, denoted by $p_{t(\mathrm{CTS})}$, is

$$p_{t(\mathrm{CTS})} = 1 - e^{-\alpha\rho_b} \tag{3}$$

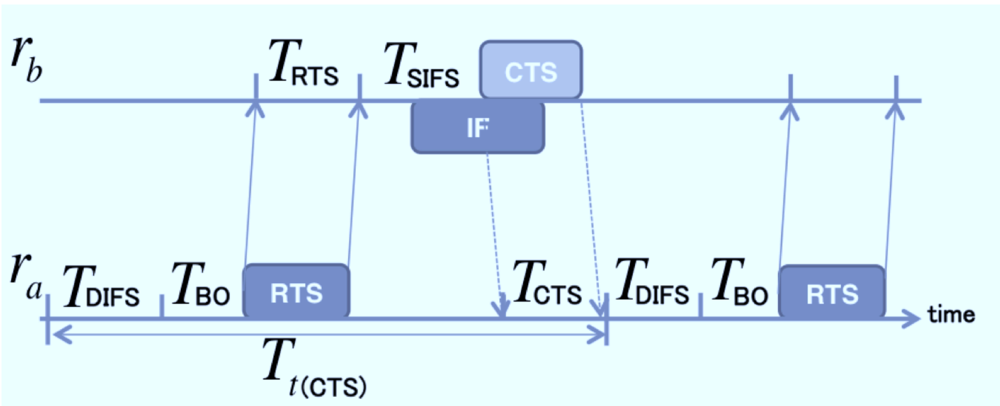
The data transmission from r_a to r_b is successfully conducted only when the above three cases do not occur during the transmission. When one of the cases occurs, r_a restart the sequence from the beginning of RTS frame transmission. The length of the sequence for the successful data transmission depends on how many times each of three cases happens during the entire sequence. Here, we define $P(i, j, k)$ as the probability at which the transmission succeeds with i time failures of the first case, j time failures of the second case, and k time failures of the third case. Then,



(a) Additional time in the case where r_a cannot transmit the RTS frame



(b) Additional time in the case where r_b cannot receive the RTS frame



(c) Additional time in the case where r_b cannot transmit the CTS frame

Figure 4: Additional time cased by interference occurrence

$P(i,j,k)$ can be calculated by using Equations (1), (2) and (3) as follows.

$$P(i,j,k) \;=\; p_{t(\mathrm{RTS})}^{i}(1-p_{t(\mathrm{RTS})})^{j+k+1}p_{r(\mathrm{RTS})}^{j}(1-p_{r(\mathrm{RTS})})^{k+1}p_{t(\mathrm{CTS})}^{k}(1-p_{t(\mathrm{CTS})}) \quad (4)$$

Note that $(i+j+k)$ should be less than retry limits [33], denoted by N.

4.2.2 Additional time cased by interference occurrence

We next consider the additional time when the frame exchange is interfered by the interference signal. Note that the backoff duration varies according to the number of retransmissions in one sequence. Therefore, we need to accommodate the change in the BO length in calculating the additional time.

First, we calculate the average backoff length. The backoff length on the l-th retransmission, denoted by $T_{\mathrm{BO}}(l)$, is calculated as

$$T_{\mathrm{BO}}(l) \;=\; W(l) \cdot T_{slot} \quad (5)$$

where T_{slot} is the slot time and $W(l)$ is chosen from a range of [0, CW_l] randomly, where CW_l is calculated as

$$CW_l = \min\left\{2^{l-1}(CW_{min}+1)-1, CW_{max}\right\} \quad (6)$$

Therefore, the average length of backoff duration on l-th retransmission, denoted by $\overline{T}_{\mathrm{BO}}(l)$, is

$$\overline{T}_{\mathrm{BO}}(l) \;=\; \frac{CW_l \cdot T_{slot}}{2} \quad (7)$$

Moreover, we take the propagation delay, denoted by T_{delay}, into consideration. T_{delay} is calculated by using the distance between r_a and r_b, denoted by L, and the speed of signal, denoted by V, as follows.

$$T_{delay} \;=\; \frac{L}{V} \quad (8)$$

In the first case in Figure 4(a), the additional time which is required because of the interference in l-th retransmission, denoted by $T_{t(\mathrm{RTS})}(l)$, can be obtained as follows.

$$T_{t(\mathrm{RTS})}(l) \;=\; T_{\mathrm{DIFS}} + T_{\mathrm{BO}}(l) + \frac{\overline{T}_{\mathrm{if}}}{2} \quad (9)$$

Here, T_{DIFS} is the length of a DIFS in unit of time and $\overline{T}_{\text{if}}$ is an average length of the interference signal. Similarly, in the second and third cases in Figure 4(b) and 4(c), the additional times for l-th retransmission, denoted by $T_{r(\text{RTS})}(l)$ and $T_{t(\text{CTS})}(l)$, respectively, are obtained as follows.

$$T_{r(\text{RTS})}(l) = T_{\text{DIFS}} + \overline{T}_{\text{BO}}(l) + T_{\text{RTS}} + T_{\text{SIFS}} + T_{\text{CTS}} + 2T_{delay} \tag{10}$$

$$T_{t(\text{CTS})}(l) = T_{\text{DIFS}} + \overline{T}_{\text{BO}}(l) + T_{\text{RTS}} + T_{\text{SIFS}} + T_{\text{CTS}} + 2T_{delay} \tag{11}$$

where T_{SIFS} is the length of SIFS and T_{RTS} and T_{CTS} are the lengths of an RTS frame and a CTS frame in unit of time, respectively. To simplify the equations, we divide $T_{t(\text{RTS})}(l)$, $T_{r(\text{RTS})}(l)$ and $T_{t(\text{CTS})}(l)$ into the backoff part and the other part.

$$T_{t(\text{RTS})}(l) = T_{w_1} + \overline{T}_{\text{BO}}(l) \tag{12}$$

$$T_{r(\text{RTS})}(l) = T_{w_2} + \overline{T}_{\text{BO}}(l) \tag{13}$$

$$T_{t(\text{CTS})}(l) = T_{w_3} + \overline{T}_{\text{BO}}(l) \tag{14}$$

where

$$T_{w_1} = T_{\text{DIFS}} + \frac{\overline{T}_{\text{if}}}{2} \tag{15}$$

$$T_{w_2} = T_{\text{DIFS}} + T_{\text{RTS}} + T_{\text{SIFS}} + T_{\text{CTS}} + 2T_{delay} \tag{16}$$

$$T_{w_3} = T_{w_2} \tag{17}$$

Using Equations (4), (12), (13) and (14), we calculate the total length of time required for data transmission with i, j and k time failures of the first, second, and third cases, respectively, as follows.

$$T(i,j,k) = iT_{w_1} + jT_{w_2} + kT_{w_3} + \sum_{l=0}^{i+j+k} \overline{T}_{\text{BO}}(l) + T_{\text{DATA}} + T_{\text{ACK}} + 2T_{delay} \tag{18}$$

where T_{DATA} and T_{ACK} are the lengths of a data frame and an ACK frame, respectively, in unit of time. Here, we divide Equation (18) into transmission, reception, and idle parts for r_a as follows.

$$T_{snd}^{r_a}(i,j,k) = (j+k)T_{\text{RTS}} + T_{\text{DATA}} \tag{19}$$

$$T_{rcv}^{r_a}(i,j,k) = T_{\text{ACK}} + \frac{i}{2}T_{\text{if}} \tag{20}$$

$$\begin{aligned} T_{idle}^{r_a}(i,j,k) &= (i+j+k)T_{\text{DIFS}} + (j+k)(T_{\text{cts}} + T_{\text{SIFS}}) \\ &\quad + \sum_{l=0}^{i+j+k} \overline{T}_{\text{BO}}(l) + (j+k+2)T_{delay} \end{aligned} \tag{21}$$

Similarly, transmission, reception, and idle parts for r_b can be represented as follows.

$$\begin{aligned}
T^{r_b}_{snd}(i,j,k) &= T_{\mathrm{ACK}} + T_{\mathrm{CTS}} &(22)\\
T^{r_b}_{rcv}(i,j,k) &= kT_{\mathrm{RTS}} + T_{\mathrm{DATA}} &(23)\\
T^{r_b}_{idle}(i,j,k) &= jT_{\mathrm{RTS}} + (j+k)(T_{\mathrm{cts}} + T_{\mathrm{SIFS}}) + (i+j+k)T_{\mathrm{DIFS}} \\
&\quad + \frac{i}{2}T_{\mathrm{if}} + \sum_{l=0}^{i+j+k} \overline{T}_{\mathrm{BO}}(l) + (j+k+2)T_{delay} &(24)
\end{aligned}$$

Note that Equations (19)-(24) are unfolded by using Equations (15)-(17). Finally, we obtain $T_{suc}(N)$, the average time for the transmission from r_a to r_b with N of retry limit, by using Equations (4) and (18).

$$T_{suc}(N) = \sum_{i=0}^{N}\sum_{j=0}^{N-i}\sum_{k=0}^{N-i-j}\left(\frac{(i+j+k)!}{i!j!k!}P(i,j,k)T(i,j,k)\right) \tag{25}$$

4.2.3 Power consumption

The power consumption in the entire sequence of the data transmission is given by the sum of multiplying the power and the time duration for each of transmission, reception and idle parts of the sequence. The transmission, reception, and idle powers are denoted by J_{snd}, J_{rcv}, and J_{idle}, respectively, The power consumption of r_a required for data transmission with i, j, and k time failures of the first, second, and third cases, respectively, denoted by $Q^{r_a}(i,j,k)$, can be obtained as follows.

$$Q^{r_a}(i,j,k) = T^{r_a}_{snd}(i,j,k)J_{snd} + T^{r_a}_{rcv}(i,j,k)J_{rcv} + T^{r_a}_{idle}(i,j,k)J_{idle} \tag{26}$$

Therefore, we obtain the average power consumption of r_a in the single-hop data transmission from r_a to r_b, denoted by $Q^{r_a}(N)$, as follows.

$$Q^{r_a}(N) = \sum_{i=0}^{N}\sum_{j=0}^{N-i}\sum_{k=0}^{N-i-j}\left(\frac{(i+j+k)!}{i!j!k!}P(i,j,k)Q^{r_a}(i,j,k)\right) \tag{27}$$

Similarly, we compute the power consumption of r_b, denoted by $Q^{r_b}(i,j,k)$ and $Q^{r_b}(N)$, as follows.

$$\begin{aligned}
Q^{r_b}(i,j,k) &= T^{r_b}_{snd}(i,j,k)J_{snd} + T^{r_b}_{rcv}(i,j,k)J_{rcv} + T^{r_b}_{idle}(i,j,k)J_{idle} &(28)\\
Q^{r_b}(N) &= \sum_{i=0}^{N}\sum_{j=0}^{N-i}\sum_{k=0}^{N-i-j}\left(\frac{(i+j+k)!}{i!j!k!}P(i,j,k)Q^{r_b}(i,j,k)\right) &(29)
\end{aligned}$$

4.3 Analysis of multi-hop data transmission

Figure 5 shows the network model for a multi-hop transmission from r_a to r_b. r_r is a relay node and r is an interference node. We now calculate the power consumed in the entire data transmission process over the multi-hop networks. The IEEE 802.11 WLAN standard has multiple data rates, each of which has different values for maximum transmission distance and the maximum transmission power. They largely affect the power consumption of multi-hop transmission since the hop count between sender and receiver nodes is highly dependent of the transmission power. We assume that when determine the distance for single-hop transmission, we place the relay node to realize the hop distance and calculate the power consumption. This is required for focusing on the effect of the hop count on the power consumption.

Here, the transmission power and transmission distance of the m-th data rate are denoted by $J_{snd}^{(m)}$ and $L^{(m)}$, respectively. We also introduce the maximum transmission power and the maximum transmission distance at the m-th data rate, denoted by $\hat{J}_{snd}^{(m)}$ and $\hat{L}^{(m)}$, respectively. We assume that when a data frame is transmitted with less than the maximum power, the transmission distance becomes shorter according to the following equation [34-36].

$$L^{(m)} = \hat{L}^{(m)} \cdot \left(\frac{J_{snd}^{(m)}}{\hat{J}_{snd}^{(m)}} \right)^{\frac{1}{\gamma}} \tag{30}$$

where γ is the parameter which describes the attenuation. We also denote the hop count between r_a and r_b as h and the distance of each relay node as L_1, L_2, ..., L_h. The propagation delay of n-th hop transmission, denoted by $T_{delay}(n)$, is

$$T_{delay}(n) = \frac{L_n}{V} \tag{31}$$

We apply the propagation delay in Equation (31) to all frame transmissions described in Section 3. We consider that it affects the length of idle time in the sequence. Then, we calculate the length of time in the entire data transmission process considering the distance between the nodes, denoted by $Ts_{idle}(i,j,k,n)$ and $T^{r}_{idle}(i,j,k,n)$, as follows.

$$T^{s}_{idle}(i,j,k,n) = (i+j+k)T_{\mathrm{DIFS}} + (j+k)(T_{\mathrm{cts}} + T_{\mathrm{SIFS}}) + \sum_{l=0}^{i+j+k} \overline{T}_{\mathrm{BO}}(l) + (j+k+2)T_{delay}(n) \tag{32}$$

$$T^{r}_{idle}(i,j,k,n) = jT_{\mathrm{RTS}} + (j+k)(T_{\mathrm{cts}} + T_{\mathrm{SIFS}}) + (i+j+k)T_{\mathrm{DIFS}} + \frac{i}{2}T_{\mathrm{if}} + \sum_{l=0}^{i+j+k} \overline{T}_{\mathrm{BO}}(l) + (j+k+2)T_{delay}(n) \tag{33}$$

Therefore, the average time for sender and receiver nodes in the data transmission from r_a to r_b, denoted by $T^{s}_{mul}(i,j,k)$ and $T^{r}_{mul}(i,j,k)$, are calculated as follows.

$$T^{s}_{mul}(i,j,k) = \sum_{n=1}^{h} \left(T^{r_a}_{snd}(i,j,k) + T^{r_a}_{rcv}(i,j,k) + T^{s}_{idle}(i,j,k,n) \right) \tag{34}$$

$$T^{r}_{mul}(i,j,k) = \sum_{n=1}^{h} \left(T^{r_b}_{snd}(i,j,k) + T^{r_b}_{rcv}(i,j,k) + T^{r}_{idle}(i,j,k,n) \right) \tag{35}$$

Then, the power consumption of the n-th hop transmission with i, j, and k time failures of the first, second, and third cases, respectively, denoted by $Q^{s}(n,N)$ and $Q^{r}(n,N)$, can be obtained as follows.

$$Q^{s}_{mul}(n,N) = \left(T^{r_a}_{snd}(j,k)J^{(m)}_{snd}(\gamma) + T^{r_a}_{rcv}(i)J_{rcv} + T^{r_a}_{idle}(i,j,k,n)J_{idle} \right) \tag{36}$$

$$Q^{r}_{mul}(n,N) = \left(T^{r_b}_{snd}J^{(m)}_{snd}(\gamma) + T^{r_b}_{rcv}(k)J_{rcv} + T^{r_b}_{idle}(i,j,k,n)J_{idle} \right) \tag{37}$$

Finally, the average power consumption in the multi-hop data transmission from r_a to r_b, denoted by $Q_{mul}(N)$, is computed by using $Q^{s}_{mul}(N)$ and $Q^{r}_{mul}(N)$, which are sum of power consumption in sender and receivers nodes, respectively, in data transmission between r_a and r_b, as follows.

$$Q^{s}_{mul}(N) = \sum_{n=1}^{h} \left\{ \sum_{i=0}^{N} \sum_{j=0}^{N-i} \sum_{k=0}^{N-i-j} \left(\frac{(i+j+k)!}{i!j!k!} P(i,j,k) Q^{r_b}_{mul}(i,j,k,n) \right) \right\} \tag{38}$$

$$Q^{r}_{mul}(N) = \sum_{n=1}^{h} \left\{ \sum_{i=0}^{N} \sum_{j=0}^{N-i} \sum_{k=0}^{N-i-j} \left(\frac{(i+j+k)!}{i!j!k!} P(i,j,k) Q^{r_b}_{mul}(i,j,k,n) \right) \right\} \tag{39}$$

$$Q_{mul}(N) = Q^{s}_{mul}(N) + Q^{r}_{mul}(N) \tag{40}$$

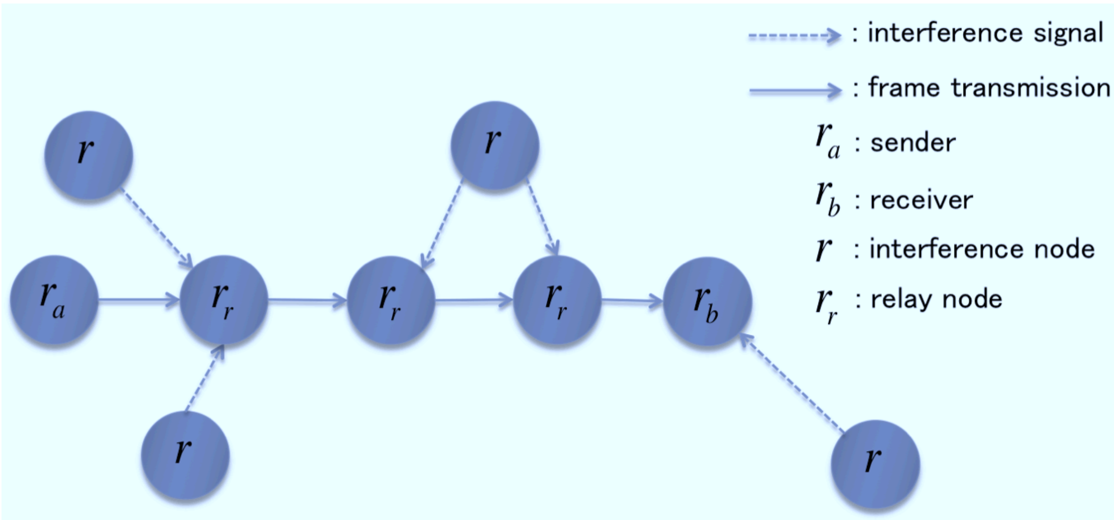


Figure 5: Network model for the analysis of multi-hop transmission

5 Numerical evaluation

5.1 Parameter settings

We set the distance L between the sender and the receiver to $1,000$ [m] and the speed of signal V to $300,000$ [km/s]. As the parameters for determining the backoff time in Equation (6), we set CW_{min} to 15 and CW_{max} to 2^{10}. The parameter α in Equation (3) is set to 1 and γ in Equation (30) is set to 2. Frame sizes and other IEEE 802.11 parameters are listed in Table 1. We utilize the specifications of a Cisco Aironet IEEE 802.11 a/b/g Wireless CardBus adapter [1], summarized in Table 2 for the maximum transmission distance and corresponding power of each data rate. In what follows, we set the sending power J_{snd} to variois values, and the receiving power and idle power are set to $J_{snd}/1.7$ and $J_{snd}/2.7$, respectively, according to the reports in [1, 37].

5.2 Numerical results and discussions

Figure 6 shows the effect of retry limit, denoted by N, on the average time for the single-hop transmission when we set the data rate to 11 [Mbps]. In this figure, x is denoted the interference ratio, determined by λ_a and μ_a for r_a and λ_b and μ_b for r_b. In this analysis, we assume that there are interference nodes sufficiently, that is, $x = \lambda_a/\mu_a = \lambda_b/\mu_b$. When the interference ratio is small, the average time for the single-hop transmission does not increase when $N \geq 2$. This is because most of the transmission can be finished with two or less retransmissions. Similarly, when $0.3 \leq x \leq 0.7$, the average transmission time does not increase in the case where N is greater than around 15. However, when the interference ratio is high, the average time continues to increase as N increases up to 30. This is because many retransmissions are required under such a heavy interference environment.

In Figure 7 we show the probability of a successful data transmission as a function of the interference ratio with various values of retry limit when we set the data rate to 11 [Mbps]. We can see from this figure that the probability of the successful data transmission can be increased simply by setting N to a larger value. However, we also confirm that we need not to set N larger than 20 since the probability of the successful data transmission becomes unchanged with larger value of N. In the following results, therefore, we set N to 20.

Figure 8 piles up the transmission, reception, and idle time in single-hop data transmission for r_a (Figure 8(a)) and r_b (Figure 8(b)) when we set the data rate to 11 [Mbps]. The values can be

Table 1: Parameter settings

item	value
S_{ACK}	40 [bytes]
S_{RTS}	40 [bytes]
S_{CTS}	40 [bytes]
T_{DIFS}	34 [μs]
T_{SIFS}	16 [μs]
T_{slot}	9 [μs]

Table 2: Maximum transmission distance and power of Cisco Aironet IEEE 802.11/a/b/g Wireless CardBus adapter [1]

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

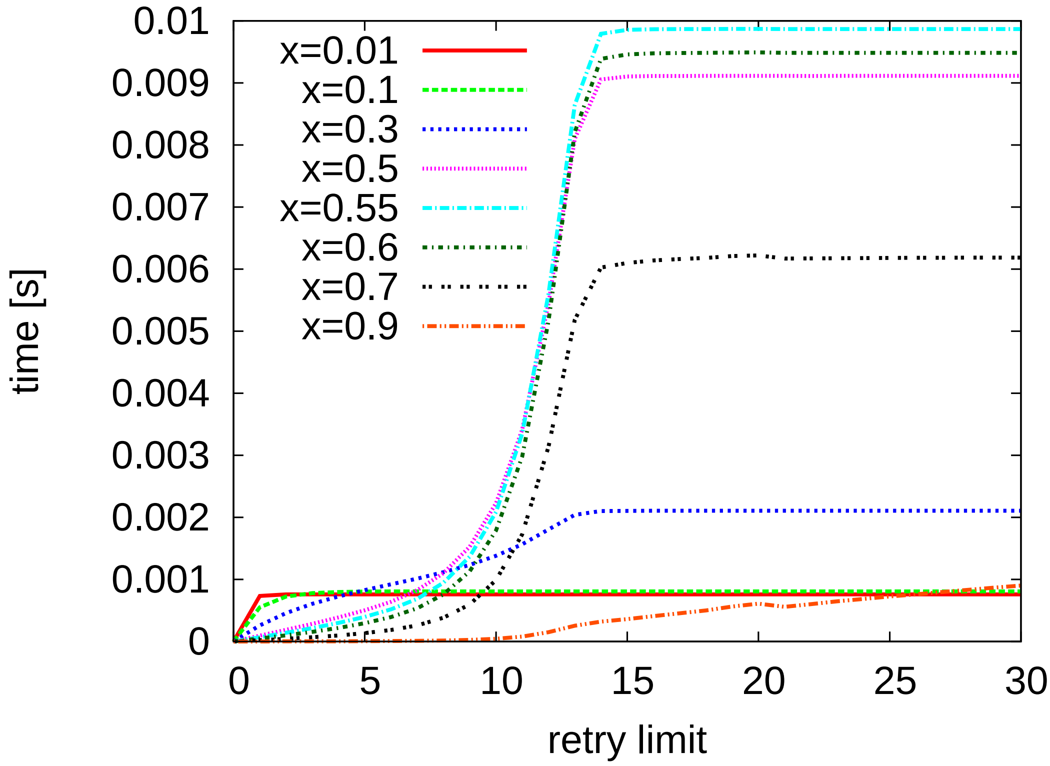


Figure 6: Effect of retry limit on average transmission time for the single-hop transmission

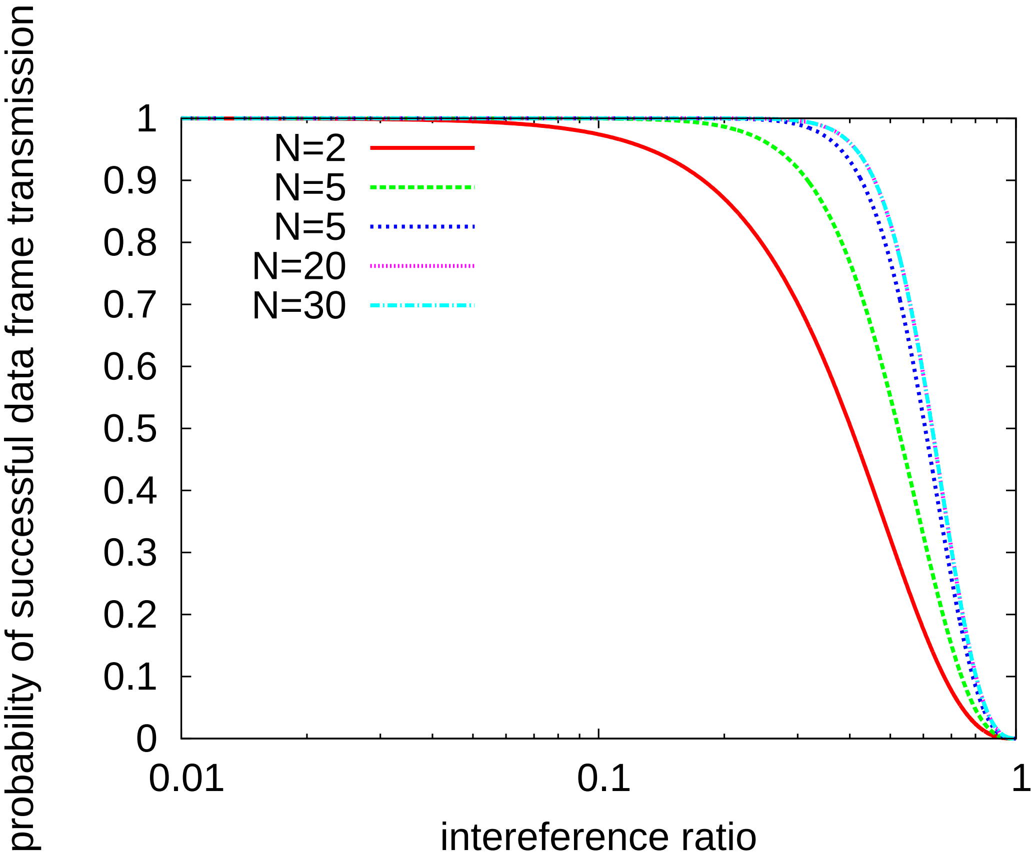
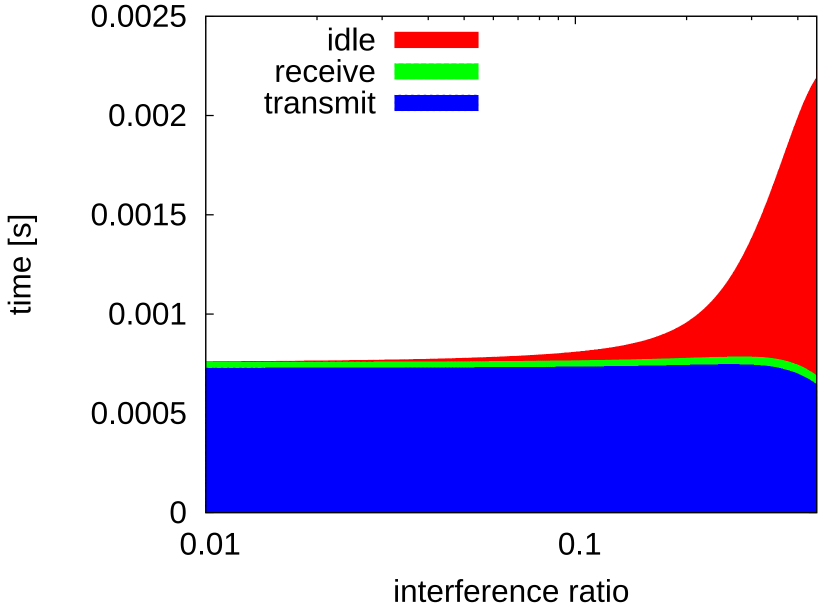


Figure 7: Probability of successful data transmission with various retry limit

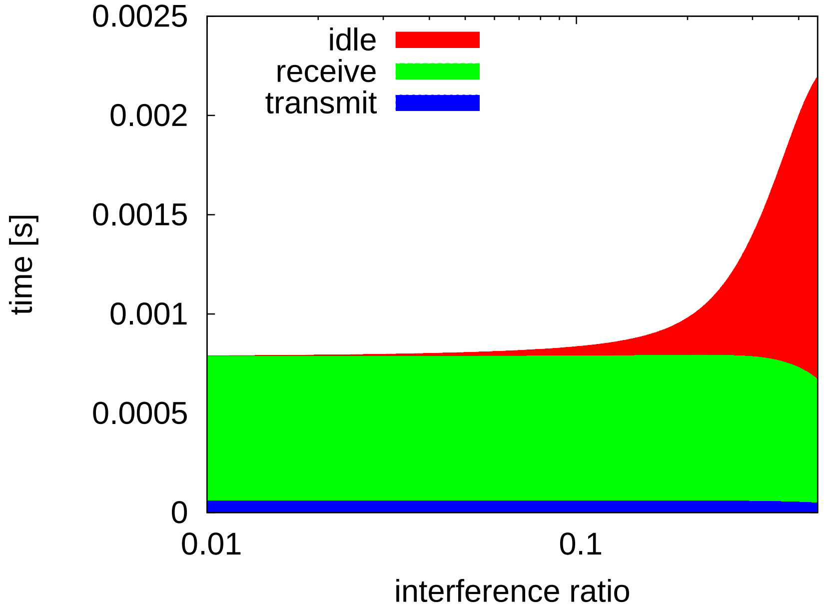
obtained by Equations (19)-(21) and (22)-(24) for r_a and r_b, respectively. When the interference ratio is high, the total length of time required for data transmission increases because the number of retransmissions increases. However, the transmission and reception time decrease when the interference ratio is quite high. This is because the number of retransmissions reaches the retry limit and r_a gives up transmitting the data.

In Figure 9, we plot the average power consumption in single-hop data transmission with 20 [mW] of the transmission power. We can see from this figure that power consumption can be decreased simply by using a higher data rate. Since the transmission power is fixed, J_{snd}, J_{rcv}, and J_{idle} in Equations (26) and (28) are also fixed. Therefore, in these equation, the power consumption is affected mainly by the lengths of time required for data transmission which is determined by the used data rate.

Figure 10 shows the power consumption in multi-hop data transmission between r_a and r_b. The transmission power is fixed to 20 [mW] in Figure 10(a) and the distance of each hop is fixed to 76 [m] in Figure 10(b). We can see from these figures that the relationships between the data rate and the power consumption becomes opposite when the interference ratio becomes high. In general, the higher data rate can reduce the air time and resulting the power consumption for transmitting a frame. However, it requires more hop count between sender and receiver because a higher data rate has a shorter maximum transmission distance as shown in Table 2. For confirming this, we present Figure 11(a), which plots the minimum hop count for the multi-hop transmission between r_a and r_b as a function of transmission power with various data rates. Furthermore, since the number of retransmissions increases by increasing the interference ratio, using higher data rate requires more hop count and larger power consumption. Similarly, in Figure 10(b), we can see the reversal of power consumption relationships among various data rates when the interference ratio is high. Comparing Figures 10(a) and 10(b), we can see that the relationships on power consumption becomes opposite at smaller interference ratio in Figure 10(b). It means that the greater effect of interference ratio on the power consumption is obtained when the distance of 1 hop is fixed than that when the transmission power is fixed. The reason for this is as follows. The higher data rate generally requires larger transmission power to transmit at a distance because a ratio of the maximum transmission power to the maximum transmission distance is smaller in the higher data rate in Table 2. In Figure 11(b), we plot the maximum transmission distance for confirming the relationships between the transmission power and the maximum transmission



(a) r_a



(b) r_b

Figure 8: Transmission, reception, and idle times for r_a and r_b

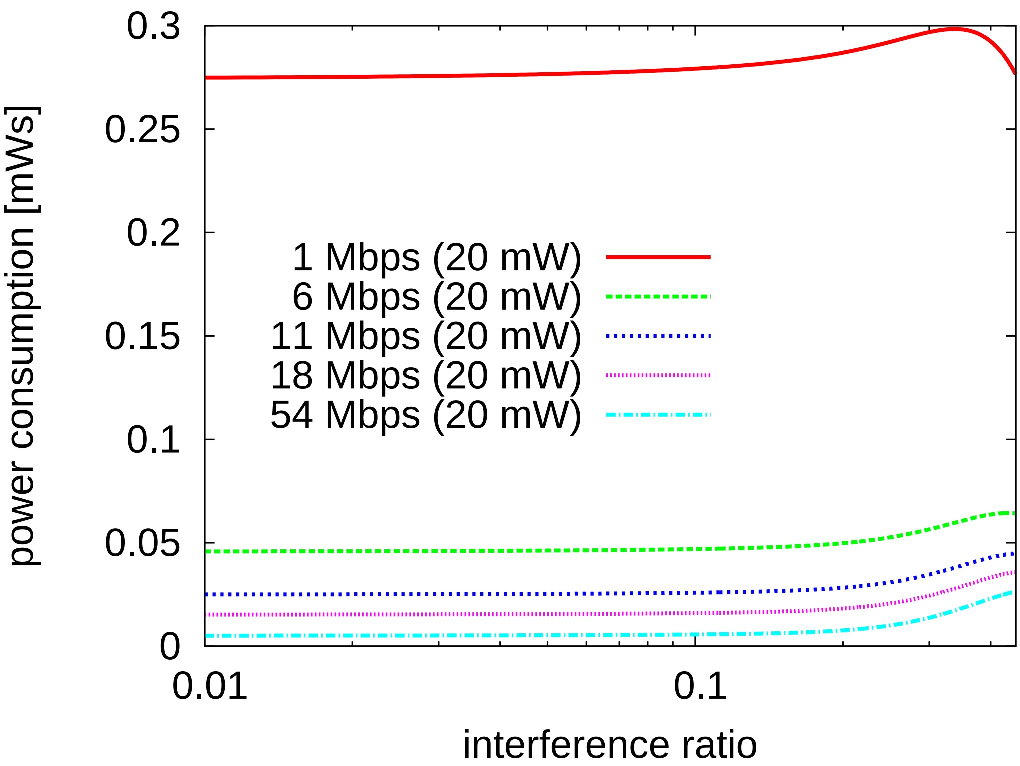
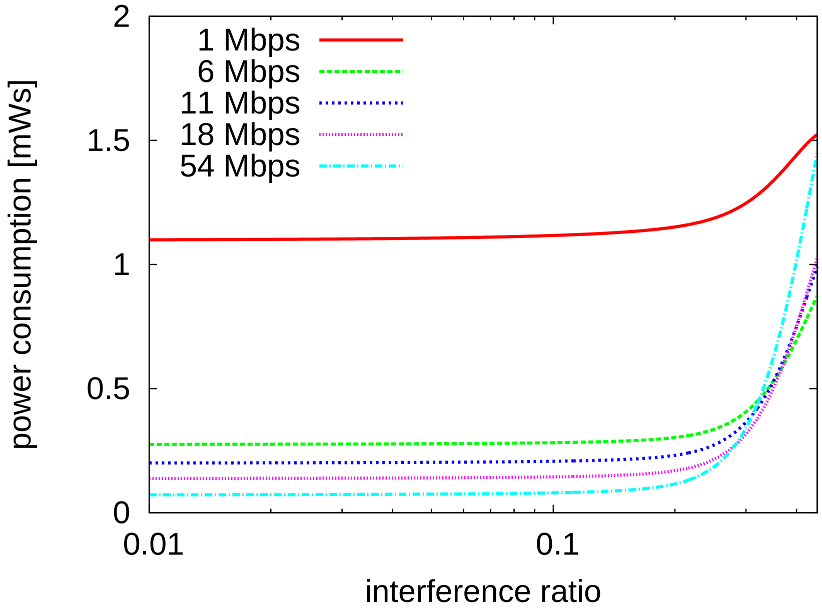
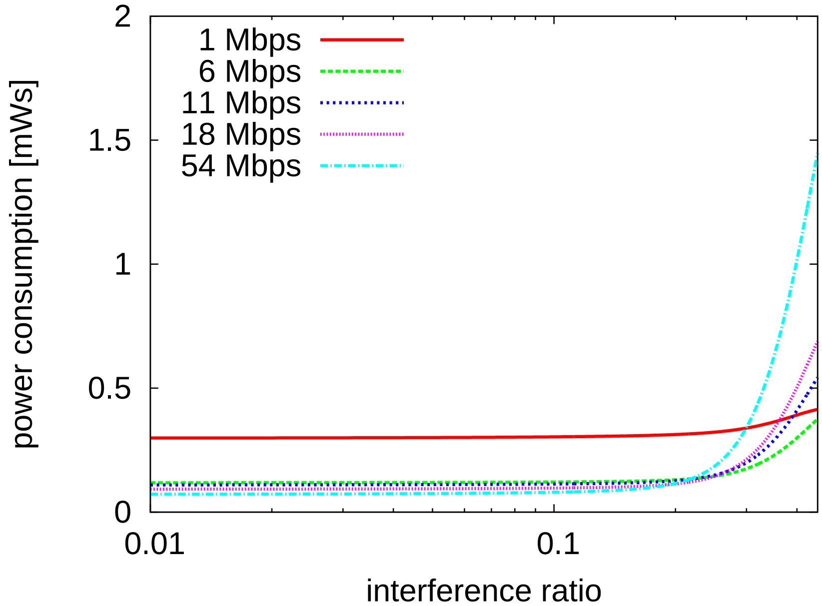


Figure 9: Average power consumption in single-hop data transmission

distance. Since the number of retransmissions increases by increasing the interference ratio, the higher data rate which requires more transmission power is also greatly affected. Note that these results differ from Figure 9, where higher data rates always small power consumption regardless of the interference ratio. This is because the hop count and the transmission power affect the power consumption for multi-hop data transmission.

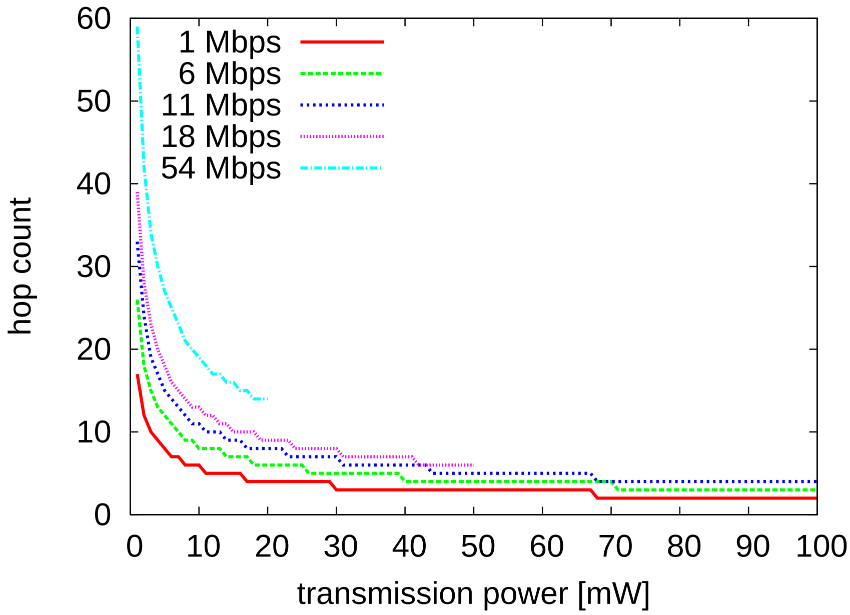


(a) Case where transmission power is fixed to 20 [mW]

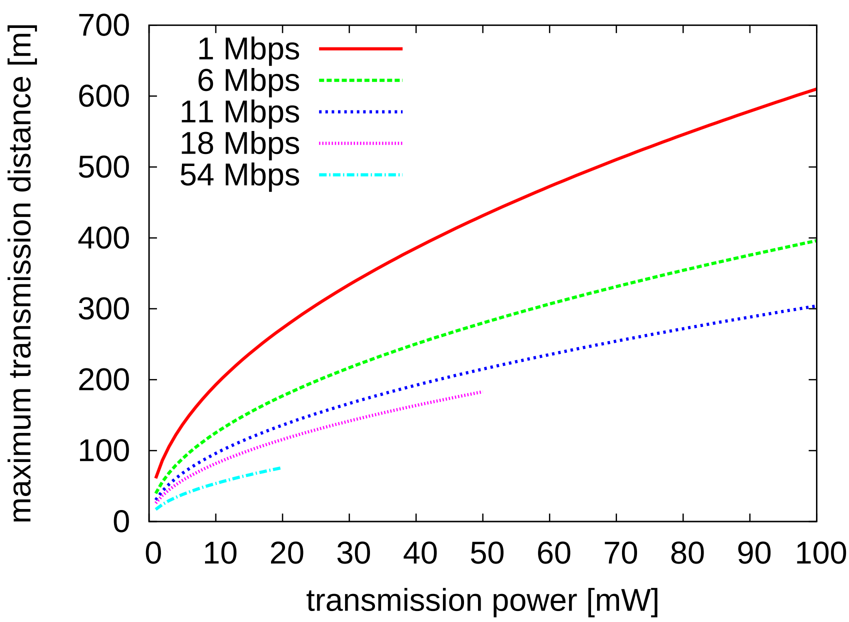


(b) Case where 1 hop distance is fixed to 76 [m]

Figure 10: Power consumption in multi-hop data transmission



(a) Minimum hop count



v

(b) Maximum transmission distance

Figure 11: Minimum hop count and maximum transmission distance with various data rates

6 Conclusion and future work

In this thesis, we presented 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 and transmission power on energy efficiency. We considered the detailed behavior of the CSMA/CA and the the effect of the interference in this analysis. The analysis revealed that power consumption can be decreased by intentionally selecting a lower data rate when the interference ratio is high. It is also revealed that the transmission power is more critical than the transmission distance for reducing the power consumption in the multi-hop data transmission.

For future work, we plan to conduct simulation experiments to accuracy of the analysis. We also plan to extend the analysis to include the effect of upper-layer protocols such as TCP. Moreover, we will propose a rate adaptation algorithm for reducing the power consumption which is considered the network environment.

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