A Dynamic Rate Adaptation with Fragmentation MAC Protocol against Channel Variation for Wireless LANs*

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Abstract

The paper proposes a fragment and rate matching (FaRM) MAC protocol for wireless local area networks (LANs) to resist the frequent changing of channel quality and increase the network throughput. In wireless environments, channel quality varies with time. FaRM dynamically detects the current SNR to estimate the channel quality through the control frame exchanges. A Finite State Markov Chain (FSMC) is adopted to predict the variation of the channel condition. According to the results generated from FSMC, FaRM enables a station to select an appropriate transmission rate as well as an acceptable fragment length dynamically to transmit in order to both increase the reliability and shorten the channel access time of the transmission. The simulation results show FaRM has better performance, higher transmission reliability, and lower transmission delay time by fragment and rate matching.

1. Introduction

Wireless medium is much unreliable compared with the wired medium due to its open nature. Therefore, an estimator to estimate the channel quality and an predictor to predict the channel quality are very important for wireless transmission. Basically, the channel quality is estimated by the received signal strength against the background noise, which is usually represented by the signal-to-noise ratio (SNR). In general, the higher the SNR is, the higher a transmission is probable to be succeeded.

IEEE 802.11 a, b, and g provide several data transfer rates, which allows dynamic rate switching to improve the performance. However, the higher the data transfer rate is, the higher the bit error ratio (BER[1]) may result in. It implies the stricter the SNR requires in a high data transfer rate.

On the other hand, fragmentation is often used to enhance the transmission reliability while the channel condition is bad. Fragmentation is a process of fragmenting a long frame, e.g. MAC service data unit (MSDU) or a MAC management protocol data unit (MMPDU), into shorter MAC level frames, MAC protocol data units (MPDUs). It is well known that a long frame has a low overhead and is efficient from the viewpoint of the network utilization. However, it suffers a high risk of collision or failure due to the long channel access time. Therefore, a long frame is advantageous when the BER is relatively low.

Therefore, adaptive rate switching and dynamic fragmentation are worth carefully being considered, especially for wireless LANs (WLANs) due to the limited bandwidth and varied channel condition. The paper proposes a MAC scheme, named FaRM (Fragment and Rate Matching), which takes adaptive rate switching as well as dynamic fragmentation scheme into consideration to instantly resist the channel variations and best utilize the channel bandwidth. Consequently, throughput and reliability in FaRM can be improved by using the most suitable data transfer rate and the fragment length. The rest of the paper is organized as follows. Section 2 introduces the related work. The basic concepts and the design flow of FaRM are described in Section 3. Channel quality prediction and frames length determination involved in the design flow of FaRM are

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[1]BER is defined as the error probability that a bit is received, also known as bit error probability (BEP).

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explained in Section 4. Section 5 presents the details of FaRM. Section 6 describes the simulation environment as well as settings and illustrates the simulation results. Section 7 concludes the paper.

2. Related Work

Adaptive rate switching and dynamic fragmentation are feasible solutions to resist the channel variation and increase or at least preserve the network performance in a time-varying wireless environment. In recent years, many researchers devote themselves to investigating adaptive rate switching in order to improve the efficiency of the channel utilization and increase the network throughput [1–7, 9, 11].

Automatic Rate Fallback (ARF) [4] is a well-known rate adaptation scheme. In ARF, rate switching is based on tracking the number of missed ACK frames in a time period. However, the threshold setting of the missed ACK frames impacts on the performance of ARF. Moreover, whether a transmission of a packet is successful depends on the packet length, which is not considered by ARF.

A protocol similar to ARF is proposed in [1]. In [1], several thresholds are cooperated to react the variation of channel quality. The protocol can reduce the overhead of frequent change among different data transfer rates. However, it can not react against channel variation immediately and may have the risk of oscillation in stable conditions. As a result, SNR-based rate adaptation schemes are proposed to improve the sensitivity to changes in channel conditions, such as RBAR [3], OAR [9], and so on.

RBAR (Receiver Based Auto Rate) [3] obtains the channel quality by the RTS/CTS handshaking. While receiving an RTS, the receiver will determine a suitable transfer rate and piggyback this information in the CTS. Since the transfer rate is not indicated in the RTS, RBAR adds a reservation subheader (RSH) field in front of the DATA frame to re-announce the duration of the transmission by the sender.

OAR (Opportunistic Auto Rate) [9] is an SNR-based rate adaptation scheme, which improves RBAR. The main concept of OAR is to opportunistically send multiple frames whenever the channel quality is good. OAR operates on the transmission of a fragment burst containing multiple frames, instead of a frame dividing into several fragments.

RRAA (Robust Rate Adaptation Algorithm) [11] is another SNR-based rate adaptation scheme. The concept of RRAA is to combine the selective RTS/CTS scheme with frame error rate (FER) threshold-based scheme. However, frame length in RRAA is not cosindered.

A frame suffers a high transmission error probability if the length of the frame is long. In [5], the authors proposed a dynamical fragmentation protocol, denoted as D-Frag protocol in this paper, to dynamically fragment the data frames according to the channel conditions. D-Frag protocol is similar to RBAR and OAR. However, D-Frag protocol transmits a long frame, instead of transmitting multiple frames with a high transfer rate, to reduce the fragmentation overhead while the channel condition is good. Moreover, the fragment size is adjustable according to the channel condition obtained from the preceding fragment transmission. Nevertheless, D-Frag, like OAR, does not consider the channel variation in the latter fragments. Transmission error may happen at the following fragments.

As mentioned above, higher data transfer rate or longer frame length cause a frame a higher transmission error probability. However, most of the previous researches emphasize much on how to adjust an appropriate transfer rate in order to adapt to the channel variation and obtain better performance. Nevertheless, frame length is not taken into account in these researches.

3. Basic Concepts and Design Flow of FaRM

Figure. 1 illustrates the design flow of FaRM. Basically, the design flow of FaRM includes five steps: *Channel Quality Estimation*, *SNR-to-BER Conversions*, *Channel Quality Prediction*, *Fragment Length Determination*, and *Like Adaptive Fragment and Rate Matching*. Firstly, a receiver receiving an RTS triggers the procedures. In *Channel Quality Estimation* step, FaRM estimates the current channel condition in terms of SNR value by received frames. According to the conversion from SNR to BER [8], in *SNR-to-BER Conversions* step, the SNR obtained from the previous step will be converted to several BER values, each for different data transfer rates. Suppose n data transfer rates are supported.As a result, there are n different BERs after the *SNR-to-BER Conversions* step, say BER_1, ..., BER_n, each respectively corresponding to different transfer rates. For some SNR value, the higher the data transfer rate is, the higher the BER incurs. Under some SNR value, a transmission will incur a higher BER if it is transmitted in a higher data transfer rate.

However, BER can not reflect the continuous variation of channel quality for the following transmissions. Therefore, a fading channel model to predict the chan-

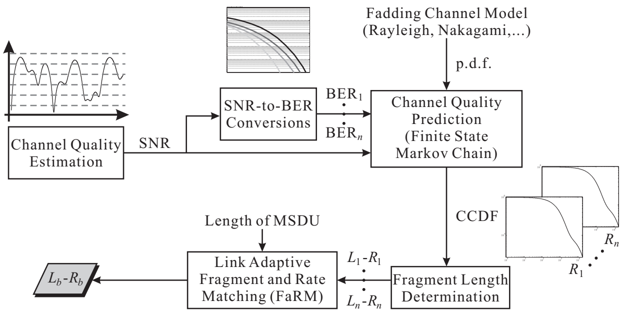


Figure 1. Design flow of FaRM.

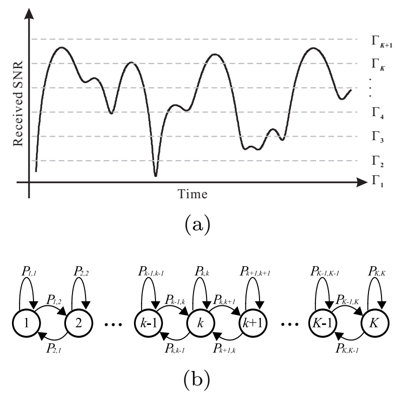


Figure 2. An illustration of the variation of a signal strength and the FSMC.

nel condition of the following transmission is needed. Finite-State Markov Chain (FSMC) is a well-known stochastic process and is suitable to model an erroneous circumstance [10, 12]. Consequently, in *Channel Quality Prediction* step, FaRM adopts FSMC as the wireless channel model. By FSMC, n CCDFs (Complementary Cumulative Distribution Function) under different transfer rates, say $\text{CCDF}_1, \ldots, \text{CCDF}_n$, can be derived accordingly. According to the probability of a successful transmission (from the CCDF) and the fragmentation overhead, in *Fragment Length Determination* step, one can obtain n fragment length and transfer rate pairs for different transfer rates, say $L_i - R_i, i = 1, 2, \ldots, n$, indicated the best fragment length under the transfer rate. Based on the original frame length of the MSDU of the sender to be transmitted, in *Like Adaptive Fragment and Rate Matching* step, the receiver can derive the best transfer rate and its corresponding fragment length by the results obtained from the previous step and send to the sender.

4. Channel Quality Prediction and Fragment Length Determination

4.1. Channel Quality Prediction

In order to model the variation of channel condition, FaRM uses Rayleigh fading channel as the propagation model for wireless transmissions. A finite state Markov model for Rayleigh fading channel is proposed in [12]. The received SNR values are divided into a finite number of states, say K states, indexed from 1 to K. As Figure. 2(a) shows, the lower and upper thresholds of the received SBR values corresponding to the kth state are Γ_k and Γ_{k+1}, respectively, $k = 1, 2, \ldots, K$. The corresponding finite state Markov chain is illustrated in Figure. 2(b). It is assumed that the state transitions only happen between adjacent states when transmitting 1 bit. The transition probability from state k to state k' is denoted $P_{k,k'}$, $1 \le k \le K$ and $|k - k'| \le 1$.

In Rayleigh fading channel, the received instantaneous SNR γ is distributed with the following probability density function, where γ_0 is the average SNR.

$$p(\gamma) = \frac{1}{\gamma_0} \exp(-\frac{\gamma}{\gamma_0}), \gamma \ge 0. \quad (1)$$

Let $N(\Gamma)$ be the average crossing rate of a fading signal crossing a given signal level Γ. According to Eq. (1), $N(\Gamma)$ is obtained in Eq. (2), where f_m is the maximum Doppler frequency caused by a STA moving at a certain speed because the movement of a STA will effect the fading of the signal transmitted from the STA.

$$N_\Gamma = \sqrt{\frac{2\pi\Gamma}{\gamma_0}} f_m \exp(-\frac{\Gamma}{\gamma_0}). \quad (2)$$

By Eq. (2), the state transition probabilities of the finite state Markov chain can be obtained as follows [10, 12], where $P_{k,k'}$ means the state transition probability from state k to state k'. Recall that the state transitions happen at adjacent states only.

$$P_{k,k+1} \approx \frac{N_{\Gamma_{k+1}}}{R_k}, k = 1, 2, \ldots, K-1, \quad (3)$$

$$P_{k,k-1} \approx \frac{N_{\Gamma_k}}{R_k}, k = 2, 3, \ldots, K, \quad (4)$$

$$P_{k,k} = 1 - P_{k,k+1} - P_{k,k-1}, k = 1, 2, \ldots, K. \quad (5)$$

where R_k is the average symbols per second which are in state k while the symbol rate of the current transmission rate is R. R_k can be obtained as follows.

$$R_k = R * p_k, \quad (6)$$

where P_k is the steady state probability of the k-th state and is derived by Eq. (7).

$$p_k = \int_{\Gamma_k}^{\Gamma_{k+1}} \frac{1}{\gamma_0} \exp(-\frac{\gamma}{\gamma_0}) d\gamma = \exp(-\frac{\Gamma_k}{\gamma_0}) - \exp(-\frac{\Gamma_{k+1}}{\gamma_0}).$$

For the channel quality of each state, a binary symmetric channel (BSC) model is adopted. The transmission error probability in state k is e_k, where the error means transmitting 0 but resulted in 1 or transmitting 1 but resulted in 0. Accordingly, the successful transmission probability in state k is $1 - e_k$.

Let e_γ^m be the error probability for the received SNR γ related to the modulation scheme m. The error probability in state k can be obtained by Eq. (7) [10, 12].

$$e_k = \frac{\int_{\Gamma_k}^{\Gamma_{k+1}} \frac{1}{\gamma_0} \exp(-\frac{\gamma}{\gamma_0}) e_\gamma^m d\gamma}{\int_{\Gamma_k}^{\Gamma_{k+1}} \frac{1}{\gamma_0} \exp(-\frac{\gamma}{\gamma_0}) d\gamma} \quad (7)$$

Suppose the duration of one bit transmission involves only one state transition. Therefore, the successful probability of a signal initially at state k and fallen at state k' after one bit transmission will be $P_{k,k'} * (1 - e_k)$, $1 \le k \le K$ and $|k - k'| \le 1$.

Let ϕ_i be a $1 * K$ row vector whose i-th element is 1 and all the other elements are 0, and ν be a $K * 1$ vector whose i-th element is $1 - e_i$, $1 \le i \le K$. In addition, let Ψ be a $K * K$ matrix represented as follows.

$$\Psi = \begin{bmatrix} P_{1,1}(1-e_1) & P_{1,2}(1-e_1) & \cdots & 0 \\ P_{2,1}(1-e_2) & P_{2,2}(1-e_2) & \cdots & 0 \\ 0 & P_{3,2}(1-e_3) & \cdots & 0 \\ 0 & 0 & \ddots & P_{K-1,K}(1-e_{K-1}) \\ 0 & 0 & \cdots & P_{K,K}(1-e_K) \end{bmatrix}$$

Accordingly, for a signal initially at state k, after l-bit transmission, the successful transmission probability, denoted $P_s^{(k)}(l)$, can be obtained as follows.

$$P_s^{(k)}(l) = \phi_k * \Psi^{l-1} * \nu. \quad (8)$$

As a result, the CCDF of the successful transmission probability in terms of the frame length can be obtained.

4.2. Fragment Length Determination

For one CCDF, the best frame length to transmit with the highest successful transmission probability under the SNR value and data transfer rate can be derived as follows. To derive the best frame length should take the fragmentation overhead into account. The overhead to fragment one more frame can be obtained.

$$\begin{aligned} T_{overhead} &= 2 * (T_{preamble} + T_{PCLP\_hdr} + \text{aSIFSTime}) \\ &\quad + T_{MAC\_hdr} + T_{MAC\_tra} + T_{ACK}, \end{aligned} \quad (9)$$

where $T_{preamble}$, T_{PCLP_hdr}, T_{MAC_hdr}, T_{MAC_tra} and T_{ACK} are the time spent in preamble, PLCP header, MAC header, MAC trailer, and ACK transmissions, respectively. Note that T_{ACK} has already taken T_{MAC_hdr} and T_{MAC_tra} into account. In addition, preamble and PCLP header are transmitted in base rate. MAC header and trailer as well as the ACK frame can be transmitted in a higher rate, depending on the rate negotiation between the sender and the receiver.

Let L be the length (in bits) of an original MSDU or MMPDU frame. If the frame is fragmented into several fragments of length L' (in bits), the transmission time to successfully transmit the frame, denoted $T_{tran}^L(L')$, can be obtained by Eq. (10).

$$T_{tran}^L(L') = [(\frac{L'}{R} + T_{overhead}) * \lceil \frac{L}{L'} \rceil] * \frac{1}{P_s^{(k)}(L')}. \quad (10)$$

As a result, the optimal fragment length to have the least transmission time to transmit an MSDU or an MMPDU of length L at channel quality state k and data transfer rate R is as Eq. (11) shows.

$$L^{opt} = \arg \min_{L' \le L} T_{tran}^L(L'). \quad (11)$$

Every transfer rate has its own CCDF at different SNR value. Consequently, given a specified SNR, FaRM will have n different CCDF curves if there are totally n available transmission rate. Through the n different CCDF curves, there will have n length-rate pairs can be derived under the specified SNR. Let the n length-rate pairs be denoted $L_1^{opt} - R_1, \ldots, L_n^{opt} - R_n$.

5. The FaRM MAC Protocol

5.1. Optimal Fragment and Rate Matching

In FaRM, a receiver receiving an RTS will determine the best matchings of fragment length of each data transfer rate according to the SNR. Then the receiver will determine the best matching of fragment length and data transfer rate through the flow chart in Figure. 3 according to the length of the pending MSDU. Suppose the current data transfer rate is R_i and the length of the MSDU is L.

The first decision block indicates that if $L_b < L_{i+1}$ is true, the data transfer rate can be raised while the MSDU is transfer directly without fragmenting. However, a fragment incur extra overhead $T_{overhead}$. If $L_b > L_{i=1}$, FaRM estimates if fragmenting an MSDU while raising the transmission rate is beneficial to shorten the channel time in the second decision block. Therefore, if $T(L_{i+1}, R_i) > T(L_{i+1}, R_{i+1}) + T_{overhead}$

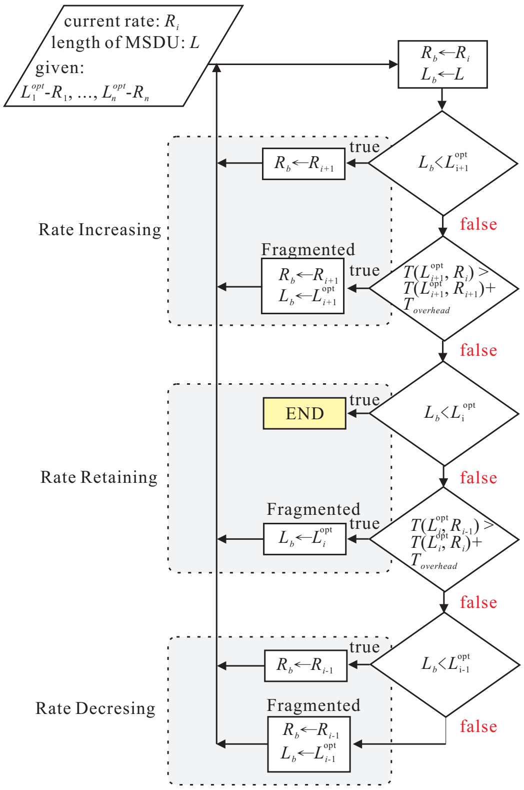


Figure 3. The best fragment length and transfer rate matching decison flow chart in FaRM.

is true, it indicates that raising the data transfer rate as well as fragmenting the MSDU is beneficial to the channel time.

The third decision block indicates that if $L_b < L_i$ is true, the data transfer rate is retained while the MSDU is transfer directly without fragmenting. However, if $L_b < L_i$ is false, it indicates that the MSDU need to be fragmented under current channel condition in the fourth decision block. Therefore, the MSDU is fragmented and transfered with the data transfer rate R_b. The fifth decision block means the receiver is in hostile environment. Therefore, the sender has to transfer the MSDU with fragmenting and lower the transfer rate.

5.2. The FaRM MAC Protocol

In FaRM, the first fragment will be transmitted by the sender according to the received best matching of fragment length and rate information piggybacked in the CTS frame. While the receiver receiving the first fragment, the receiver can estimate the SNR again. Then the receiver assesses the best matching of fragment length and transfer rate again. The assessed information is also piggybacked to the sender with the ACK frame. Consequently, the sender can transmit the remaining part of the MSDU in the same manner until the whole MSDU has been received by the receiver successfully.

When the sender is sending a RTS frame, the sender does not know the duration of the upcoming fragment length. For the sake of correct NAV setting, the NAV duration is set to the time which is required for the sender to transmit the header of the first fragment. Until the receiver reply the correct information in the CTS frame, the sender then set the correct NAV value in the header of the first fragment.

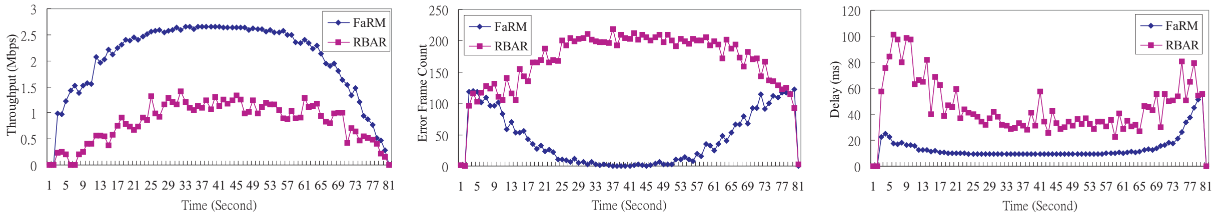
Some fields need to be added in the CTS/ACK frame in order to carry the determination information. Two Extra fields can be added between the RA and FCS field. The first added field is the *Fragment Length*. It is used to indicate the estimated fragment length. The unit of the stored value is byte. Consequently, 12 bits for Fragment Length can separate at most 4096 bytes which is greater than the longest fragment length in IEEE 802.11. The other added field is the Rate. It is used to indicate the estimated transmission rate. 4 bits for Rate can separate 16 different transmission rates.

6. Performance Evaluation

In order to evaluate the performance of FaRM, ns2 2.27 is used. To reflect the signal variation in wireless and mobile environment, Rayleigh Fading Channel is adopted as the propagation model in the performance evaluation. Gauss distribution is used as the background noise distribution. The traffic type is UDP CBR traffic with 2048 KB per second. The frame size is 1024 bytes. Two stations are transmitting data in the experiment. The receiver is static, and located at coordination 0. The sender is mobile, and firstly located at coordination 800. The sender begins to move from coordination 800 to 0 to 900 at the speed of 18 m/s in the evaluation. The transmission range is set to 150 m. RBAR [3] is used to compare with FaRM.

Figure. 4(a) shows the throughput result of FaRM and RBAR. In the simulation results, it can be observed while the receiver is moving close to the sender (1s to 50s), FaRM gets better throughput than RBAR due to the quicker reflection of channel quality. When the sender moves away from the receiver (50s to 80s), throughput of both protocols are decreased due to the poor channel quality. Because the fragment length in RBAR is longer than that in FaRM, throughput in FaRM is higher than in RBAR, especially when the channel condition is varied.

Figure. 4(b) shows the error frame counts. RBAR



(a) (b) (c)

Figure 4. Evaluation Results of (a) Throughput, (b) Frame error counts, and (c) Transmission delay.

incurs more error frame transmissions because the fragment length in RBAR is longer than in FaRM. However, the length of fragments in OAR only depends on the measured SNR during RTS/CTS exchange. Short fragments are more reliable than long fragments. When the sender are moving toward the receiver, it can be observed that the counts of error frames is decreased. Contrarily, when the sender is moving away from the receiver, the counts of error frames in increases. FaRM dynamiclly fragments an MSDU or an MMPDU into several fragments with different transfer rates and fragment lengths. As a result, FaRM is superior than RBAR in scalability. The evaluation result of delay is shown in Figure. 4(c). FaRM has lower frame transmission delay due to the high probability of frame transmission successful rate. As a result, FaRM outperforms RBAR in transmission delay.

7. Conclusions

Instead of using SNR value to represent the channel quality, FaRM adopts FSMC to estimate the variation of the channel quality. Besides, FaRM takes the advantage of RTS/CTS handshake to measure the channel quality of the receiver. Consequently, FaRM obtains accurate and almost read-time channel quality. Besides, FaRM dynamically fragments data frames into fragments. FaRM is likely to transmit fragments in high transmission rate and to increases the transmission scalability. The evaluation results show that FaRM can adaptively and instantly choose the best transfer rate and fragment length to send. The channel in FaRM can be utilized efficiently.

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