Research Article

Efficient MAC Protocol for Subcarrier-Wise Rate Adaptation over WLAN

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While bit-loading algorithms over wireless systems have been extensively studied, the development of a protocol which implements bit-loading-based rate adaptation over wireless systems has not been highlighted. The design of such a protocol is not a trivial problem, due to the overhead associated with the feedback information. In this paper, a novel protocol is proposed to provide an efficient way to implement subcarrier-wise rate adaptation in OFDM-based wireless systems. When receiving a Ready-To-Send (RTS) packet, the receiver determines the number of bits to be allocated on each subcarrier through channel estimation. This decision is delivered to the sender using an additional OFDM symbol in the Clear-To-Send (CTS) packet. That is, bit-allocation over subcarriers is achieved using only one additional OFDM symbol. The protocol enhances the channel efficiency in spite of the overhead of one additional OFDM symbol.

1. Introduction

Wireless communication is experiencing an explosive growth of rate demand. The high demand for wireless communication services requires increased system capacity. Orthogonal Frequency Division Multiplexing (OFDM) is a promising technology allowing wireless networks to provide high spectral efficiency into relatively small spectrum bandwidths. The attention has been focused on the application of the OFDM in the wireless local area network (WLAN). The existing examples of these systems are IEEE802.11a and HIPERLAN-2 standards which have chosen OFDM as a modulation scheme due to its good performance in multipath fading environment and its robustness against intersymbol interference.

Conventional rate-adaptive OFDM-based wireless systems use a fixed constellation size and power level over all subcarriers, as in the case of the IEEE802.11a standard [1–3]. However, all or some of the subcarriers experience different channel conditions due to multipath fading. As a consequence, applying a different constellation size (or number of bits or data rate) to each subcarrier according to its channel condition provides more reliable and efficient data transmission than applying the same constellation size to all subcarriers.

The allocation of a unique number of bits to all subcarriers in an OFDM symbol, called bit-loading, has been used in wired communication systems, such as digital subscriber lines (DSLs). Since the wired channel is slowly time-varying, the receiver can provide reliable channel state information to the transmitter using robust feedback channel. Therefore, adaptively loading the carriers seems to be an interesting approach for increasing the channel utilization. The theoretical channel capacity can be achieved by distributing the total transmitted energy according to the water-filling principle [4]. However, this distribution has computational complexity and assumes infinite granularity in constellation size. In the realistic case where a finite granularity in constellation size is required, the rounded bit distribution obtained starting from the water-filling solution could still

not be the optimum. Some suboptimum algorithms to reduce the complexity have been proposed in [5–7].

The performance of wireless networks is degraded by the adoption of the bit-loading scheme, since, unlike wired channels, wireless channels have fast time-variant property. The fast time-variant nature of wireless channels requires more frequent changes in the number of bits allocated in the subcarriers. Furthermore, since the sender and receiver have to share this allocation information, frequent exchanges of the bit-loading information between them are required. This increases the overhead and, as a consequence, degrades the network performance.

The problem of increased feedback overhead in centralized networks such as cellular systems may be less severe than that in distributed networks, since all of the terminals communicate with an Access Point (AP) and the AP can control the feedback information without disturbing the ongoing traffic. In addition to this, terminals in centralized networks can periodically send Channel State Information (CSI). However, in distributed networks such as ad hoc networks, the communication occurs in a peer-to-peer way and there is no such arbitrator. Therefore, since each communication pair has to exchange its CSI, more feedback packets are generated than in centralized networks. In addition to this, since the feedback packets are not controlled by an AP, collisions can occur with ongoing packets. Furthermore, the volume of the feedback information, including the subcarrier condition, increases as the number of subcarriers increases. Therefore, in order to utilize subcarrier-wise bit allocation in wireless ad hoc networks, an efficient protocol with minimum feedback information is required.

However, researches in this area have focused on allocating the optimal energy and rate and reducing the complexity of the bit-loading calculation itself [8–13] with the assumption of the availability of the feedback channel information. On the other hand, little effort has been made to design efficient protocols for bit loading in wireless networks. Designing an efficient protocol is not a trivial problem, because not only is the feedback information quite voluminous but also the time-varying wireless channel requires frequent transmissions of such large amounts of information. The research in [12] targeted centralized networks; so it assumed the existence of a central node which knows all the channel conditions of all member nodes. Moreover, due to the slow fading channel model used in this research, it does not suffer from feedback overhead. In the method proposed in [14], only the strongest subcarriers are used with high-order constellation to meet the target total data rate. The receiver informs the sender of the identification numbers (IDs) of the subcarriers which will be used for the next data transmission. Even though the feedback overhead is reduced to two OFDM symbols, the method in [14] cannot fully utilize all of the subcarriers. In effect, some of the chosen subcarriers may not be strong enough to deal with the high-order constellation. In addition, a separate feedback channel is used in [14]. Thus, such voluminous and frequent feedback information does not deteriorate the performance of wireless networks. However, all the previous works do not propose the feedback

method how the transmitter and receiver estimate and share the dynamic channel status. To the best of our knowledge, no work has been published about bit-loading in distributed wireless networks with practical feedback overhead.

An efficient method of implementing subcarrier-wise rate adaptation with minimum overhead over a wireless system is proposed in this paper. The proposed method requires only one additional OFDM symbol. In spite of the overhead engendered by this additional OFDM symbol, the network throughput and delay performances are improved. In Section 2, the motivation for the development of the proposed method is presented, followed by a detailed description. In Section 3, the proposed method is evaluated through simulations and the resultant performance improvements are demonstrated. Finally, the conclusion is given in Section 4.

2. Subcarrier-Wise Rate Adaptation with Minimum Overhead over WLANs

The proposed protocol is designed for WLANs with heavy traffic such as those including the download of large size files (music, video, documents, etc.). It is assumed that the wireless stations move at pedestrian speed so that the wireless channel changes slowly. The method proposed in this paper is based on the 4-way handshaking mechanism composed of RTS/CTS/DATA/ACK sequences specified in IEEE 802.11 [15].

The proposed method is based on the use of a Bit Map. The Bit Map is a table recording and indicating how many bits were or are allocated on each subcarrier of OFDM symbols in a previous or current packet, respectively. In fact, the number of bits is directly proportional to the data rate of each subcarrier (data rate = the number of bits/OFDM symbol duration). In order to avoid confusion, hereinafter we use only the data rate. The overall operation of the protocol is as follows. The sender sends an RTS to the receiver. When it receives the RTS, the receiver estimates the condition of all subcarriers and determines the data rate that can be sent on each of them. After updating its Bit Map, the receiver sends a CTS packet, which uses a modified packet format derived from the IEEE 802.11 standard. The detailed CTS packet format is described in Section 2.2. The sender updates its Bit Map according to the information embedded in the CTS. The details of the method are illustrated in the following subsections.

2.1. Bit Map. The Bit Map indicates how many bits are allocated to each subcarrier in the OFDM symbol for the communication between a pair of stations. It is located in their internal memory. The stations generate the Bit Map when a communication is initiated and maintain the Bit Map for each communication pair. The Bit Maps of a communication pair, namely, a sender and a receiver, have to be synchronized with each other. The processes employed to update and synchronize the Bit Maps of a sender and a receiver will be detailed in Section 2.2. The Bit Map stores the currently updated bit allocation information as

Sub-channel # Time Index	Ch1	Ch2	...	Ch n
t	2	3		3
$t-1$	3	3		3

FIGURE 1: An example of the Bit Map.

Preamble	PLCP header (one OFDM)	Bit map adjustment (one OFDM)	MPDU

Bit map flag 4 bits	Reserve 1bit	Length 12 bits	Parity 1 bits	Tail 6 bits
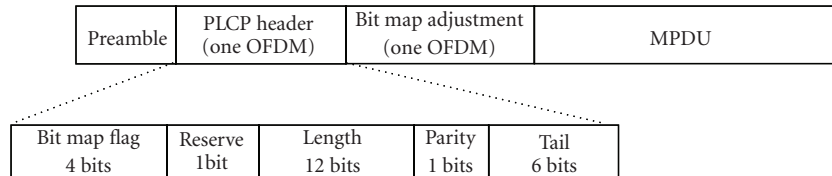
FIGURE 2: OFDM symbol of Bit Map adjustment in CTS packet.

well as the previous allocation information. Figure 1 shows an example of the Bit Map. t and t-1 in Time Index in Figure 1 indicate the current and previous allocation times, respectively.

2.2. Revised Formats of CTS and DATA Packets. The method proposed in this paper revises the packet formats of the CTS and PLCP header in DATA. Figure 2 shows the packet format of CTS and Figure 3 shows that of DATA. The "Rate" subfield in the CTS PLCP Header of IEEE 802.11a is changed to a Bit-Map-Flag subfield to indicate the use of the Bit Map. When the Bit-Map-Flag subfield is set to 1111, a "Bit-Map-Adjustment" OFDM symbol is inserted between the PLCP header and MPDU. A Bit-Map-Flag with the value 0000 indicates that the Bit allocation is not changed, so that no "Bit-Map-Adjustment" follows after the PLCP header. Since the value of 1111 is reserved in the "Rate" subfield, the modified CTS packet is compatible with legacy IEEE 802.11 devices.

This additional single OFDM symbol is composed of 48 data subcarriers and 4 parity subcarriers. Each parity bit covers 12 subcarriers. Each subcarrier is set to 1/−1 (BPSK) or one of the BPSK symbols. The objective of this additional OFDM symbol is to adjust the data rate allocated on the subcarriers for the subsequent data transmission. The method employed to allocate the data rate to each subcarrier is described in the following subsection. For the DATA packet, only one subfield is changed, as shown in Figure 3. The "Reserved" subfield in the DATA PLCP header in IEEE 802.11a is used as a "Confirmation" subfield. This subfield is used as an Acknowledgment for the Bit Map in the CTS packet. If the sender agrees with the Bit Map, the bit is set to 1. Otherwise, it is set to 0. The "Confirmation" subfield is used for the error recovery process, which is described in detail in Section 2.4.

In order to provide the backward compatibility of the protocol with legacy devices, "Reserved" subfield in RTS packet shown in Figure 4 is utilized. To negotiate the use of the proposed rate adaptation method with the receiver,

a sender sends an RTS packet with "Reserved" subfield set to 1. Receiving the RTS packet with "Reserved" subfield set to 1, if the receiver is a node with the proposed rate adaptation capability, it sends the proposed CTS packet shown in Figure 2. Otherwise, it sends a conventional CTS packet to the sender. By checking the value of "Rate" subfield in the received CTS packet, the sender decides which one of the transmission methods, the proposed method or the legacy method, is carried out. As a result, the proposed method is compatible with the operation of legacy devices.

2.3. Rate Selection and Rate Change Procedure in Receiver. The process used to update the data rate of each subcarrier for a subsequent data transmission is as follows.

Step 1 (Negotiation of using the proposed subcarrier-wise rate adaptation). A sender sends an RTS packet setting "Rate" subfield in PLCP header to 1111. This informs a receiver the use of the subcarrier-wise rate adaptation method. If the receiver can process the proposed method, it goes to the next steps. Otherwise, the receiver sends a legacy CTS packet back to the sender and then the conventional procedure as defined in IEEE 802.11 standard is processed.

Step 2 (Estimate the channel condition of each subcarrier and find the optimal data rate). The channel condition of a subcarrier (e.g., Signal-to-Noise Ratio (SNR)) is estimated from the received RTS packet. The receiver chooses a data rate suitable for the channel condition. We assume that the data rate is selected based on the predetermined threshold value [1–3].

Step 3 (Compare the chosen data rate with the data rate in the Bit-Map). The chosen data rate for the subcarrier is compared to the data rate in the current Bit-Map. After comparison, the receiver chooses one of three actions: to increase, decrease, or not to change the data rate on each subcarrier. For example, if the data rate in the current Bit
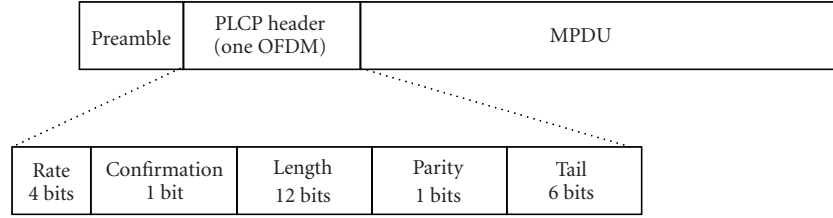
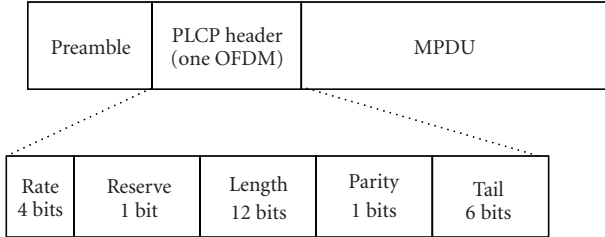FIGURE 3: Fig. 3. PLCP header structure with confirmation subfield in Data packet.

FIGURE 4: Fig. 4. A conventional RTS packet.

TABLE 1: Data rate adjustment on each subcarrier according to symbols assigned in bit-map-adjustment ofdm symbols.

Symbol on a subcarrier in previous Bit-Map-Adjustment OFDM symbol	Symbol on a subcarrier in current Bit-Map Adjustment OFDM symbol	Data rate adjustment in Bit Map
−1	−1	Decrease one level from the previous data rate
−1	1	Do not change
1	−1	Do not change
1	1	Increase one level from the previous data rate

Map is smaller than the chosen data rate, the receiver chooses to increase the data rate for that subcarrier.

Step 4 (Set the value of the Bit-Map-Adjustment symbol of the CTS). According to the decision in Step 2, the receiver sets the Bit-Map-Adjustment symbol to 1 to increase or -1 to decrease the data rate on each subcarrier. If the decision of a subcarrier is not to change the data rate, the receiver sets the Bit-Map-Adjustment symbol to a different value from the one used in the same subcarrier of the previous CTS.

Step 5 (Update the Bit-Map). Once the values of the Bit-Map-Adjustment symbol are decided, the actual data rate for the upcoming data transmission is selected according to Table 1. Table 1 illustrates how to choose the data rate based on the values on both the current and previous CTS Bit-Map-Adjustment OFDM symbols. As noted in Step 3, if the current value is different from the value used in the previous

CTS, the data rate is not changed. The Bit-Map is updated with the currently chosen data rates.

The rate transition diagram is shown in Figure 5. In the figure, "∗/∗" denotes "a value on a subcarrier of the current CTS Bit Map Adjustment OFDM symbol/a value on a sub channel of the previous CTS Bit Map Adjustment OFDM symbol", and *K* denotes the data rate in the current Bit Map.

2.4. Rate Change Procedure at a Sender and Error Recovery. After the process illustrated in Section 2.3 is completed, the receiver (i.e., the destination of the RTS packet) sends a CTS packet to the sender (i.e., the source of the RTS packet). The CTS packet includes the Bit-Map-Adjustment OFDM symbol updated by the receiver. After receiving the CTS packet, the sender also updates its own Bit Map following the rule shown in Table 1. By using the data rates represented in the updated Bit-Map, the sender generates and sends a DATA packet with the "Confirmation" subfield set to 1. When the receiver receives this DATA packet, it demodulates the packet based on the Bit Map information and sends an ACK to the sender.

This process is shown in Figure 6(a). If the sender fails to receive an ACK packet, as shown in Figure 6(b), it changes the current data rate information to the previous information contained in its previous Bit Map and retransmits an RTS. When the receiver receives an RTS with a nonzero retry bit, it changes the current data rate information to the previous information contained in its previous Bit Map.

If the reception of the DATA packet at the sender fails for some reason (e.g., channel error or collision), as shown in Figure 7(a), the receiver changes the current data rate information to the previous information contained in the Bit Map. In this case, since an ACK will not be sent, the sender also changes the current data rate information to the previous information contained in its Bit Map.

If the transmission of the CTS packet fails, the receiver goes back to the previous bit allocation information contained in the Bit Map, as in the case of DATA packet loss. This case is shown in Figure 7(b).

3. Performance Evaluation

A centralized WLAN system is simulated. The system is composed of one AP and *N* stations. In the simulation, the physical (PHY) layer defined in the IEEE 802.11a standard is considered. The PHY layer has eight PHY modes characterized by different modulation schemes and convolutional
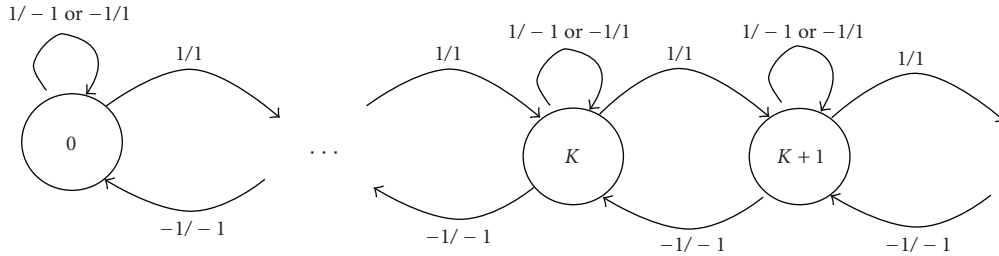
FIGURE 5: Data rate transition diagram.

TABLE 2: IEEE 802.11a PHY modes.

Mode	Modulation	Code rate	Data rate	Minimum sensitivity (dBm)
1	BPSK	1/2	6 Mbps	−82
2	BPSK	3/4	9 Mbps	−81
3	QPSK	1/2	12 Mbps	−79
4	QPSK	3/4	18 Mbps	−77
5	16-QAM	1/2	24 Mbps	−74
6	16-QAM	3/4	36 Mbps	−70
7	64-QAM	2/3	48 Mbps	−66
8	64-QAM	3/4	54 Mbps	−65

coding rates, as shown in Table 2. More details can be found in [16]. We use a Ricean fading broadband channel model. All of the stations except for the AP are randomly distributed in a circular area with a diameter of 100 meters and move randomly at a speed of 1 m/sec. The AP is located at the center of the area. The traffic load is saturated in each station. The packet size is 1024 bytes.

For the purpose of the evaluation, the proposed method, which is referred to as "Adaptive", is compared with two prior art methods. The first one is a method proposed in [14] that is also briefly described in Section 1. We name this method "OSS". The other one is a packet-based rate adaptation method described in [2, 3, 17, 18], which changes the data rate based on the channel condition, but uses the same PHY mode over all subcarriers. Since this method uses a fixed PHY mode over all subcarriers in an OFDM symbol, we name it "Fixed". "Fixed" chooses a data rate, which is appropriate for a subcarrier having the worst channel condition over all subcarriers. All three methods use the 4-way handshaking procedure (RTS/CTS/DATA/ACK) defined in the IEEE 802.11 standard. In terms of the overhead in the control packets, such as RTS, CTS, and ACK, our method has one more OFDM symbol compared to "Fixed" due to the addition of the "Bit-Map-Adjustment" OFDM symbol. Although it might need two or more OFDM symbols, we assume that OSS also uses one OFDM symbol for the feedback of the subcarrier information. In OSS, the threshold level used to select the strongest subcarriers is set to 54 Mbps, which corresponds to −65 dBm in Table 2. Only the selected strongest subcarriers are used for packet transmission, as described in [14]. The value of −65 dBm is selected as the threshold level for OSS, because this level provides the best throughput performance among the 8 levels in Table 2.

Figure 8 shows the changes of the channel condition (in Rx Power), the transmission rate (in Tx rate), and the feedback bit as a function of time. The changes shown in Figure 8 are for only one subcarrier. The received signal power changes due to the fading channel. According to the received signal power, the receiver sends the feedback information, 1 or −1, to change the data rate as described in Section 2.3. When the transmission rate is lower than the marginal rate, the receiver sends the feedback of 1 to increase the rate. During the time duration of 0.1 ∼ 0.2 sec, the receiver sends the feedback of 1 four times consecutively and the transmission rate increases to the maximum value. On the contrary, during the time duration of 0.2 ∼ 0.3 sec, there are continuous feedbacks of −1 and the transmission rate decreases. In Figure 8, the transmission rate closely follows the change of the channel condition, although not exactly. The reason for this discrepancy is that the transmission of the feedback information is not always available. Note that the feedback happens only when there is a data packet in the queue to be transmitted. Moreover, the feedback interval varies because each station has to compete with the other stations to have the opportunity to transmit.

Figure 9 shows the throughput performance improvement of the proposed method over Ricean fading channel with the Ricean parameter, 10. As the number of stations increases, the number of collisions also increases. Because of the increased number of collisions, each station has longer average backoff window and waits more time to transmit a data packet. Thus, the system throughput is degraded as the number of stations increases. The proposed method, "Adaptive", provides an improvement in the throughput ranging from 8% to 11.5% compared to the other two methods. This is because the proposed method adapts the data rate for each subcarrier dynamically according to
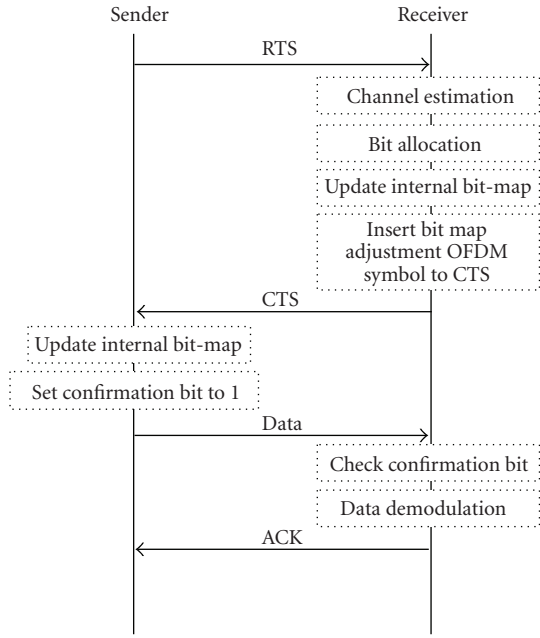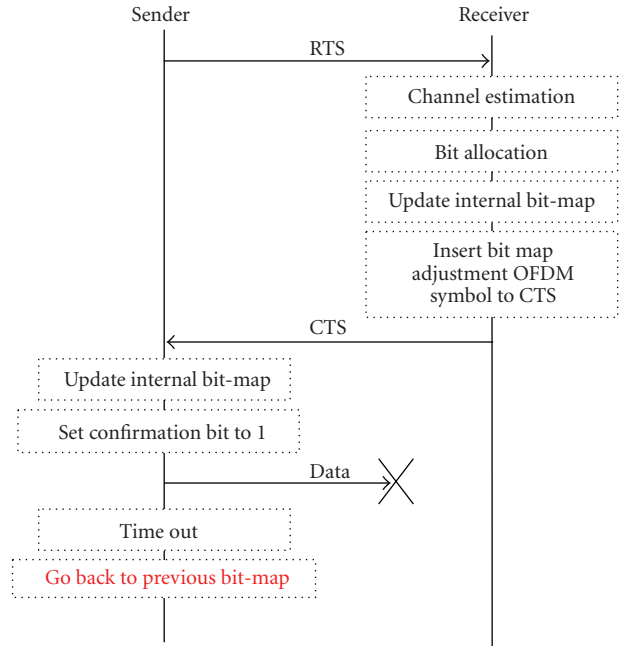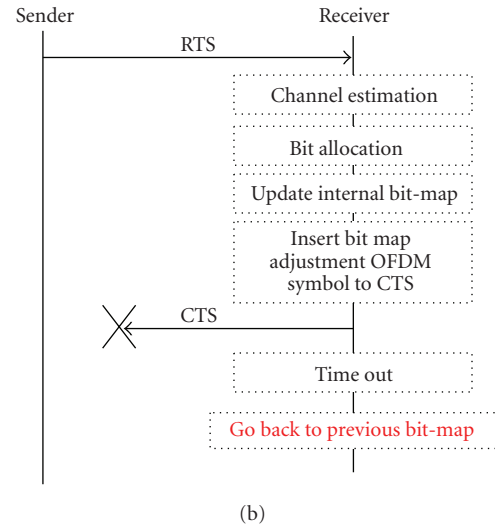
(a)
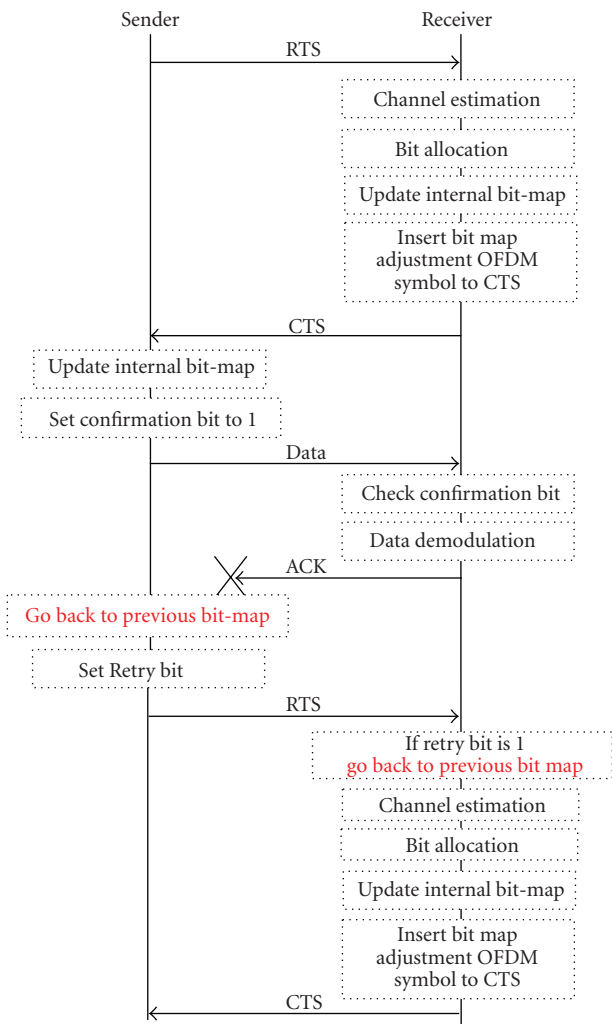
(b)

Figure 6: Protocol operation in cases of (a) successful transmission and (b) ACK loss.

(a)

(b)

Figure 7: Protocol operation in cases of (a) Data loss and (b) CTS loss.

the channel conditions. "OSS" shows similar throughput as "Fixed". Even though "OSS" uses only selected subcarriers, the selected subcarriers are used in the optimal data rate. Thus, "OSS" achieves the similar throughput performance as "Fixed" while reducing the complexity and overhead.

Average packet delay is shown in Figure 10. As the number of stations increases, the number of collisions also increases and the data packets should wait more time to be transmitted. Thus, average delay is inversely proportional to the throughput. Regarding the delay performance, the proposed method also provides an improvement ranging from 7.5% to 10.5% compared to the other two methods, as shown in Figure 10.
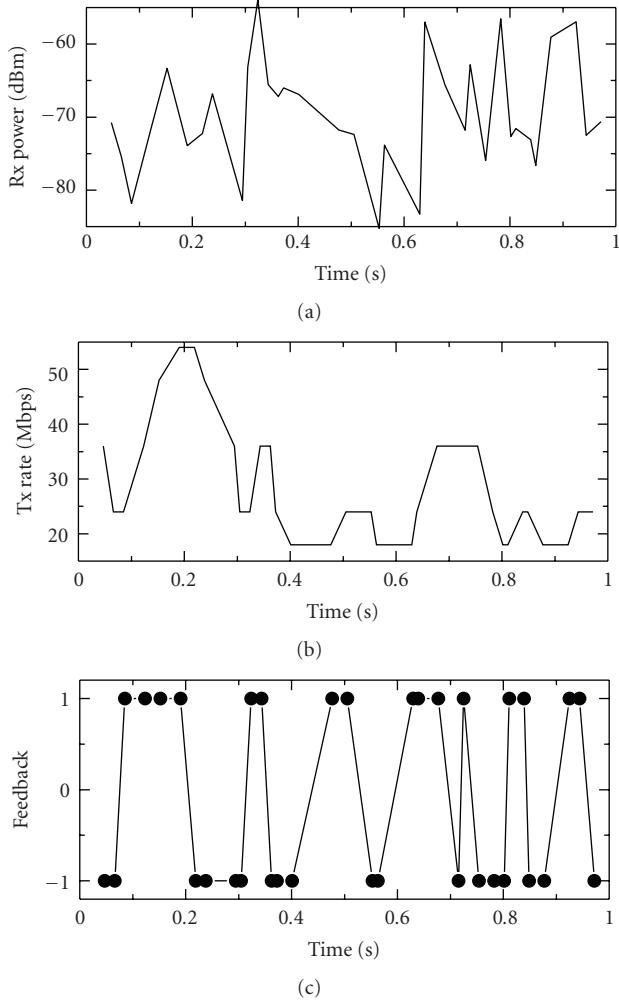
(a)

(b)

(c)

FIGURE 8: Data rate allocation according to feedback information.
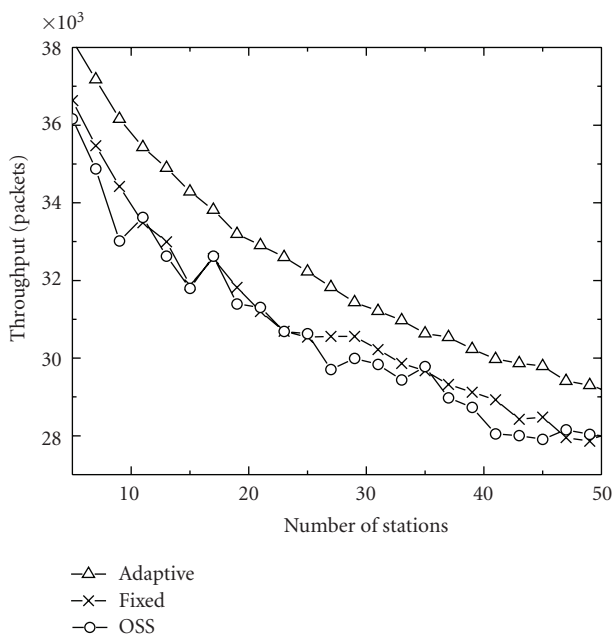

FIGURE 9: Throughput as a function of number of stations.
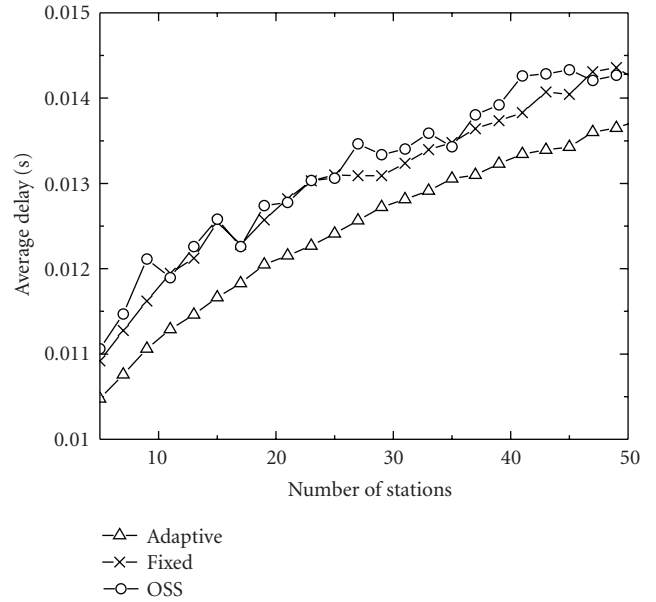

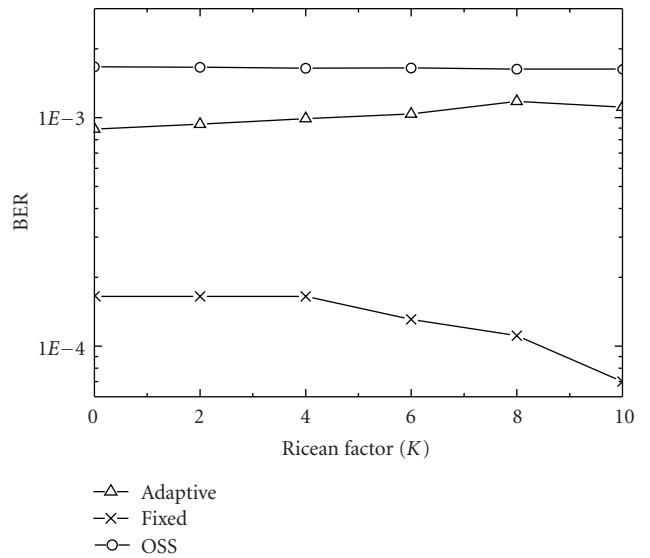FIGURE 10: Average packet delay as a function of number of stations.

FIGURE 11: BER performance as a function of Ricean factor, K.

Figure 11 shows the BER performance as a function of the Ricean parameter, K, with 25 stations. "Fixed" shows the best performance among the three methods. Since this method chooses a data rate based on the subcarrier having the worst channel condition, it is normally robust over error prone wireless channels. However, the low BER performance of "Fixed" is obtained by sacrificing the throughput and delay performances, as shown in Figures 9 and 10. "Adaptive" has a slightly better BER performance than "OSS". Since "OSS" uses the strongest subcarriers to cope with the 54 Mbps PHY mode, it is more sensitive to the change of the channel condition during 4-way handshaking (RTS/CTS/DATA/ACK)

than "Adaptive" is. Overall, in spite of its relatively higher BER than "Fixed", the proposed method, "Adaptive", shows a higher throughput and less packet delay compared to the other two methods. Compared with "OSS", "Adaptive" utilizes the entire set of subcarriers, each of which has optimal modulation regarding the current channel condition. Compared with "Fixed", "Adaptive" allows the subcarriers to use a higher data rate. Such performance improvements of "Adaptive" are achieved because the subcarrier-wise rate adaptation is implemented with the method proposed in this paper. Also, note that no implementation method for the channel state feedback has been proposed in the case of "OSS" and "Fixed". The subcarrier state feedback, which is the main obstacle to the implementation of subcarrier-wise rate adaptation, does not have a significant effect on the network performance in the proposed method.

4. Conclusion

An efficient protocol which realizes subcarrier-wise rate adaptation over wireless channels has not previously been proposed, due to the large overhead caused by the frequent transmission of the feedback information, which is not small. In this paper, we propose a novel rate-adaptive MAC protocol for OFDM-based wireless communication systems. The proposed method provides an efficient way to implement subcarrier-wise rate adaptation by designing a protocol which has a relatively small feedback overhead associated with the subcarrier state information. The proposed protocol plugs one OFDM symbol into a CTS packet. By utilizing the OFDM symbol and synchronously maintaining the bit allocation maps at both the sender and receiver, it can adaptively change the data rate allocated to each subcarrier. To synchronize the bit allocation maps at both the sender and receiver over an error-prone wireless channel, a detailed error recovery procedure is also proposed.

The simulation results show that the proposed method increases the network performances, because it utilizes the entire set of subcarriers more efficiently than the prior art methods. Even though we add one OFDM symbol to the CTS packet, the overhead caused by this extension is relatively small in terms of the overall packet size. As a result, the performance improvement due to the subcarrier-wise rate adaptation surpasses the performance degradation that results from the feedback overhead associated with the subcarrier state information.

Acknowledgments

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