New frame-based network allocation vector for 802.11b multirate wireless LANs

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Abstract: To enhance the system capacity of the IEEE 802.11 wireless local area networks (WLANs), a frame-based adaptive multirate transmission scheme is envisaged. The medium access control (MAC) operation and the selection of parameters, such as the thresholds of request to send (RTS) and fragmentation, are discussed. The original virtual carrier sense mechanism in the IEEE 802.11 WLAN standard is no longer suitable because the transmission rate is adaptively selected such that it is prone to allocate a wrong network allocation vector (NAV) to jam or inhibit the radio transmission that degrades the performance. A modification of the NAV reservation scheme must be made to adopt this change. The authors have performed simulations to illustrate the performance improvement to the modification of the NAV reservation scheme. Simulations are based on a time-correlated multipath fading channel model and a movable mobile station assumption, where the station may be out of range from certain mobile stations.

1 Introduction

Wireless local area networks (WLANs) provide users with network connectivity without being tethered to a wired network and provide more flexible and convenient user interfaces. The IEEE 802.11 WLAN standard was approved on June 1997 with data rates of 1 and 2 Mbit/s. To provide high bandwidth to users, a number of drafts have recently been proposed to provide high-rate extensions of the PHY layer [1, 2]. Among these drafts, The IEEE 802.11b [2] for the direct sequence spread spectrum (DSSS) system is specified in the 2.4 GHz band. The specification defines two additional data rates 5.5 and 11 Mbit/s in addition to the 1 and 2 Mbit/s. The same carrier frequency, band, and phase shift keying (PSK) modulation are used, and it is easy to interoperate with the 802.11 WLANs by using the same preamble and header. Other possibilities of WLANs are the IEEE 802.11a, which uses the orthogonal frequency-division multiplexing (OFDM) as the basis for the new 5 GHz standard, targeting a range of data rates from 6 up to 54 Mbit/s and the HIPERLAN type 2, which is standardised by ETSI BTAN [3].

Since modern wireless communication systems are expected to support multimedia services, not only high quality, high speed, and high flexibility are required, but temporal and spatial control of traffic under severe fading environments is also needed. Traditional single transmission rate wireless communication systems cannot fulfil this need. Morinaga *et al.* [4] proposed the concept of selecting transmission rates according to the channel estimation of a system. This concept, called link adaptation (LA), is currently being researched, especially on the cellular systems [5, 6]. In such systems, the principle idea is that the mobile station transmits its data payload as fast as possible when the channel is detected to be good, which implies that the transmission will suffer a lower frame error rate. On the other hand if the mobile station perceives that the channel condition is becoming worse, it decreases the transmission data rate. The decrease in data rate often implies that a larger codeword is being used or some lower speed modulation in order to confront the bad channel condition.

In this paper, we investigate the medium access control (MAC) performance of the frame-based adaptive multirate IEEE 802.11b WLAN. In general, a higher transmission rate is used in smaller radio coverage areas. In the frame-based multirate scheme, the transmission rate of each frame is selected, dynamically based on the detected signal-to-noise ratio (SNR) of the previous transmission/reception. Dynamic rate selection will improve the flexibility of deploying WLANs and is helpful in QoS control. An even more important advantage in using frame-based rate selection is its ability to deal with the dramatic fluctuation of the wireless channel quality [7, 8].

In contrast to cellular systems using a dedicated channel to communicate, the challenges, which are faced in the WLANs to make the LA possible, involve coordinating the transmission among the mobile stations, which share the medium, as well as choosing a good rate adaptation algorithm. This paper provides a modification for the MAC operation to obtain the benefit of LA and maintain the nature of fair contention of WLANs. The rate adaptation algorithm and physical implementation can be found in the related LA research on cellular systems [5, 6]. The problems encountered in the WLANs when LA is applied are discussed in Section 2.

Detailed simulation results are provided in the paper. In the simulation, a time-correlated multipath fading channel is used to model the channel condition and to determine whether a frame is transmitted successfully or not. It is also assumed that mobile stations are movable and may be out of range from certain stations. In other words, the effect of hidden terminals is considered in this simulation. The provided modification can be directly applied to the IEEE 802.11a, adapting a range of data rates from 6 up to

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54 Mbit/s. While HIPERLAN type 2 uses a centralised and scheduled MAC based on wireless ATM, for which the individual LA design is needed.

2 Scenario descriptions

2.1 Multirate system

The strategy that we propose in implementing the multirate WLANs uses the 'request to send' (RTS) and 'clear to send' (CTS) frames for channel estimation. If the length of an arriving frame is longer than the RTS threshold the mobile station will estimate the channel condition via RTS/CTS frame exchange and determine the modulation mode and fragmentation threshold to be used in the successive data payload. Otherwise, the frame will be transmitted in the same modulation mode as the previous data payload.

In a WLAN, the physical carrier sense is used to detect whether a channel is busy or idle. However, a hidden terminal may contend the shared medium when it detects the channel idle, this is the well-known hidden terminal problem [9]. Consequently, the network allocation vector (NAV) reservation scheme, also referred to as virtual carrier sense, is performed in the MAC layer. The NAV is an indicator, maintained by each station, of time periods during which the station will not initiate transmission onto the wireless medium. In other words, it is used to prevent the station from disturbing the frame-exchange procedure that is being performed by other stations. The high-rate extension in the IEEE 802.11a and 802.11b specifies the physical layer extension, but the MAC layer is preserved and is identical to the original IEEE 802.11 specification. If multirate transmission is applied in WLANs, two problems occur which will impair the performance when the original MAC protocol is applied directly without any modification.

The major problem is over-inhibition or inadequate inhibition, as shown in Fig. 1. Because the transmission rate is selected according to the current channel condition, the mobile station does not know the transmission rate of the next fragment and makes proper NAV reservation in the RTS/CTS frame exchange. In Fig. 1*a*, the excessive NAV-reservation will bias in favour of the source and the destination to access the channel. In Fig. 1*b*, the inadequate NAV-reservation will aggravate the hidden terminal problem, i.e. a mobile station will be more likely to jam the transmission.

Another problem in the NAV reservation scheme of a multirate 802.11b WLAN is that the scheme may fail due to decoding error. Suppose that the transmitted power is the same for all data rates, and the physical carrier sense scheme is the same as that of a single-rate WLAN. That is, stations can detect if the physical channel is busy or idle. However, decoding error may occur in the PHY layer when a station, neither the transmitter nor the receiver, falls outside the decoding region, while the transmitter transmits frames using high-rate modulation. In the IEEE 802.11 specification, a station should wait for an extended interframe space (EIFS) before accessing the channel again if it decodes an error frame. The EIFS is a long time compared with the mean time of a frame exchange. However, in single-rate WLANs, decoding errors occur rarely, but in multirate WLANs, decoding errors occur often. If every station waits for an EIFS when decoding an error frame, the WLAN will be severely biased in favour of those stations using high-rate modulation. Stations located on the edge of the WLAN and using the low-rate modulation will not be treated fairly.

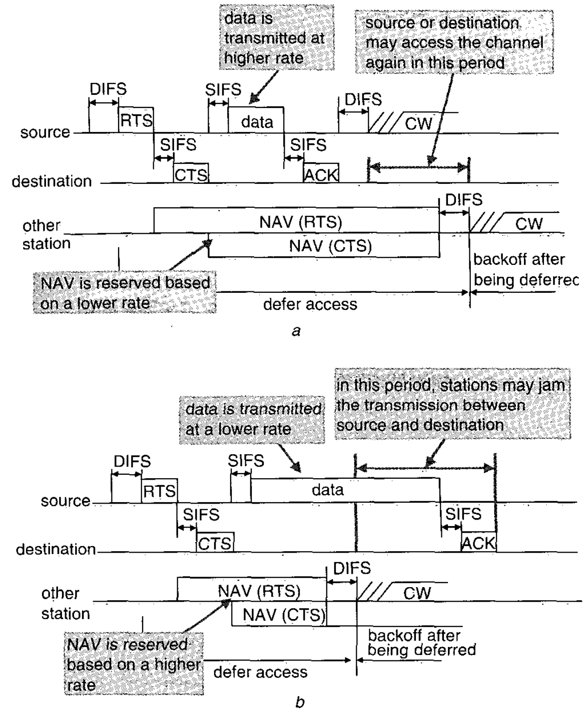

Fig. 1 *Inhibition in the multirate WLAN when using the original MAC protocol*
CW: contention window
DIFS: DCF inter-frame space
NAV: network allocation vector
SIFS: short inter-frame space
a Over-inhibition
b Inadequate inhibition

2.2 Proposed scheme

A two-phase NAV-reservation scheme is proposed to deal with the two problems described in the previous subsection. In the first phase, the whole duration of a pending MAC service data unit (MSDU) including the time of the necessary short interframe spaces (SIFSs) and ACKs at 2 Mbit/s will be reserved by the RTS/CTS exchange. Because the RTS/CTS is transmitted at the 2 Mbit/s data rate, most mobile stations will detect and decode the frames and reserve the NAV properly. In the following data fragmentation/ACK frames, the duration/ID field in the MAC header indicates the difference between the actual transmission time and the reserved time. A mobile station, neither the transmitter nor the receiver, receives the frame extracts the information in the duration/ID field and subtracts it from the value of the reserved NAV to obtain the correct value of the NAV. The procedure is shown in Fig. 2. In addition, stations which cannot decode the frame but can detect the channel busy calculate the correct NAV according to the information in the physical layer convergence protocol (PLCP) signal, which indicates the data rate of this PHY service data unit (PSDU) referred to as r, and length fields in the PHY header, which indicates the number of microseconds required to transmit the PSDU referred to as l. Thus, the correct NAV value equals that subtracts the value of $l(r-2)/r$ from the old NAV value. The idea of the proposed scheme is based on the fact that the PHY header of a frame is transmitted at the same rate in WLANs no matter what data rate is used. Thus, all stations will detect and recognise the information in the PHY

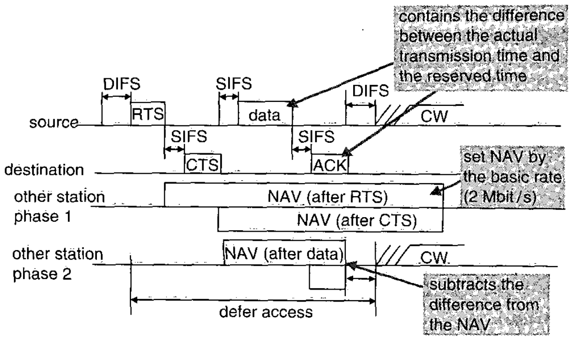

Fig. 2 *Modified NAV-reservation scheme*

header. Although using the information in the PHY layer to help solve a problem in the MAC layer somewhat violates the concept of layering, it is a trend in modern wireless communications design, especially in LA [5, 6] and soft QoS control.

3 Simulation model

An example geographical condition for the simulation is shown in Fig. 3, an access point (AP) is located in the centre of a single basic service set (BSS), and stations are randomly located inside a BSS. The stations are movable, the direction relative to the horizontal and the velocity of a station are assumed to be uniformly distributed in $[0, 2\pi]$ and 1–5 km/h, respectively. For maintaining the constant number of mobile stations in a BSS, when a station moves out from the BSS a new station will be created with a new location, direction, and velocity inside the BSS. The AP is assumed to be the call party of all mobile stations and takes the responsibility for replying with the CTS and ACK frames. The AP is assumed to be stationary and does not contribute traffic to the BSS.

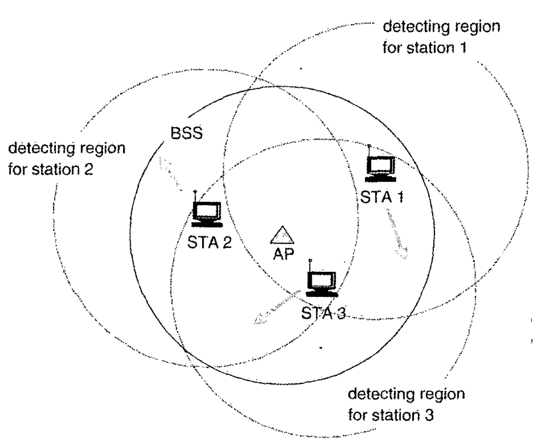

Fig. 3 *Example geographical condition for the simulation*

The data rate selection is based on the received signal power. The selection algorithm used is the received signal strength indicator [6]. We assume that the received signal power, denoted by a_t, is modelled as

$$a_t = P_0(\text{dBm}) - 10n\log(d_t/d_0) + F_t, \qquad (1)$$

where t denotes the instant of signal estimation, P_0 is the power received at a close-in reference point at a small distance d_0 from the transmitting station, d_t is the distance from the mobile station to the reference point and n is the attenuation factor. The first two terms model the channel path loss [8] and F_t is the resultant envelope of the time-correlated multipath fading signal generated by Jakes' model [11]. In the simulation, P_0 is assumed to be 100 mW, and the attenuation factor n is chosen to be 3.3 according to Hashemi's work [7]. We assume that a station chooses a transmission data rate 2, 5.5, and 11 Mbit/s when the received signal power level is larger than −80, −76, and −70 dBm, respectively. In addition, we assume that the required signal power level to ensure correct reception of the frame is −84, −80, and −74 dBm, respectively. A frame is referred to as being 'undetectable' if the received signal power is less than −84 dBm; a frame is referred to be 'undecoded' if the received signal power is less than the corresponding required signal level. The simulations are programmed in C language, which is an extended version of our previous work [10].

4 Simulation results and discussion

4.1 RTS and fragmentation thresholds

For the reason of accuracy in the simulation results, we first perform simulations to evaluate the thresholds of RTS and fragmentation. Figs. 4–6 show the impact of the RTS threshold on data throughput in the single-rate WLAN when there is no fragmentation in data frames and the channel is assumed to be error-free to accurately evaluate the effects of collisions. A transmitted frame is collided or not cannot be determined until the transmitter receives the CTS. The throughput refers to the average number of bits per second sent from the MAC sublayer to the upper layer at the destination. The right-most points in Figs. 5 and 6 represent the throughput when no RTS/CTS is sent before a data frame is sent to the channel.

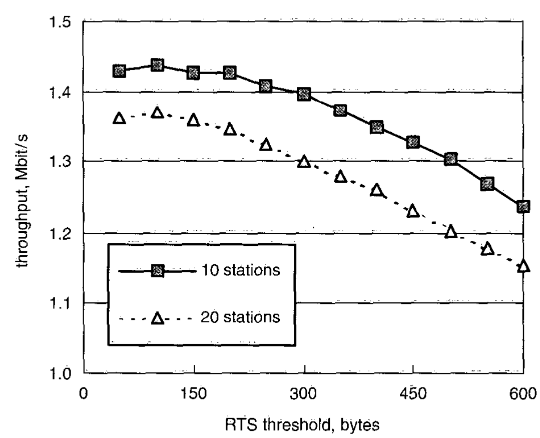

Fig. 4 *RTS threshold effects on data throughput in a 2 Mbit/s WLAN*

Fig. 7 shows the impact of fragmentation threshold on saturated data throughput in the single-rate WLANs, where the multipath fading channel model is applied. We perform this simulation with geographical constraints. For the 2 and 5 Mbit/s WLANs, mobile stations are uniformly distributed within the received power level range from −76 to −80 dBm and from −70 to −76 dBm, respectively. For the 11 Mbit/s, mobile stations are located within the range of the received power level larger than −70 dBm. The RTS thresholds in this simulation are chosen from the results of Figs. 4–6. The right-most point is the throughput without fragmentation. It can be found that, for 2 and 5.5 Mbit/s WLANs, fragmenting an MSDU is not better than not fragmenting.

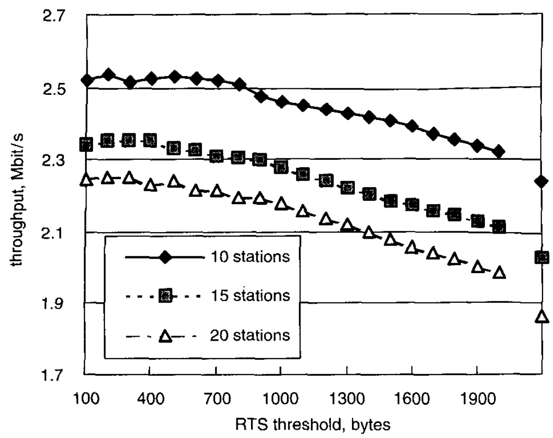

Fig. 5 *RTS threshold effects on data throughput in a 5.5 Mbit/s WLAN*

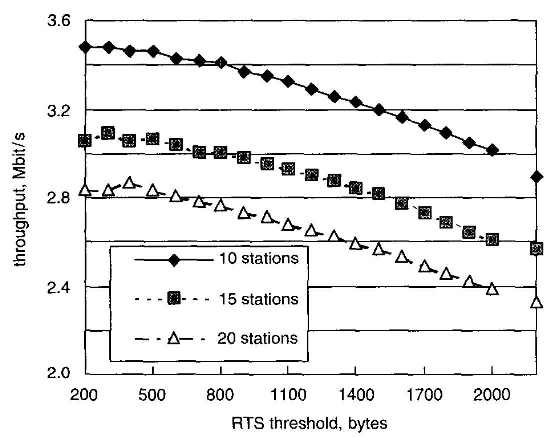

Fig. 6 *RTS threshold effects on data throughput in an 11 Mbit/s WLAN*

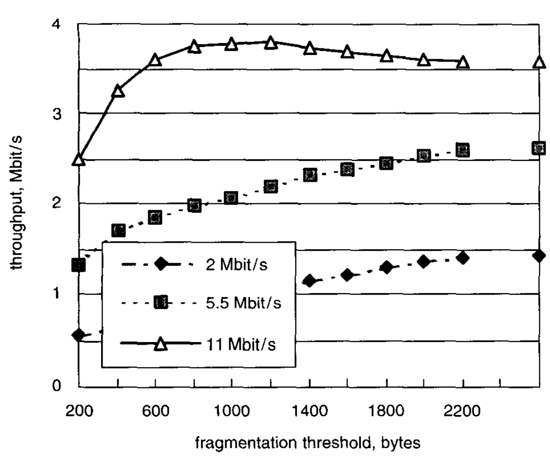

Fig. 7 *Fragmentation threshold effects on data throughput in the single-rate WLAN with 10 stations*

This is because of the effects of the time-correlated multipath fading channel model. For the 2 and 5.5 Mbit/s WLANs in this simulation, mobile stations are located in a restrictive region where the received signal power is prone to fade out below the required decoding signal level. Unfortunately, if the MSDUs are fragmented, a longer transmission time for the whole MSDU is needed and there is a greater probability of it falling into the fading region. The suggested values of the RTS threshold and the fragmentation thresholds for different data rates are summarised in Table 1.

Table 1: RTS and fragmentation thresholds for WLANs with different data rates

Data rate	RTS threshold	Fragmentation
2 Mbit/s	100 octets	never
5.5 Mbit/s	200 octets	never
11 Mbit/s	400 octets	1200 octets

4.2 Performance of the frame-based multirate WLAN

Figs. 8 and 9 show the throughput and average delay for different data rates with 10 mobile stations and the arrival rate being normalised to 2 Mbit/s. The average delay is measured from the time an MSDU arrives at the MAC layer of the transmitter up until the MSDU is received completely by the receiver. In these Figures, data for multirate WLANs with and without modification by our proposed method and for single-rate WLANs with rates of 2 or 11 Mbit/s are plotted. Table 2 summarises the maximum arrival rate, the corresponding throughput and the average delay. The maximum arrival rate is determined by the reasonable corresponding average delay. Beyond these values, the average delay increases very fast to the values that a network system cannot accept.

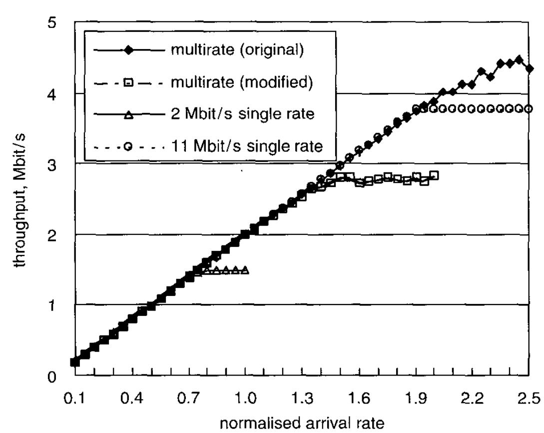

Fig. 8 *Effect of arrival rate on the data throughput*

Bizarrely, in the multirate WLANs, the throughput keeps increasing when the arrival rate exceeds the values listed in Table 2. Moreover, the throughput of the multirate WLAN without NAV modification exceeds the maximum throughput of the single-rate 11 Mbit/s WLAN. This is because of the over-inhibition problem. Under heavy load conditions, most of the mobile stations, bar the transmitter and the receiver, have been inhibited from accessing the channel. The transmitter or the receiver, which transmits frames using 11 Mbit/s, is able to access the channel without contention most of time, so the maximum throughput exceeds the single-rate 11 Mbit/s WLAN.

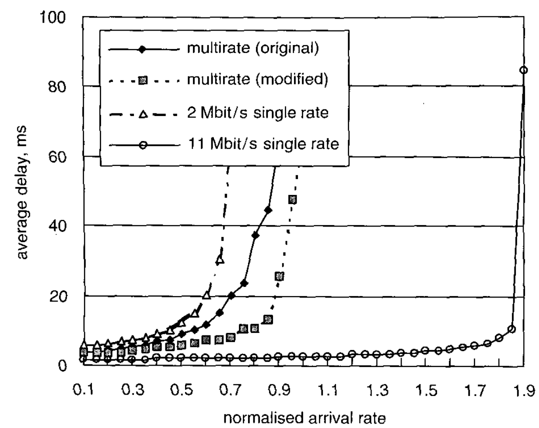

Fig. 9 *Effect of arrival rate on the average MSDU delay*

Table 2: Some meaningful outcomes resulting from Figs. 8 and 9

	Maximum arrival rate	Throughout (Mbit/s)	Average delay (ms)
single rate (11 Mbit/s)	1.85	3.68	10.9
single rate (2 Mbit/s)	0.7	1.39	63.6
multirate (original)	0.9	1.78	63.6
multirate (modified)	1.0	1.99	69.3

However, in the reasonable region where the arrival rate is less than the maximum arrival rate, we find that the throughput of the single-rate WLAN with 11 Mbit/s data rate is only about 3.68 Mbit/s. It is less than three times the throughput of a 2 Mbit/s WLAN. Basically, this is because a longer header (compared to the payload length) is used in the 11 Mbit/s WLAN. However, the coverage area of the 11 Mbit/s WLAN in the simulation model is about one quarter of the coverage area of the 2 Mbit/s WLAN. If the frame-based multirate WLAN is available, the throughput is 1.99 Mbit/s which is an improvement of about 600 kbit/s with the same coverage area compared with the 2 Mbit/s WLAN.

5 Conclusions

This paper studies the MAC operation performance when applying the LA methodology to the IEEE 802.11b WLANs. We consider in this paper a frame-based multirate scheme in which the transmission rate of each frame is selected dynamically based on the detected SNR of the previous transmission/reception rather than on a predetermined rate. Dynamic rate selection improves the flexibility of deploying WLANs and will be helpful for QoS control. The challenges, which are faced in the WLANs to make the LA possible, are how to coordinate the transmission among the mobile stations which share the medium, and how to choose a good rate adaptation algorithm. This paper provides a modification for the MAC operation to obtain the benefit of LA and maintains the nature of fair contention of WLANs. We investigate the problems in the NAV reservation scheme and proposed a modification. The thresholds of RTS and fragmentation, throughput, and packet delay in a multirate WLAN are illustrated through simulation.

The provided modification of MAC operation can be directly applied to the IEEE 802.11a, adapting a range of data rates from 6 up to 54 Mbit/s. While HIPERLAN type 2 uses a centralized and scheduled MAC based on wireless ATM, a specific LA design is thus needed.

6 Acknowledgments

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