MRMC: A Multi-Rate Multi-Channel MAC Protocol for Multi-Radio Wireless LANs

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Abstract

Dynamic transmission rate selection is widely used in IEEE 802.11b wireless LANs (WLANs) to combat adverse wireless channel conditions. However, overall system throughput suffers when stations with different transmission rates share the same physical channel. In this paper, we describe and evaluate a multi-rate multi-channel Medium Access Control (MAC) protocol to solve this problem. Our approach uses different transmission channels to isolate high-rate stations from low-rate stations. Simulation (ns-2) is used to evaluate the performance of the proposed protocol, assuming 4 channels and 4 transmission rates (1, 2, 5.5, and 11 Mbps). Our simulation results show throughput improvements of up to 450% compared to the IEEE 802.11b MAC protocol.

Keywords: IEEE 802.11, Wireless LANs, Simulation

1. Introduction

In recent years, IEEE 802.11 [2] wireless local area networks (WLANs) have been widely deployed in universities, offices, hotels, airports, and other public places. These WLANs, which use an Access Point (AP) to relay traffic to and from the Internet, offer physical-layer transmission rates of 11 Mbps for IEEE 802.11b [3] and 54 Mbps for IEEE 802.11a [4].

The IEEE 802.11 specification allows an AP and the associated mobile stations to communicate using transmission rates other than the maximum physical-layer rate. For example, the IEEE 802.11b specification defines four bit rates (1, 2, 5.5, and 11 Mbps), each with a different modulation scheme. For each outgoing frame, the sender's Medium Access Control (MAC) layer dynamically chooses the transmission rate to use based on current wireless channel conditions. Since the lower transmission rates use simpler modulation schemes, the transmitted frame is less likely to experience bit errors [12, 20]. Changing transmission rates on a per-frame basis can combat the detrimental effects of wireless channel propagation, such as path loss, shadowing, and multipath fading [20]. Dynamic rate selection also allows a mobile station far from the AP (i.e., weak receiving power) to use a lower transmission rate. Holland *et al.* [12] demonstrate the performance advantages of multi-rate protocols over single rate protocols.

While multiple transmission rates offer flexibility and performance advantages, problems can arise when several mobile stations share the same physical channel [7, 11]. In particular, the saturation throughput of the WLAN degenerates to that of the station using the lowest bit rate. This phenomenon happens because once a low-rate station acquires the channel, it occupies the channel for a long time. High-rate stations have to wait for the channel during this time. If low-rate and high-rate stations have equal opportunity to access the channel, and transmit frames of the same size, then high-rate stations suffer from the presence of low-rate stations. The net result is a degradation in total throughput.

Cantieni *et al.* [7] proposed two solutions to this problem. One solution is to reduce the channel access probability for low-rate stations, by manipulating the contention window CW. The other solution is to restrict the frame size of the low-rate stations. Both mechanisms reduce the channel occupancy time of the low-rate stations, allowing high-rate stations more time to use the channel. These mechanisms improve fairness as well as the total throughput [7].

In this paper, we consider a multi-channel solution to the performance problem. The key idea in our MAC protocol is to keep low-rate and high-rate stations on different physical channels, so that the channel access of low-rate stations does not affect high-rate stations. More specifically, in our *Multi-Rate Multi-*

Channel (MRMC) protocol, *multiple* channels are used in an AP *simultaneously*, each with a different transmission rate (i.e., modulation scheme) and transmission range (i.e., distance). A station associates with a channel based on the signal strength received from the AP. With this approach, high-rate stations compete with each other on one channel, while low-rate stations compete with each other on another channel. Since the high-rate stations are isolated from the low-rate stations, the total system throughput increases.

The multiple physical channels required by our MRMC protocol can be obtained in several ways. For example, in the widely-deployed IEEE 802.11b WLANs, three non-overlapping channels can be used simultaneously, though some engineers advocate four slightly overlapped channels [16]. In the IEEE 802.11a WLANs, eight non-overlapping channels can be used simultaneously. In Code Division Multiple Access (CDMA) systems [20], different chip codes can be used to obtain different physical channels. Therefore, we believe that our protocol can be implemented on current hardware, as well as on future WLANs.

The rest of the paper is organized as follows. Section 2 provides a brief description of the background and prior related work. Section 3 describes the proposed MRMC MAC protocol. Section 4 describes the performance evaluation methodology. We evaluate the MRMC protocol using the `ns-2` [21] network simulator. Section 5 presents the simulation results. Section 6 discusses additional issues related to the MRMC protocol. Finally, Section 7 concludes the paper.

2. Background and Related Work

2.1. IEEE 802.11 WLANs

An IEEE 802.11 WLAN can be configured in either *infrastructure* mode or *ad hoc* mode. In infrastructure mode, an AP acts as a central point to relay traffic to and from the Internet. In ad hoc mode, no AP is required; stations communicate among themselves in a peer-to-peer fashion.

In this paper, we only study infrastructure mode. The AP broadcasts a *beacon* frame every 100 ms. A mobile station receiving the beacon frames uses the signal strength to determine if it is well-connected, or needs a handoff.

The IEEE 802.11 standards specify the physical layer and MAC layer protocols for IEEE 802.11 compliant WLANs. The physical layer specifies the modulation scheme for the air interface. In IEEE 802.11b, four modulation schemes are defined, corresponding to transmission rates of 1, 2, 5.5, and 11 Mbps.

The IEEE 802.11 MAC layer requires a positive ACK for every received frame. If no ACK is received, the sender retransmits the frame. If there is still no ACK received after the maximum number of retries, the sender aborts transmission of the current frame.

The MAC layer can also do dynamic transmission rate selection. Implementation of this automatic rate selection feature is vendor-specific. Most commercial APs and wireless NICs use an algorithm similar to the following, which is based on Lucent's WaveLAN-II [13]:

- When a station associates to the AP for the first time, it defaults to a transmission rate of 11 Mbps.
- If two consecutive frames at the current rate receive no ACKs, then the sender tries the next lower rate (if any). The sender also sets a timer (60 ms) to try a higher rate later.
- If 10 consecutive transmissions are successful, or the timer expires, the sender tries the next higher rate (if any). In the former case, the sender cancels the timer. In the latter case, if the (higher-rate) transmitted frame is unsuccessful, the sender reverts to the current rate immediately, since the channel probing is unsuccessful.

We use this WaveLAN-II algorithm as the baseline for comparison in our simulation study. This algorithm is sender-based. That is, the sender makes the decision without the help of the receiver. The sender must probe the channel occasionally with a higher transmission rate (hence the timer in the algorithm).

2.2. Wireless Channel Modeling

One important issue in WLAN simulation studies is modeling the wireless channel. This subsection provides some background on wireless channel modeling, and the model used in our work.

In digital communication theory, the bit error rate (BER) of a modulation scheme depends on the received *signal-to-noise ratio* (SNR) [18]: the higher the received SNR, the lower the BER. On the other hand, for a given SNR, simpler modulation schemes tend to have lower BER. That is, since simpler modulation schemes generally represent lower bit rates, a frame transmitted with a lower bit rate is less likely to experience errors than a frame transmitted with a higher bit rate at the same SNR.

The received SNR is largely determined by the propagation environment. In a wireless channel, the large-scale path loss and small-scale (multipath) fading are the two main factors that affect the SNR [20]. Path loss determines the *mean* signal strength at a certain receiver distance. Multipath fading is caused by the superposition of multiple in-phase and out-of-phase copies of the original transmitted signal. It can cause rapid fluctuations in received signal strength over very short time scales. The received signal strength depends on the transmitted power, the path loss, and the multipath fading characteristics.

There are well-established mathematical models for path loss and multipath fading [20]. In a non-line-of-sight wireless propagation environment, multipath fading is usually represented with a Rayleigh channel model, which we use in our simulations in Section 4.1. The path loss (PL) can be calculated [20] using:

$$\overline{PL(dB)} = \overline{PL(d_0)} + 10\ n\ log(\frac{d}{d_0}) \qquad (1)$$

where n is the *path loss exponent* (typically 2-6 for indoor propagation environments, and 3 in our simulations), d is the distance between the transmitter and the receiver, and d_0 is the close-in reference distance (typically 1 meter for indoor propagation environments). $\overline{PL(d_0)}$ is the mean received power (in dB) at the close-in reference distance d_0. The mean received power (in Watts) at d_0 can be estimated using the Friss free space propagation model:

$$\overline{P_r(d_0)} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_0^2 L} \qquad (2)$$

where P_t and P_r are the transmit and receive powers, G_t and G_r are the transmit and receive antenna gains (typically 1), λ is the carrier wavelength, and L is the system loss factor (typically 1). $\overline{PL(dB)}$ is then equal to 10 $log_{10}(\overline{P_r(d_0)})$.

The BER for a given modulation scheme can be calculated from the received SNR. For well-known modulation schemes, theoretical work expresses the relationship between BER and SNR. For example, the BER of Binary Phase Shift Keying (BPSK), used for the 1 Mbps transmission rate in IEEE 802.11b, is given by:

$$P_b = Q\sqrt{\frac{2 \cdot SNR \cdot B}{R}} \qquad (3)$$

where B is the bandwidth (in Hz) of the modulated signal and R is the bit rate of the modulation scheme [18].

Figure 1 shows the BER versus SNR performance for all modulation schemes used in IEEE 802.11b. The 2 Mbps transmission rate uses Quadrature Phase Shift Keying (QPSK), while the 5.5 and 11 Mbps transmission rates use Complementary Code Keying (CCK) [3]. CCK modulation is a variation of M-ary biorthogonal modulation [17]. The results in Figure 1 were calculated using Equation 5.2-34 in [18]. The other relevant BER formula can also be found in [18].

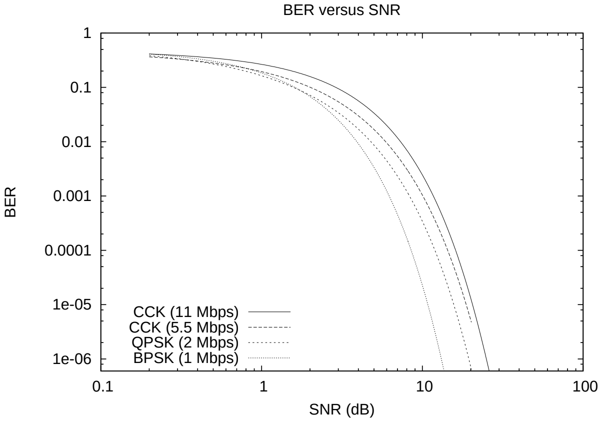


Figure 1. BER Performance of IEEE 802.11b Modulation Schemes

Figure 1 indicates the required SNR for a specific BER, given a modulation scheme. This knowledge can be used to set the threshold for transmission rate selection (i.e., modulation scheme) based on the received SNR. For example, if the maximum BER is 10^{-5}, and the SNR falls below the required value for the current modulation scheme, then the station needs to adjust its rate.

2.3. Related Work

Heusse *et al.* [11] first reported the performance problem mentioned in Section 1, and Cantieni *et al.* [7] later confirmed its existence. Heusse *et al.* offered no solution to the problem, while Cantieni *et al.* proposed two mechanisms to limit channel usage by low-rate stations. Holland *et al.* [12] and Liu *et al.* [15] proposed multi-rate MAC protocols with dynamic transmission rate selection. However, these works consider only a *single* physical channel. In contrast, our work uses multiple channels and multiple rates.

Multi-channel MAC protocols are receiving greater attention recently, particularly for wireless ad hoc networks [14, 19, 22]. In these protocols, multiple channels are used to transmit frames between different pairs of nodes. Channel selection is done on a per-frame basis.

There is growing evidence that multi-channel and multi-rate protocols are technologically and commercially feasible [5, 6, 9]. For example, Engim [9] describes a multi-channel protocol similar to our own. However, it mostly focuses on physical-layer interference reduction when multiple channels are used simultaneously. No MAC layer algorithms are described and no performance data are given.

Multi-radio systems are also emerging as a practical way to implement multi-channel protocols [1, 6, 8]. These protocols offer significant advantages over traditional wireless networks, with modest added cost [6].

Our work differs from the foregoing studies in several subtle but important ways. First, we consider multiple channels in an infrastructure-based WLAN, rather than in an ad hoc network. Multiple radios are required only in the AP, not elsewhere in the network (e.g., mobile stations, wireless routers [1]), simplifying the network, and lowering its cost. Second, the AP transmit power for each channel is carefully controlled to provide concentric rings of coverage around the AP. Each ring corresponds to a different data rate. Third, our protocol supports dynamic assignment of data rates to each ring of coverage, though we do not evaluate this feature in this paper. Finally, channel selection and rate adaptation are determined by the mobile stations, and not centrally by the AP. That is, node mobility largely determines channel selection.

3. MRMC Protocol

Our Multi-Rate Multi-Channel (MRMC) protocol has three components: an algorithm to assign the bit rate for each channel (e.g., channel A is 11 Mbps, channel B is 5.5 Mbps, and so on); an algorithm to determine the desired transmission rate (i.e., channel) for each station; and a procedure to exchange channel selection information between a station and the AP.

The bit rate assignment can be done statically or dynamically. In a static assignment, the bit rate associated with each channel is fixed, usually at configuration time. In a dynamic assignment, the bit rate for each channel changes with time. In this paper, we assume static assignment, leaving dynamic assignment for future work.

The rate assignment information is broadcast in the beacon frames: each channel broadcasts its own beacon frames advertising its rate. When a station associates to the AP for the first time, it scans all channels by listening to the beacon frames. From the rate information carried in the beacon frames, the station knows all the $(channelID, data\ rate)$ pairs.

Each mobile station associates to one channel at a time. A station decides what rate to use based on the received SNR. By checking the $(channelID, data\ rate)$ information, it knows with which channel to associate. The station then sends a *channel association* frame to the AP on the current channel. After receiving the channel association frame, the AP marks in its internal channel association table that the station is listening on the indicated channel. A *channel association grant* frame is sent by the AP to the requesting station. After receiving the channel association grant, normal communication can be conducted between the AP and the station using the indicated channel.

The algorithm to estimate the desired transmission rate is based on the received SNR. During normal communication, a station maintains a moving average of the SNRs of the incoming beacon frames. That is, the station calculates the new SNR as $SNR_{avg} = \alpha \cdot SNR_{avg} + (1-\alpha) \cdot SNR_{new}$, where SNR_{new} is the SNR of the incoming beacon frame.

The purpose of the moving average is to smooth small-scale signal variations due to multipath fading, which may cause unnecessary channel switching. After calculating the SNR_{avg}, the station switches to the corresponding channel C_j according to the following algorithm:

$$C_1 \text{ if } SNR_{avg} > T_1 \qquad \text{(highest bit rate)}$$

$$C_i \text{ if } T_i < SNR_{avg} \leq T_{i-1},\ i = 2, \ldots, N-1$$

$$C_N \text{ otherwise} \qquad \text{(lowest bit rate)}$$

where the T_i's are threshold values determined from a graph like Figure 1 for the target BER.

When a station decides to switch channels, it sends a channel association frame on the *old* channel. Only after receiving a channel association grant on the old channel does the station switch to the new channel.

The new protocol can be implemented by modifying the IEEE 802.11 MAC protocol. The IEEE 802.11 beacon frames can be modified to carry the transmission rate information. The channel association and grant frames can be implemented by modifying the 802.11 association and grant frames to include the desired channel. Note that our new protocol does not attempt to change the transmission rate on a per-frame basis. Instead, the station adjusts the transmission rate at most once per beacon interval (100 ms). This adjustment frequency is suitable for stationary or slow-moving WLAN users (0-4 m/s).

4. Performance Evaluation Methodology

We evaluate the MRMC protocol using simulation, with the `ns-2` network simulator [21]. The performance metric of interest is TCP throughput, since TCP is widely used on the Internet. We test stationary and mobile scenarios exemplifying typical WLAN usage.

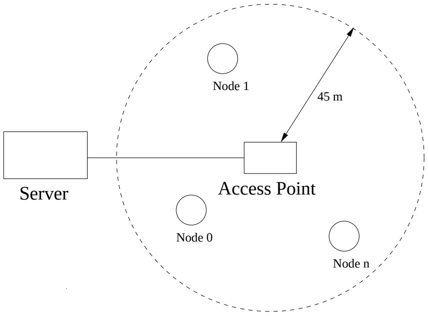


Figure 2. General Simulation Model

The general simulation model is shown in Figure 2. A wired TCP server is connected to an AP via 100 Mbps Ethernet. The transmission power of the AP is set to cover (on average) a circular area with a radius of 45 meters. Multiple stations placed within this range communicate with the AP via the wireless channel(s). They act as the TCP clients, downloading data from the server using fixed-size 1500-byte packets (frames).

The TCP model in the `ns-2` network simulator is used to simulate the TCP server and clients. All simulations use the TCP NewReno model, which tolerates multiple packet losses in a window of data. The application layer has infinite data to send (i.e., FTP-like bulk transfers). Each experiment runs for 300 seconds of simulated time.

The `ns-2` simulator has limited wireless channel models. We extended the model to include path loss, multipath fading, and modulation errors. The following subsections describe wireless error modeling and the experimental design for the simulation study.

4.1. Wireless Channel Error Modeling

Wireless channel errors are simulated as follows:

- For each received frame, calculate the SNR according to the method in Section 2.2.
- Substitute the SNR into the formula for the appropriate modulation scheme to obtain the BER.
- Generate a Uniform(0,1) random number to determine if the frame is valid or not, based on the BER. A frame with errors is dropped. Otherwise, the frame is accepted.

There are several ways to simulate the Rayleigh channel, one of which is Jakes' method [12]. We use an improved Jakes' method from the literature [23]. The algorithm first generates two random numbers $X_c(t)$ and $X_s(t)$ as follows:

$$X_c(t) = \frac{2}{\sqrt{M}} \sum_{n=1}^{M} cos(\psi_n) \cdot cos(\frac{2\pi vt}{\lambda} \cdot cos\alpha + \phi) \quad (4)$$

$$X_s(t) = \frac{2}{\sqrt{M}} \sum_{n=1}^{M} sin(\psi_n) \cdot cos(\frac{2\pi vt}{\lambda} \cdot cos\alpha + \phi) \quad (5)$$

with

$$\alpha_n = \frac{2\pi n - \pi + \theta}{4M}, \quad n = 1, 2, \ldots, M \quad (6)$$

where ψ_n, ϕ, and θ are all uniform random variables distributed over $[-\pi, \pi)$, v is the moving speed of the mobile, and λ is the carrier wavelength. The received signal amplitude is then $|a(t)| = \sqrt{X_c^2(t) + X_s^2(t)}$.

In our simulation, we vary v from 0 to 4 m/s for mobile stations. For stationary clients, we set $v = 1$ m/s so that even if the clients are stationary, the channel varies because of the changing environment. For example, even people walking near the AP and the stations can cause transmission path changes. The variation of signal strength in stationary stations has been confirmed by measurement in [10].

The rapid variations of multipath fading could cause the SNR to change during the reception of a frame. According to [20], the stable duration of a wireless channel is characterized by $T_c = \frac{0.423}{f_m}$, where f_m is the maximum Doppler shift given by $f_m = v/\lambda$. For a slow-moving mobile station with $v = 4\ ms$, $T_c = 13.2\ ms$ for a carrier frequency of 2.412 GHz. Transmitting a 1500-byte frame at 1 Mbps takes about 12 ms. Since $T_c >$ 12 ms, we assume in the simulation that the channel does not change during the reception of a frame. (This may not hold for higher velocities.)

4.2. Simulation Experiments

Three sets of experiments were conducted to evaluate the performance of the MRMC protocol.

The first set of experiments investigates the effect of the smoothing factor α. Both stationary and mobile scenarios are tested, using the general model shown in Figure 2. In the stationary scenario, a station was placed at different distances from the AP, namely 5, 15, 25, and 35 meters. For each distance, the value of α was varied between 0 and 1. In the mobile scenario, a station was moving randomly with a speed of 0.5 m/s, 1 m/s, 2 m/s, 3 m/s, or 4 m/s) within the 45m circular area around the AP. For each speed, α was varied from 0 to 1. For both stationary and mobile experiments, the TCP server sent TCP transfers continuously to each station. An α value with consistently high throughput was chosen for the remaining experiments.

The second set of experiments was designed to show the performance advantages of the proposed MRMC over the WaveLAN-II protocol in a static network topology. More specifically, multiple stationary clients were placed randomly within the WLAN. The number of stations was varied from 2 to 50, in steps of 2. Each station initiated a TCP transfer from the server. The total TCP throughput was calculated after each experiment. We repeated each experiment 30 times, with different seeds for the random placement of stations and the FTP start times. We calculated the mean of the total throughput, as well as 99% confidence intervals.

The third set of experiments studies the impact of mobility. These experiments use 20 stations, each moving randomly in the circular area around the AP. Five velocities were tested, namely 0.5 m/s, 1 m/s, 2 m/s, 3 m/s, and 4 m/s. The speed of each station was randomly chosen within ± 10% of the mean. For each experiment, we calculated the total throughput. The experiment was repeated 30 times, with different seeds for the FTP start times. We calculated the mean of the total throughput, and 99% confidence intervals.

In all experiments, we use 4 channels and 4 transmission rates. This approach simplifies the problem, since each rate is assigned to its own channel. If the number of rates exceeds the number of channels, then multiple rates must share a physical channel, reducing the performance advantages of our MRMC protocol. However, other techniques [7] can be used to mitigate this effect. We discuss this issue further in Section 6.

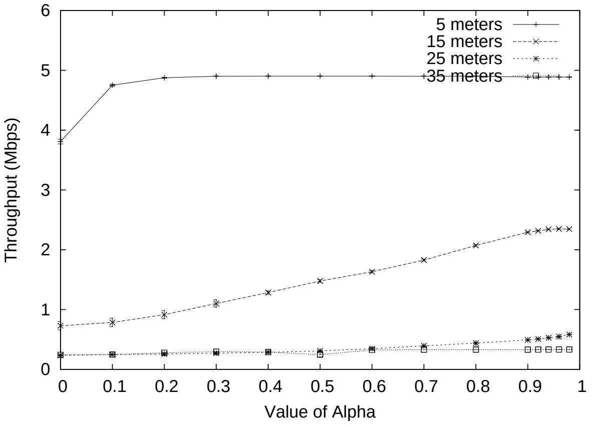
Note that the four-channel assumption is not unrealistic. Although the IEEE 802.11b standard suggests 3 non-overlapping channels be used, some engineers advocate 4 slightly overlapped channels [16].

5. Simulation Results

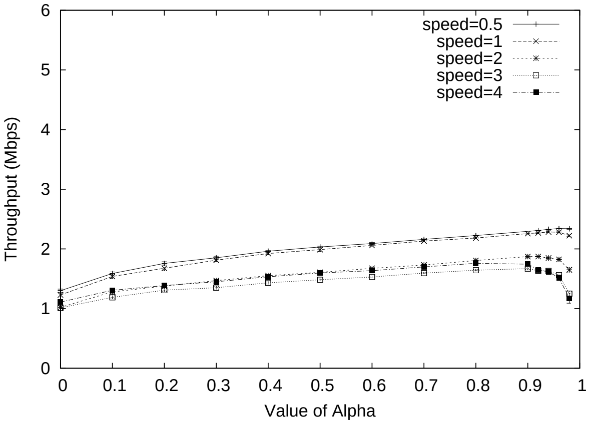
5.1. Effect of Smoothing Parameter α

Figure 3 shows the results for the first set of experiments, studying the effect of α. In general, the performance of the protocol is not very sensitive to α, though increasing α often tends to improve throughput.

For stationary stations (Figure 3(a)), throughput is primarily a function of distance. Stations far from the AP (e.g., 25 or 35 meters) usually receive weak signals, and consistently select a low transmission rate. For example, detailed results show that a station 35m from the AP uses 1 Mbps most of the time, regardless of the value of α. A similar observation applies for nearby stations. A station 5 meters from the AP has a smoothed



(a) Stationary Scenario



(b) Mobile Scenario

Figure 3. Effect of Smoothing Parameter α

SNR large enough to select 11 Mbps most of the time, so there is no throughput improvement with varying α. If α is too small (less than 0.1), the station is overly sensitive to the instantaneous SNR value. A transient low SNR could cause the station to switch to a lower data rate (e.g., 5.5 Mbps), yielding lower throughput.

Stations at an intermediate distance (e.g., 15 meters) are the most sensitive to the value of α, and its influence on dynamic rate selection. These stations observe widely ranging SNR values. For this case, larger α values provide more stable rate selection.

The results in Figure 3(b) for the mobile scenario also show low sensitivity to α. One new observation is that when α is too large (e.g, ≥ 0.95), the smoothed SNR fails to reflect current channel conditions, compromising throughput. This trend is more obvious as the mobility speed increases.

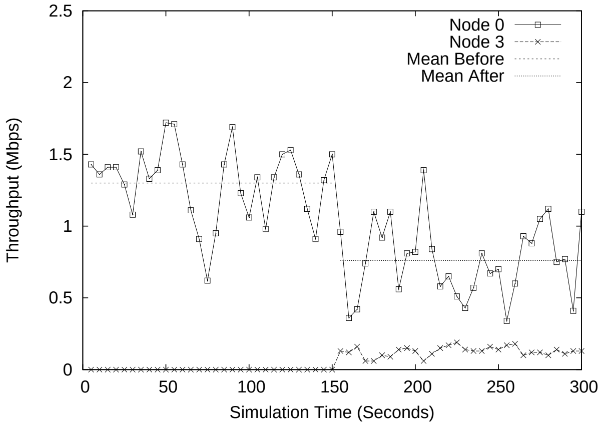
In the rest of the experiments, we use $\alpha = 0.9$, which performs well for all cases studied.

5.2. Stationary Scenario

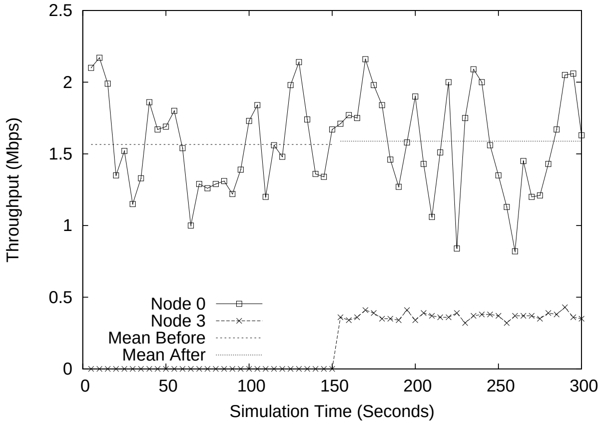
In this section, we evaluate our MRMC protocol in a stationary topology. Before we report the main results, we show a simple experiment to confirm the throughput degradation problem for the original IEEE 802.11b MAC protocol and how the MRMC protocol solves the problem. More specifically, we use the general model shown in Figure 2, with four stationary stations. One of the stations was placed 35m from the AP, while the other three were all within 8m of the AP. In this setting, the far station receives weak signals and selects a low transmission rate. At the transport layer, the server transfers data to all mobile hosts. The TCP transfers start at 0s for the near stations, and at 150s for the far station. For each transfer, the average throughput over each 5s interval is plotted.

Figure 4 shows the simulation results. There are three important observations. First, the overall throughput with the MRMC protocol in Figure 4(b) is slightly higher than that with the WaveLAN-II algorithm in Figure 4(a). This difference is attributed to the greater stability of rate selection in the MRMC protocol. Second, when the low-rate station starts its transfer at 150s, the mean throughput in Figure 4(a) decreases. For the MRMC protocol in Figure 4(b), the high-rate stations are unaffected. Third, the low-rate station (Node 3) achieves a higher throughput in Figure 4(b) than it does in Figure 4(a). These results demonstrate the benefits of isolating low-rate sources from high-rate sources in MRMC.

Having illustrated the performance advantages of the MRMC protocol, we now report the simulation

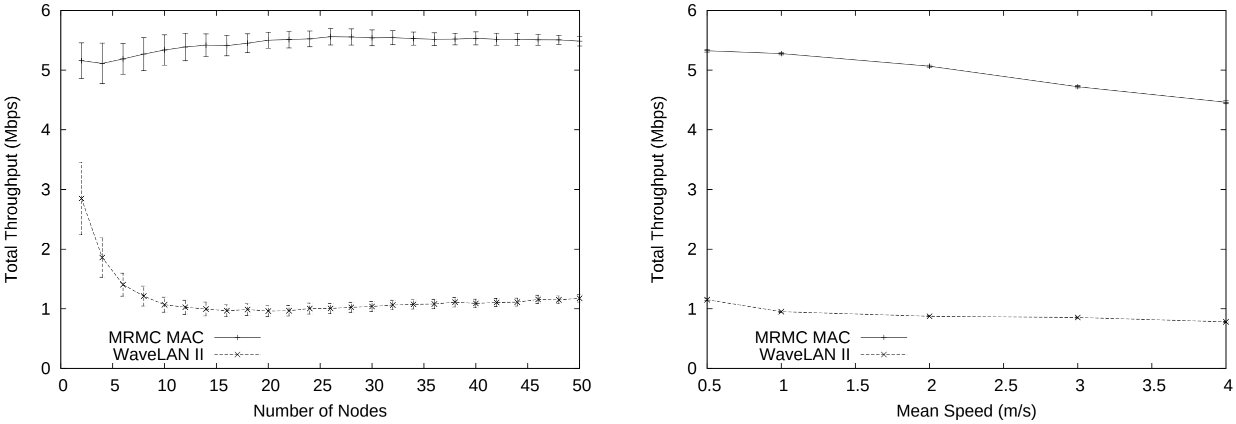


(a) WaveLAN-II



(b) MRMC

Figure 4. Effect of Low-Rate Stations



(a) Stationary Scenario (b) Mobile Scenario

Figure 5. Simulation Results for MRMC Performance

results for the second set of experiments described in Section 4.2. The experiments compare the MRMC protocol and the WaveLAN-II approach as the number of (stationary) stations in the WLAN is increased.

Figure 5(a) shows the simulation results. The top line in the graph shows that the MRMC protocol achieves consistently high aggregate throughput as the number of stations is increased. The behaviour is quite different for the WaveLAN-II protocol, for which the throughput drops when the number of stations is increased from 2 to 10. The aggregate throughput then remains steady as more stations are added.

The throughput drop for the WaveLAN-II protocol in Figure 5(a) reflects the impact of low-rate stations. Even with just *one* station far from the AP (i.e., transmitting at a low rate), the overall system performance suffers. With many stations randomly placed, it is highly likely that at least one station is far away. With few stations, this probability is lower: total throughput is higher, and more variable.

The MRMC protocol provides the important property of traffic isolation. The total throughput stays roughly the same, as long as the WLAN is not congested. Of course, the average throughput per station decreases as the number of stations increases.

The MRMC protocol outperforms the WaveLAN-II protocol in all cases considered, with an average throughput advantage of 450%. This advantage comes from the 4 concurrent channels, which increase the effective WLAN capacity by about 80% (the sum of the additional channel rates supported). The super-linear performance comes from dedicating the 11 Mbps channel to the stations that can use it most effectively. Separate experiments with a two-channel system (1 Mbps and 11 Mbps) show a 400% throughput advantage.

5.3. Mobile Scenario

Figure 5(b) shows the simulation results for the mobile experiments. The MRMC protocol has roughly the same performance advantage over the WaveLAN-II protocol as in the stationary scenario. The total throughput decreases for both the MRMC protocol and the WaveLAN-II protocol as the velocity of mobile stations is increased. However, the throughput is not very sensitive to this mobility. These results are consistent with those in Section 5.1 for the effects of smoothing parameter α.

6. Discussion

The proposed MRMC protocol makes use of all the available channels in current IEEE 802.11 WLANs. This could cause deployment problems. For example, if there is another WLAN nearby, there may be interference problems.

There are two potential solutions to this problem. One approach is to use another chip code for the adjacent cells. This solution requires a modification to the IEEE 802.11 WLAN hardware, as the chip code is fixed in the specification. The other approach is to adjust the transmit power of each channel.

The latter solution is preferred, since it requires no hardware changes. Only the transmission power for each channel has to be adjusted. If the transmission power of the channels are arranged in such a way that the highest-rate channel transmits at a lower power, and the lowest-rate channel at a higher power, then an adjacent WLAN may only see one channel in use (i.e., the channel with the highest transmission power). The adjacent WLAN can therefore use other channels.

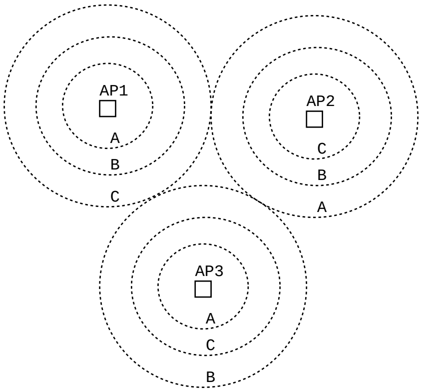


Figure 6. MRMC WLAN Deployment Example

Figure 6 illustrates this scheme for three APs. The first AP (AP1) has three channels, with the transmission power increasing from channel A to channel B to channel C (the concentric rings indicate the transmission range of the channels). The adjacent APs are only aware that channel C is in use. AP2 can choose transmission powers in the order C, B, and A. Similarly, AP3 might use the order A, C, and B.

We call this WLAN architecture *RainDrop*, because of the patterns of concentric circles induced. In this paper, we only consider this architecture for infrastructure-based WLANs. We are yet to consider this solution for wireless ad hoc networks.

Another challenge for the MRMC protocol is if the number of transmission rates exceeds the number of channels available. In this case, several transmission rates have to share the same transmission channel, which can degrade the performance if low-rate stations affect high-rate stations.

Our recommended solution is to assign the high-rate stations to one channel, while letting stations with lower rates share the remaining channel(s). Stations sharing a channel with heterogeneous rates can use the method proposed in [7] to restrict the channel occupancy by the lowest-rate stations.

7. Summary and Conclusions

This paper describes a multi-rate multi-channel (MRMC) MAC protocol to solve the throughput degradation problem caused by low-rate stations sharing the same channel with high-rate stations. The proposed protocol uses multiple channels, each with a different transmission rate. High-rate stations associate on one channel, while lower-rate stations associate on other channels. Isolating high-rate stations from low-rate stations improves the overall system throughput.

We evaluated the MRMC protocol by simulation, using the `ns-2` network simulator. Our simulation results show that with 4 channels and 4 rates, the MRMC protocol can provide 450% higher throughput than the conventional IEEE 802.11b protocol. This performance advantage applies not only for the stationary scenario, where the stations are placed randomly within a circular area around the AP, but also for the mobile scenario, where the stations are moving randomly at a speed of 0.5 m/s to 4 m/s around the AP.

We believe that the MRMC protocol is promising. Our future work involves the comparison of the MRMC protocol with other protocols in literature, and the evaluation of the extensions discussed in Section 6. Finally, we are interested in exploring dynamic rate assignment algorithms, for both infrastructure-based and ad hoc wireless networks.

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