Opportunistic Random Access in CSMA/CA-Based Wireless Networks

by

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Abstract

IEEE 802.11 MAC based CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) is the most widely used protocol in wireless networks. In CSMA/CA, every node listens to the shared wireless medium and transmits only when the channel is sensed idle to avoid possible collisions. CSMA/CA allows each user of equal probability in accessing wireless channel, which incurs equal throughput in long term regardless of the channel conditions. To exploit user diversity that refers to the difference of channel condition among users, we proposed three opportunistic random access mechanisms: overlapped contention, segmented contention and normal distribution based contention, to favor the user of best channel condition in channel access. In the overlapped contention, the contention windows of all users share the same ground of zero, but have different upper bounds upon channel condition. In the segmented contention, the contention window upper bound of a better channel condition is smaller than the lower bound of a worse channel condition; namely, their contention windows are segmented without any overlapping. In the normal distribution based contention, the back-off interval is determined using normal distribution with the expectation of proper mean and standard deviation value within the contention window. These algorithms are also enhanced to provide temporal fairness and avoid starving the users with poor channel conditions. The proposed mechanisms are implemented and evaluated in the NS3 simulator. Extensive experiments show that the proposed opportunistic random access schemes can significantly improve the network performance in throughput, delay, and jitter over the current CSMA/CA in IEEE 802.11 networks. In particular, the overlapped contention scheme can offer 73.3% and 37.5% throughput improvements in the infrastructure-based and ad-hoc networks, respectively.

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Chapter 1

Introduction

1.1 An Overview

Carrier sensing multiple access/collision avoidance (CSMA/CA) is widely used in many wireless networks as it can reduce potential collisions and, thereby, improve the overall network performance. It allows each user of equal probability in accessing wireless channel, which incurs equal throughput in long term regardless of the channel conditions. An interesting question arises: can network throughput be improved if users with temporally better channel conditions have higher chances in accessing wireless media? If users channels oscillate between good and poor conditions, which is a common phenomena observed in wireless networks, the fairness among different users of channel accessing is still assured. The signal transmitted on a wireless channel may reach the destination directly (line of sight) or through multiple reflections on local scatterers (buildings, mountains, etc.). As a result, wireless channel conditions are affected by multiple random attenuations and delays. Moreover, the mobility of users or scattering environment may cause these random fluctuations to vary with time. In wireless networks, the channel conditions are determined by many factors such as fading, mobility, shadowing and location. Therefore, wireless users often experience different channel conditions, which are referred as spatial diversity or user diversity in wireless communication. Due to the spatial diversity, a wireless user with excellent channel condition may be able to transmit data at the highest bit rate while others with poor links may not be able to transmit any data even at the lowest rate. Channel condition variations also lead to time diversity: a user may have a link of high bit rate now, but may have to use a low rate thereafter. The user diversity of channel conditions is often considered detrimental in traditional wireless communication systems because it is unpredictable and thus each user is treated with no difference. In recent years, opportunistic approaches have been attempted to exploit the inherent randomness of wireless channel to improve wireless network performance and utilization, including opportunistic rate adaptation, transmission, scheduling and routing. Opportunistic protocols exploit user diversity by granting higher priority to users with good channel conditions and/or time diversity by extending the use of channel in good conditions. Unlike the above-mentioned opportunistic transmission schemes, we propose and evaluate three opportunistic access schemes that exploit user diversity in the CSMA/CA. These schemes enable the user with the best channel condition to have the largest probability of accessing the shared channel, but do not starve the users with poor links. In the long run, each user probably obtains a throughput proportional to its channel conditions.

1.2 Objective of the Thesis

The main contributions and objectives of this work consist of:

- propose three distributed opportunistic random access variants for wireless networks,
- theoretical analysis of their opportunism and
- the implementation of the proposed algorithms in NS3- simulator.

1.3 Organization of this work

The rest of this thesis is organized as follows.

- Chapter 2 (Literature Review) provides details about the CSMA/CA mechanisms and related opportunistic access schemes are briefly reviewed.
- Chapter 3 (Problem Statement and Motivation) presents the problems that motivates this work.

- Chapter 4 (Design of Opportunistic Random Access) discusses about the design of three proposed opportunistic random access variants and also analyzes the opportunism of the proposed schemes.

- Chapter 5 (Performance Evaluation) presents the experiment settings, implementation details and the performance evaluation of the proposed schemes in the NS-3 simulator.

- Chapter 6 finally concludes this thesis.

Chapter 2

Literature Review

2.1 Overview of CSMA/CA

Many wireless networks such as IEEE 802.11 adopt CSMA/CA [4] as the core media access mechanism. The opportunistic algorithms proposed in this work are therefore based on this mechanism. CSMA/CA is a contention-based MAC protocol. In a typical CSMA/CA network, regardless of ad-hoc or infrastructure mode, all nodes that have data to transmit on the shared wireless link must undergo a contention procedure first. Only the node that wins the contention can transmit while all others freeze the contention procedure until the winner completes its transmission.

2.1.1 Binary Exponential Back-off Scheme

The contention is regulated by a binary exponential back-off process in which each node maintains a contention window that has a lower bound of 0 and an upper bound that starts with an initial value and may exponentially increase when network becomes congested. Then, a node that is ready to transmit randomly selects a back-off value Tb from the contention window using a uniform distribution. The node will keep sensing the channel.

If the channel is busy, the back-off value is frozen until the channel becomes idle. Otherwise, it is decremented by one at every (idle) time slot. When the back-off value reaches 0, the node starts its transmission. If the transmission fails, the current contention window upper-bound is doubled unless it has reached the maximum. Then another back-off procedure is repeated with the updated contention window. Although this back-off was created to avoid possible collisions from simultaneous transmissions from multiple nodes, it actually also regulates the likelihood of channel access using the size of the back-off interval.

Normally the value of back-off interval is selected within the default contention window and the contention window size varies depending upon the IEEE 802.11 MAC protocols. Without opportunism on random access protocols, all nodes have equal initial contention window regardless of their channel conditions. Therefore, they have an equal probability of selecting a back-off interval and win the channel in contention. For example, in IEEE 802.11g, the initial contention window size is 15 and each node selects a value from 0-15 as its back-off interval in uniform distribution. If a node consecutively losses the contention, its contention window size exponentially or linearly increases to avoid further collisions.

Although CSMA/CA has been used widely in wireless networks, it also has hidden terminal problem if multiple stations cannot hear each other. This is due to differences in transmitting power, receiver sensitivity, as well as distance and location with respect to each other. This issue can be avoided considerable by sending RTS (Request to Send) and CTS (Clear to Send) frames but still the network performance is not achieved similar to the one enjoyed in normal wireless networks in which nodes can hear each other. This is because RTS-CTS frame tend to use the channel resource and it is an extra overhead to the wireless channel utilization.

Many attempts has been made to improve the resource utilization and performance of wireless networks. Some of the works related to our opportunistic access scheme are discussed below:

2.2 Opportunistic Scheduling

An opportunistic CSMA/CA was proposed by Hwang and Cioffi [24], which targets the user diversity in WLAN. Their algorithm schedules a node to transmit at a specific time slot according to the signal-to-noise-ratio (SNR) of its channel. To avoid the nodes with the same SNR to collide with each other on the same time slot, a random number is introduced when the time slot is determined. These algorithms prioritize the users having high signal to noise ratio to gain earlier channel access.

Zhai et al. [21], [11] proposed an opportunistic media access control protocol that focused on the opportunistic scheduling of traffic at a node to its neighbors based on their channel conditions. The traffic to the neighbor with the best channel conditions is scheduled first for transmission. This protocol takes advantage of both multi-user diversity and rate adaptation techniques.

Qin and Berry [27] proposed an media access protocol to enable the user to transmit opportunistically when stations have favorable channel conditions without the use of a centralized scheduler. Each user measures the current channel conditions using the pilot signal broadcasted by the base station. This distributed approach to identify channel conditions adaptively scales up as the number of users increases and considerably reduces the overall round trip time of the frames.

2.3 Opportunistic Transmission

Opportunistic transmission based on multiple rates was demonstrated to yield a significant improvement of the network performance in IEEE 802.11 networks [1], [2], [3] where a node opportunistically transmits multiple frames if its bit rate is high, instead of traditionally one frame. These algorithms rely on rate adaptations such as RBAR [5] to estimate the channel conditions in terms of bit rate and then a sender calculates the number of frames that should be transmitted based on the adapted bit rate to maintain temporal fairness among nodes.

For example, opportunistic auto rate (OAR) protocol exploits time diversity to opportunistically send multiple back-to-back data packets whenever they have better channel quality. This is achieved by using the fragmentation mechanism of IEEE 802.11. If the channel conditions of a particular user are measured at a data rate above the base rate, the more fragments flag in the frame control field of MAC header is enabled by the sender until transmission rate divided by base rate number of packets are transmitted. The sender also needs to set the fragment number to zero in the sequence control field of MAC header to make sure that the transmitted frames are a data packet.

On the other hand, a multi-channel opportunistic auto rate media access protocol (MOAR) exploits frequency diversity (in the form of multiple frequency channels) to opportunistically select a better quality frequency channel to transmit data at high bit rates if the signal to noise ratio on the existing channel is not good.

These opportunistic transmission protocols occur after the contention of channel access that is still conducted with traditional non opportunistic approach: equal probability access. It exploits the time diversity and frequency diversity of a node, not the user diversity of a network.

Xin, Edwin and Ness [28] proposed an opportunistic transmission scheduling protocol exploiting time diversity of scarce wireless channel conditions to improve the network performance under a certain stochastic resource allocation constraint. This protocol assigns each user a number between 0 and 1 to represent the long-term fraction of time assignments to the user. With the resource allocation constraint and fairness constraint, a scheduling scheme that maximizes the channel utilization is proposed to determine which user should be scheduled to transmit at every time slot such that the network performance is optimized.

IEEE 802.11e [7] categorizes network traffic into various types and specifies different contention window size for each traffic type such that the highest priority traffic type such as real time video/audio is assigned in smallest size. In this way, the higher priority traffic has a chance to be delivered before lowest priority traffic types.

Vaidya [22], [23] proposed to dynamically vary the contention window to achieve the distributed proportional scheduling in IEEE 802.11 WLANs. Based on the weight assigned to each traffic flow, the contention window is calculated such that a more weighted flow has a smaller contention window. Then, the flow has more chances to use the channel for delivering more data than less weighted flows. Unlike opportunistic transmission taking advantage of time diversity due to the temporal dynamic characteristics of the wireless channel, opportunistic access exploits user diversity in wireless networks. In opportunistic transmission, after a node wins the contention, it tries to transmit aggressively while its channel remains good because the condition may degrade later.

In CSMA/CA, a node only transmits one frame when it wins the channel while in opportunistic transmission schemes such as OAR [1] and MOAR [3], more than one frame may be transmitted when a node wins access. The number of frames to be transmitted is determined by the channel conditions. In OAR and MOAR, the number of frames transmitted after a node wins the contention is calculated as the ratio of current bit rate over the basic rate.

2.4 Opportunistic Routing

Opportunistic Adaptive Routing protocol [25] focuses on multiple simultaneous flows in wireless mesh networks by 1) Exploiting path diversity to select the forwarding path opportunistically; 2) prioritize time-based forwarding to favor the user with best forwarding path and 3) adaptively determine the sending rate based on the current channel conditions.

kai and Zhenyu [26] proposed an opportunistic routing protocol for multi-channel multi-radio multi-hop wireless networks. This protocol focuses on the co-channel interference and the tradeoff between multiplexing and spatial diversity. The forwarding candidate selection is achieved opportunistically using linear programming approach to improve the network performance.

Petar and Hiroyuki [29] proposed an opportunistic scheduling for wireless network coding which takes advantage of multiple fading due to time diversity between the relay and the destination nodes. A relay node can combine many packets into a single packet and broadcasted to different receivers. Each receiver extracts the desired packet from the network codes packet thus reducing the number of transmissions. The relay is scheduled opportunistically to transmit network-coded packets based on the instantaneous channel conditions intended for different receivers. It takes advantage of both network coding and opportunistic scheduling in a wireless multi-hop network to improve the network performance. Therefore, various mechanisms have been proposed to opportunistically transmits frames depending upon the current channel conditions.

These observations motivates me to work on providing opportunism on the contention window mechanisms of binary exponential back-off schemes which are discussed in the following sections.

Chapter 3

Problem Statement and Motivation

The motivation of this work is to exploit user diversity in random access wireless networks. This motivation stems from a few observations as described below.

3.1 Impact of Access on Network Performance

The access mechanism in a wireless network with user diversity has significant impact on the network performance and channel utilization. Let us examine a network with a base station and two client nodes: A and B. Suppose A has poor channel conditions supporting a bit rate of R_l and B has good channel conditions supporting a bit rate of R_h. In one extreme case where only A has the access to the channel, the network throughput is A's bit rate R_l assuming no packet failure. In the other extreme case where only B uses the channel, the network throughput is B's bit rate R_h. Otherwise, if A and B share the channel, the network throughput will be some value between R_l and R_h. Namely, R_h and R_l are respectively the upper and lower bounds of the network throughput. Therefore, to improve the network throughput and channel utilization, B should be favored for accessing the channel, which is referred as *opportunistic access*.

3.2 Equal Probability Access in CSMA/CA

From the brief review of CSMA/CA in Section 2.1, regardless of the channel conditions, all nodes probabilistically have **equal** opportunities to access the channel because they **uniformly** select the back-off value from the **same** initial contention windows. In a two-node network with CSMA/CA, a node A with poor channel condition may beat the node B with good channel condition because both nodes have equal probability in channel access. However, intuitively and from the discussion in the last section (Section 3.1), it is more beneficial to allow B to transmit under these conditions for two reasons. *First*, B would use the wireless channel more efficiently because it takes less time in transmitting the same amount of data at a higher bit rate than A. This opportunism can lead to higher utilization, efficiency, and throughput of the overall network. *Second*, because of the inherent temporal variations of the wireless channel, B with presently good channel conditions may not keep as good when it wins the channel later.

3.3 Opportunistic Transmission vs. Opportunistic Access

Unlike opportunistic access that exploits user diversity in wireless networks, opportunistic *transmission* takes advantage of *time* diversity due to the temporal dynamic characteristics of the wireless channel. In opportunistic transmission, after a node wins the contention, it tries to transmit aggressively while its channel remains good because the condition may degrade later. In CSMA/CA, a node only transmits one frame when it wins the channel while in opportunistic transmission schemes such as *OAR* [1] and *MOAR* [3], more than one frame may be transmitted when a node wins access. The number of frames to be transmitted is determined by the channel conditions. In *OAR* and *MOAR*, the number of frames transmitted after a node wins the contention is calculated as the ratio of current bit rate over the basic rate. For example, if the current bit rate of a node is 11 Mbps and the basic rate is 2 Mbps, then the ratio should be $\lfloor 11/2 \rfloor = 5$, so the node will transmits five packets before the channel is released for contention. Each communication cycle in the random access wireless networks can actually be considered as two phases: *access* (contention) followed by *transmission*. From the above discussion, opportunistic transmission focuses on the transmission phase but not the access phase. Although opportunistic transmission improves the network performance by exploiting time diversity, it does not guarantee the node with the best channel condition has the best chance to win the channel. However, the node with the best channel conditions deserves the chance to use the channel because its channel may degrade later. To improve the utilization of scarce wireless resources, we are motivated to design opportunistic *access* algorithms that grant the channel in probability to the node that has the best channel condition, namely that is most likely to generate the largest instantaneous network throughput. With the observations discussed above, to improve network efficiency and channel utilization, we are motivated to design distributed opportunistic access algorithms that probabilistically favor the users with best channel conditions in winning the channel contention.

Chapter 4

Design of Opportunistic Random Access

To achieve opportunistic random access, we propose three algorithms based on the contention mechanism in the CSMA/CA. Two of these algorithms target at calculating the contention window for each node based on its instantaneous channel conditions. The third algorithm proposes to select a back-off value from the contention window with a *normal* distribution, rather than a uniform distribution as in the CSMA/CA. In addition, opportunistic access inherently tends to starve nodes with poor channel conditions. This section elaborates on these algorithms and how to address the starvation problem with temporal fairness.

4.1 Contention Window Based Opportunistic Access

The following two algorithms achieve opportunistic random access by determining contention windows based on channel conditions and are discussed as follows.

4.1.1 Overlapped Contention

In the first approach, the contention windows of all nodes share the same lower bound of "0" as CSMA/CA does, but have different initial upper bounds that are determined by the channel conditions in terms of achievable bit rates. Therefore, the contention windows of all nodes overlap in ranges as plotted on the left plot in Figure 4.1. The initial upper bound CW is inversely proportional to the ratio of current achievable bit rate over the basic bit rate and computed as in Formula 4.1 below whenever a node is ready to contend on the channel for a new transmission.

$$CW = \lceil \alpha \times \frac{R_b}{R_i} \times CW_{base} \rceil \tag{4.1}$$

where R_i refers to the current achievable bit rate of a particular node i, R_b denotes the basic rate in a bit rate set and CW_{base} is a constant base value, e.g. 15 in IEEE 802.11n. Note that $\frac{R_b}{R_i}$ may be very small, for example, in IEEE 802.11n, $\frac{6.5Mbps}{600Mbps}$ is almost 0.01. Therefore, a coefficient, α, is introduced to make sure that the computed window for the highest bit rate is no less than a certain small value to maintain a random access. From this formula, intuitively, a high bit rate, namely good channel conditions, leads to a small CW and thereby a larger probability to win the channel contention with the uniform selection of a back-off value from the contention window. Then, the computed CW can be used by the *Binary Exponential Back-off* procedure in the CSMA/CA to fulfill the opportunistic access. Note

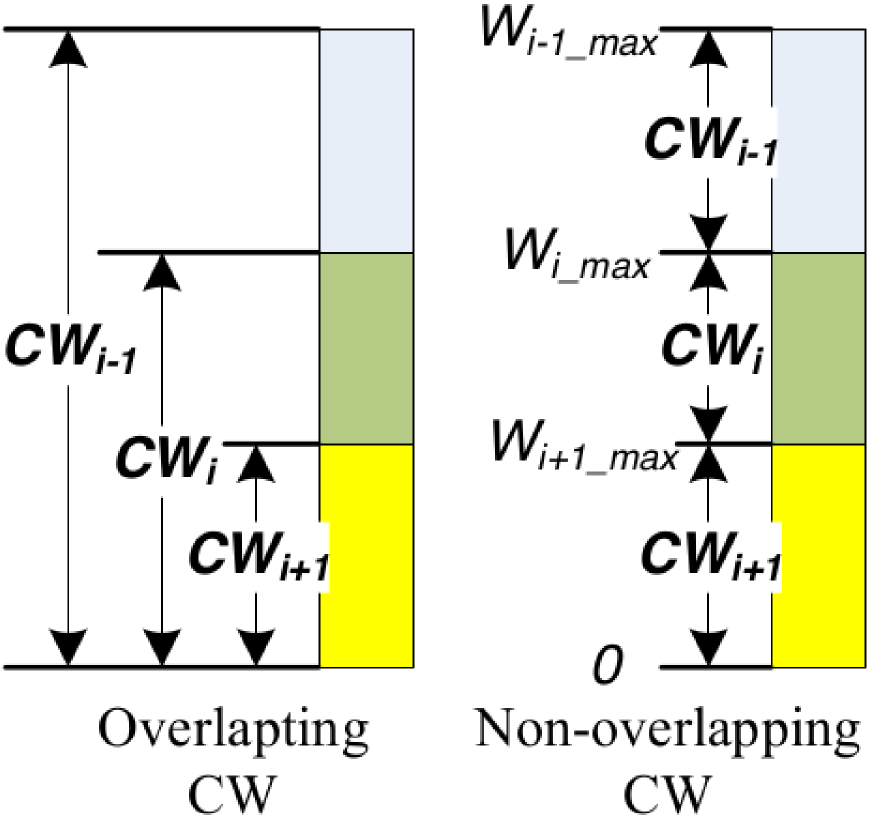

Figure 4.1: Illustration of Contention Window

that, in the *Overlapped Contention*, a node with low bit rate still has the probability to beat another node with a high bit rate: the lower rate node still has chance to select a smaller back-off value because their contention windows have the same lower bound of ”0”.

Opportunism of Overlapped contention

As discussed above, the overlapped contention is an opportunistic access that assigns larger probability of wining the channel to the node with higher rate. Denote P_e^i as the probability that a node i attempts to transmit a frame. According to [8], with different contention window size, the P_e^i is calculated as:

$$P_e^i = \frac{2}{CW_{max}^i + 1} \tag{4.2}$$

where CW_max^i is the contention window size of node i. Define P_t^i the successful transmission probability of node i. Then

$$P_t^i = P_e^i * \prod_{j \neq i} (1 - P_e^j) \tag{4.3}$$

Define $\frac{P_t^i}{P_t^j}$ as the opportunism metric that node i will compete node j in accessing the channel. Based on Eq. (1), Eq. (2) and Eq. (3), we have

$$\frac{P_t^i}{P_t^j} = \frac{\Delta(\lambda - R_j)}{\lambda - \Delta R_j} = 1 + \frac{(\Delta - 1)\lambda}{\lambda - R_j} \tag{4.4}$$

where $\Delta = \frac{R_i}{R_j}$ and $\lambda = \alpha.CW_b.R_b$. According to Eq. (1)

$$\lambda = CW_{max}^j X R_j \tag{4.5}$$

Because the contention window CW_max^i is always larger than 1, we have $\lambda > R_j$. Assume that node i has the largest bit rate R_i in the networks, then we have $\Delta > 1$ and also $\frac{P_t^i}{P_t^j} > 1$.

This clearly shows that the overlapped contention opportunistic access helps those nodes at higher rates to win the contention.

4.1.2 Segmented Contention

To strictly grant a higher priority of accessing channel to the users with better channel conditions, another algorithm *separates* the contention windows for nodes at different bit rates as illustrated on the right of Figure 4.1. In this approach, the initial contention window is still computed as in Formula 4.1. However, unlike the *Overlapped Contention* that maintains the same lower bound of "0" for all contention windows, this algorithm differentiates the lower bounds of the contention window for different channel conditions. A higher bit rate results in an *upper* bound of the contention window *smaller* than the *lower* bound of a node at a lower bit rate. For example, on the right of Figure 4.1, W_{i_max} and W_{i+1_max} respectively denote the computed initial upper bounds of the contention window of bit rate R_i and R_{i+1} according to Formula 4.1. Then, the lower bound of the contention window CW_i of bit rate R_i is assigned the value that is larger by one than W_{i+1_max}, the upper bound of CW_{i+1}, i.e. the window is $[W_{i+1\_max} + 1, W_{i\_max}]$. This segments the contention of nodes with different channel conditions in that a node at bit rate R_i can never get a back-off value smaller than a node at bit rate R_{i+1}. This approach can be considered semi-probabilistic in that (1) the access of the nodes at the same bit rate is random since they have the same initial window size to randomly generate a back-off value, but (2) the access of nodes at different rates is deterministically prioritized because the lower rate nodes can never get a smaller back-off value than the higher rate nodes. This approach provides a tight opportunism by grouping nodes with similar channel conditions into the same random access team at the cost of randomness across teams. Note that this approach leads to a significant problem: starvation of nodes with poor conditions. This problem will be addressed in Section 4.2.

4.1.3 Comparison between Segmented and Overlapped Opportunistic Accesses

The segmented contention deterministically guarantees that nodes at higher rates will win the lower rate nodes because the latter can never have chance to obtain a smaller back-off window than the former. Therefore, the opportunism is deterministically maintained. In this section, we compare the system performance of segmented and overlapped contentions while both provide opportunism in access. For comparison, we define a system performance metric $\chi = \frac{R}{E(T_b)}$, where R refers to the bit rate of a node that wins the access and $E(T_b)$ is the expected back-off time slots before transmission. Clearly, larger the value of χ, the better the network performance. χ serves as an network efficiency metric to evaluate the system performance of contention based opportunistic variants. In the segmented contention, nodes at different bit rates do not share the same lower or higher bounds. Refer to the right plot of Fig. 1. The expectation of back-off for node i becomes $E(T_b) = (CW^i_{min} + CW^i_{max})/2$ where CW^i_{min} is the lower bound of node is contention window, which is also the higher bound of node i+1. So if node i run the segmented contention algorithm, we have its efficiency metric as:

$$\chi^i_s = \frac{2R_i}{CW^i_{max} + CW^{i+1}_{max}} = \frac{2\theta(R_i)^2}{\lambda} \tag{4.6}$$

where $\theta = \frac{\varepsilon}{1+\varepsilon}$ and $\varepsilon = \frac{R_i}{R_i+1}$. In the overlapped contention, a node at higher bit rate does not deterministically beat a lower bit rate node because of the overlapped contention windows. Consider two nodes i and j having bit rates $(R_i > R_j)$. Denote P_i the probability that node i wins over j in channel access. Similarly, P_j refers to the probability that node j wins over i in channel access. Then, P_j and P_i can be calculated as follows:

$$P_j = \sum_{x=1}^{CW_i} \frac{1}{CW_j} . \frac{CW_i - x}{CW_i} \approx \frac{CW_i}{2CW_j} \tag{4.7}$$

$$P_i = \frac{CW_j - CW_i}{CW_j} + \frac{CW_i}{CW_j} \sum_{x=1}^{CW_i} \frac{1}{CW_i} . \frac{x-1}{CW_i} \approx 1 - P_j \tag{4.8}$$

where $CW_j = CW^j_{max}$ and $CW_i = CW^i_{max}$. Therefore, the efficiency metric of node i with overlapped contention scheme can be derived as:

$$\chi^i_o = P_i . \frac{2R_i}{CW_i} + P_j . \frac{2R_j}{CW_j} \tag{4.9}$$

By substituting Eq. (1) into Eq. (4) and (5), we can obtain:

$$\frac{\chi^i_o}{\chi^i_s} = \frac{\Delta^2 + 2(\Delta - 1/2}{2\theta\Delta^3} \tag{4.10}$$

In this equation, ε takes values from [1.1, 2] in 802.11n, then θ will be constants falling into [0.5,0.7]. Therefore, Eq. (6) is a monotonic decreasing function of Δ. It decreases to 1 when $\Delta \approx 1.5$ and approaches to 0 hereafter. This means that segmented contention outperforms overlapped contention when $\Delta > 1,5$ that happens at the probability of 85% in IEEE 802.11 with rates (13, 26, 39, 52, 78, 104, 117 and 130 Mbps) for 20MHz bandwidth if two nodes have different bit rates.

4.1.4 Normal Distribution Based Back-off Selection

In the *Overlapped Contention*, although nodes with different channel conditions obtain different initial contention windows, each node still uses a uniform distribution to select the back-off value from its contention window. The third proposed opportunistic access approach consists of using a normal rather than a uniform distribution, in selecting the back-off value once the contention window is determined as in the *Overlapped Contention*. With the expectation of the normal distribution set to a proper value within the contention window and a proper standard deviation, a node with higher bit rate has significantly greater probability to obtain a smaller back-off value than a lower bit rate node. Systematically, the expectation of the normal distribution of a node at rate R is computed as below:

$$E = \lceil \frac{CW}{2} \rceil \tag{4.11}$$

where CW is computed as in Formula 4.1. Let us examine an example where a network has two nodes A at rate R and B at rate $\frac{R}{2}$. Then, the expectations of the normal distribution at A and B are respectively set as $\frac{N}{4}$ and $\frac{N}{2}$ to select their back-off values as shown in Figure 4.2. As a result, in the long run, A will select a smaller back-off value than B because most likely the selected values are near to the expectation in the normal distribution.

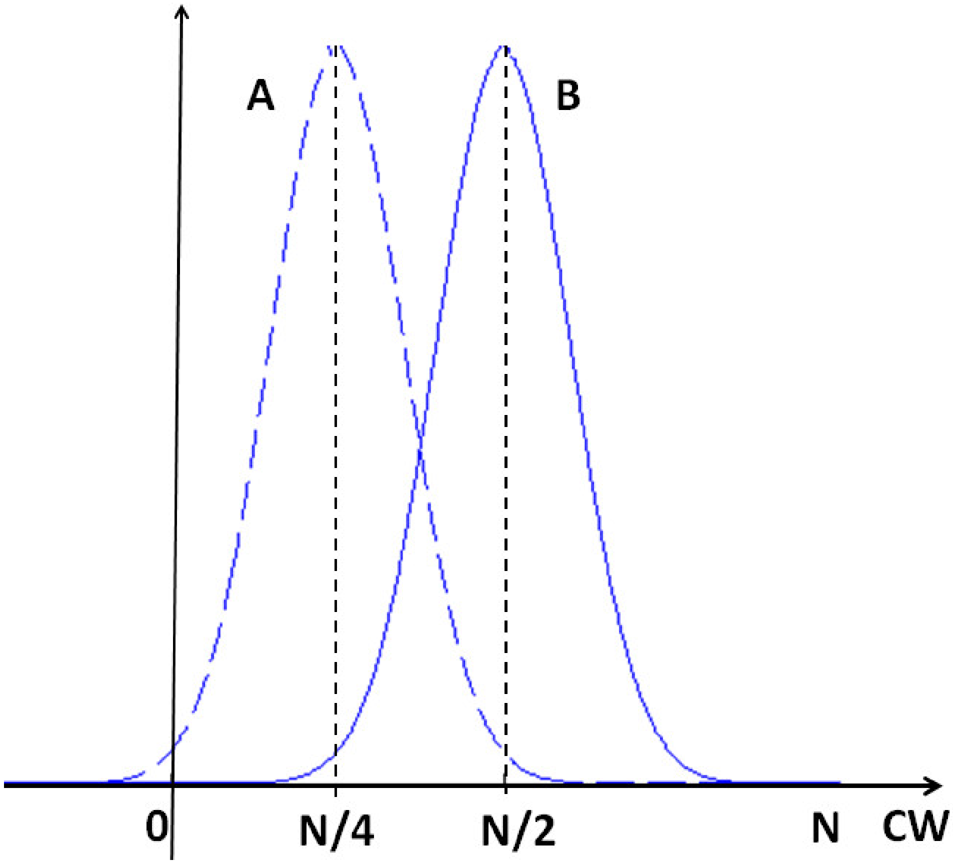

Figure 4.2: Normal Distribution Back-off

4.2 Temporal Fairness to Avoid Starvation

The equal probability access regardless of channel conditions in the CSMA/CA leads to an anomaly that all nodes will have identical throughputs in the long run [8], which is called *throughput fairness*. It is obvious that the nodes at lower bit rate hurt the throughputs of the nodes at higher bit rates as well as the overall throughput of the network. This fairness is not "fair" in temporal use of the channel among nodes. With the identical throughput, a node at the lowest bit rate in a network will use the channel for the longest time. On the other hand, as discussed in Section 3, although opportunistic access can improve the network throughput by always favoring the users with the best channel conditions, it may starve the users with poor channel conditions. A solution both problems of identical throughputs and starvation is to achieve *temporal fairness* among nodes [19] that is defined as each node has approximately the identical amount of time in using channel. To achieve temporal fairness, we propose to use a *bit rate normalized average throughput* as a metric in computing the initial contention window. Each node tracks the average throughput T updated in an exponentially weighted window t_w. Suppose Node K is the transmitter at a certain moment, T is updated at each node k that has packets ready for transmission in each time slot with a low-pass filter as:

$$T_k[m+1] = \begin{cases} (1-\frac{1}{t_w}) \times T_k[m] + \frac{1}{t_w} \times R_k[m] & \text{if } k = K \\ (1-\frac{1}{t_w}) \times T_k[m] & \text{if } k \neq K \end{cases}$$

The *bit rate normalized average throughput* for node k having bit rate R_k in the m-th window is defined as:

$$T_{normalized}[k,m] = T_k[m]/R_k \tag{4.12}$$

This is used to compute the initial contention window. As a result, Formula 4.1 is accordingly updated as:

$$CW = \alpha \times T_{normolizd}[k,m] \times CW_{base} \tag{4.13}$$

The contention with Formula 4.12 maintains two important features: temporal fairness and opportunism. The temporal fairness is achieved because the bit rate normalized average throughput can actually be explained as the *temporal quota* of a node in transmission period. This is clear if we rewrite the definition of $T_{normalized}[k,m]$ as $(t_c \times T_k[m]/R_k)/t_c$ in a period of length t_c: $t_c \times T_k[m]$ is the average transmitted data in bits and thereby $t_c \times T_k[m]/R_k$ is the transmission time. Thus, $(t_c \times T_k[m]/R_k)/t_c$ is the the percentage of the time that node

k gains for transmission in a period of t_c. The opportunism in Formula 4.12 is driven by the bit rate. If a node has a high bit rate, its $T_{normalized}[k, m]$ tends to be small. According to Formula 4.13, a small $T_{normalized}[k, m]$ leads to a small contention window CW to win the channel. If a node uses the channel for too long, it will end up with a large average throughput $T_k[m]$, thereby a large $T_{normalized}[k, m]$ that enlarges its contention window and decreases its chance to win the channel. Note that the size of the weighted window, t_w, is associated with the latency requirement of applications. If t_w is large, it allows the node with the optimal channel condition to use the channel for a long duration, but may hurt other nodes having applications requiring low latency. If it is small, the channel is frequently switched among nodes of different bit rates and the overall performance degrades. Another concern is the support of QoS. If multiple classes of applications are involved, each class has different requirements, especially regarding latency. Then, a weight parameter ϕ_c for each class of application is necessary in updating the average throughput as: $T_k[m+1] = (1 - \frac{1}{t_w}) \times T_k[m] + \frac{1}{t_w} \times \phi \times R_k[m]$. Then, the basic contention window size CW_b for each packet will be updated according to its priority.

Chapter 5

Performance Evaluation

We extensively evaluated the performance of the proposed opportunistic access algorithms with simulation in NS-3.

5.1 Evaluation with Simulation

We developed all three proposed algorithms into the simulator *NS3* [30] and comprehensively evaluated the performance with extensive simulations. Our algorithms were compared with the default CSMA/CA without opportunism for each case. The evaluation began with a simple infrastructure topology having one access point and two clients, then studied the impact of hidden terminal on opportunistic access, compared with opportunistic transmission in the case of mobility, and finally evaluated the performance on a multiple-hop mesh network. All experiments were performed with constant bit rate (CBR) UDP traffic at a rate of 10 Mbps for 5 minutes with packet size of 1K bytes. The results are averaged over 50 runs for each case. In simulations, α in Formula 4.1 was set to 1.7 and the weighted window t_w was set to 50 ms. In the following performance figures, “Original” represents the default algorithm in the CSMA/CA, “Overlapped” for the *Overlapped Contention*, “Segmented” for the *Segmented Contention* and “Normal” for the *Normal Distribution Based Back-off Selection.* The following table represents the experiment settings for the simulation performed in NS-3.

5.1.1 Triple-node Infrastructure Topology

We first evaluated the throughput and jitter performance of opportunistic access over the original algorithm in a simple topology: one access point and two client nodes. All nodes

Table 5.1: Parameters used for Evaluation

Parameters	**Values**
MAC Protocol	IEEE 802.11g
Slot time	20μs
SIFS	10μs
DIFS	50μs
Data rate	(6,9,12,18,24,36,48,54) Mbps
CWmin	15
CWmax	1023

were in radio range of each other. These client nodes transmitted packets to the access point at different bit rates. One client node was set to a 54 Mbps, but the other node changed its bit rate from the IEEE 802.11 rate set consisting of 6, 12, 24, 36, and 48 Mbps.

Throughput Performance :

Figure 5.1 plots the throughput performance when one client changes its bit rate each time to imitate the changes of channel conditions. The X-axis represents the different bit rates and the Y-axis represents the throughputs of opportunistic access algorithms and the original one in the CSMA/CA. From the figure, opportunistic access improves the throughput by approximately 30 - 100% based on channel conditions as compared to the original algorithm.

Delay Performance:

Figure 5.2 plots the measured average delay at different bit rates The opportunistic access shows a significant improvement in delay as compared to the original access. This is because the high bit rate nodes in opportunistic access has very less contention time and transmits packets rapidly. The lower bit rate nodes experiences a much larger delay comparatively because of collision due to back-off terminate at the same time and the contention window size gets doubled every time when it encounters a collision. Yet the overall network performance in delay is improved significantly over the default CSMA/CA method. To show

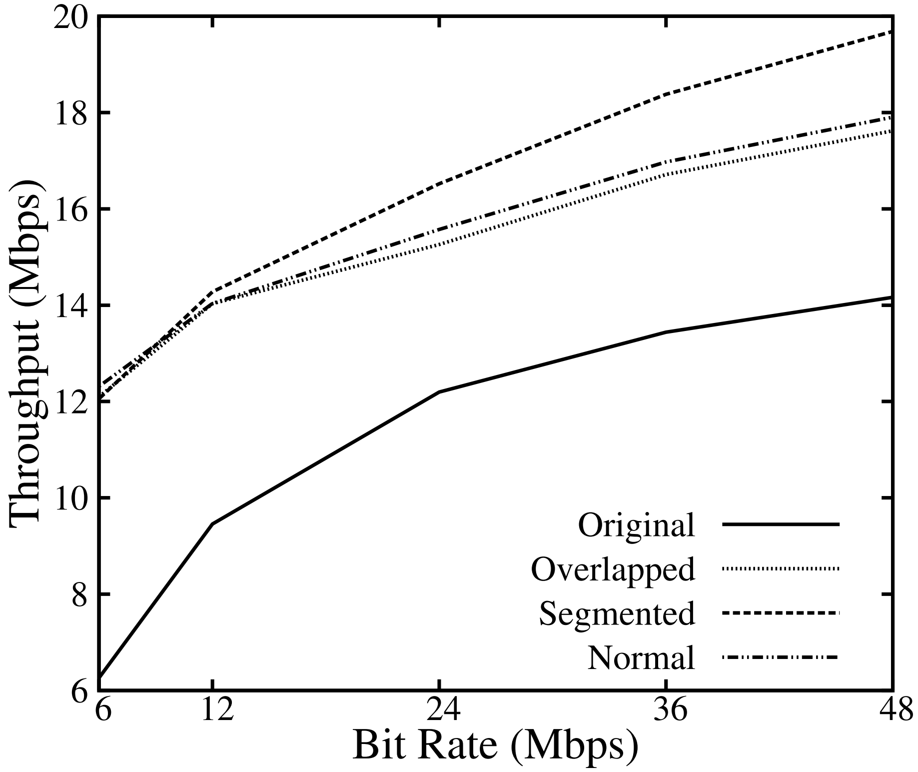

Figure 5.1: Throughput

more clearly, we further studied the delay performance with increase in traffic rate Figure 5.3. As expected, the delay gets increased as CBR traffic rate increases because more packets are transmitted frequently. Although the variation in individual packet delay between high bit rate nodes and low bit rate nodes is high, the overall network performance of opportunistic access is improved.

Jitter Performance :

Figure 5.4 shows the measured jitters at different bit rates. Jitter is the delay variation between two consecutive successful packet receptions and the result plotted is the average of delay variation of total received packets. Surprisingly, the opportunistic access outperforms the original one in jitter as well. This is because, with opportunistic access, the high bit rate nodes obtain much smaller initial contention windows than those in the default CSMA/CA

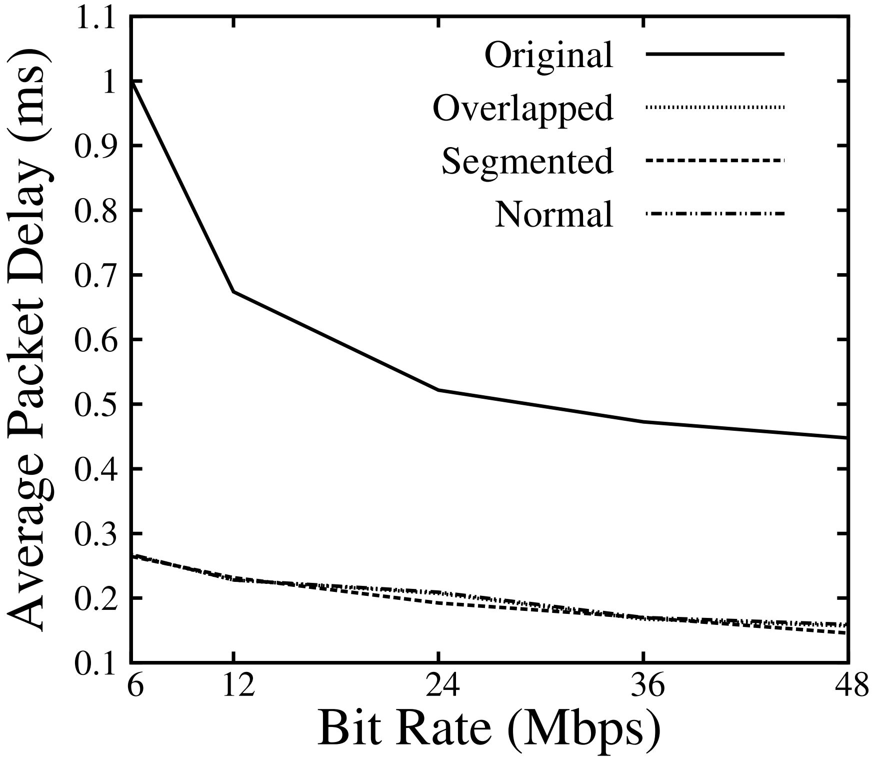

Figure 5.2: Average Delay

and the selected back-off in the contention is thereby significantly reduced. As a result, although lower bit rate nodes experience larger jitters than higher bit rate nodes, the overall jitter across the network is improved because of the shortened time spent on the contention with opportunistic access.

Average Back-off Time:

To further investigate how the opportunistic access improves the throughput and jitter, we collected the back-off time in terms of time slots of each transmission. Figure 5.5 shows the average back-off time per successful transmission for each access algorithm. Average back-off slot time per packet is calculated as the sum of individual packet back-off time slots over the total number of packets transmitted successfully. From the figure, the opportunistic access algorithms consume much less time in back-off than the original access, up to 400% less at 48

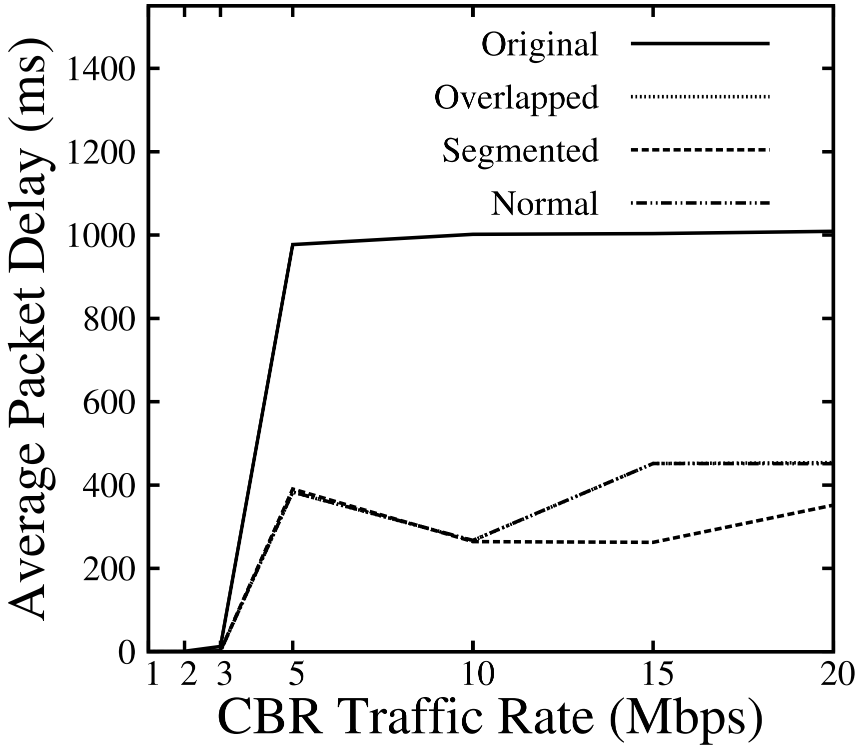

Figure 5.3: Traffic Rate Vs Delay

Mbps. The overall network performance improves because 1) the equal probability access in the original algorithm results in almost constant average back-off, and 2) the opportunistic access algorithms spend less time on back-off, namely contention.

5.1.2 Discussion on Opportunistic Access Algorithms :

Among the proposed three opportunistic access schemes, the *Segmented Contention* yields in general the best performance from Figure 5.1 to 5.5. This is because the channel access of nodes at different bit rates is deterministically prioritized when their contention windows are segmented. Nodes with lower rates never get a smaller back-off value than the ones with higher bit rates. The *Overlapped Contention* and the *Normal Distribution Based Back-off* result in almost identical performance. This is because both of them have a similar expectation in selecting back-off values for the nodes at the same bit rate. Because they both

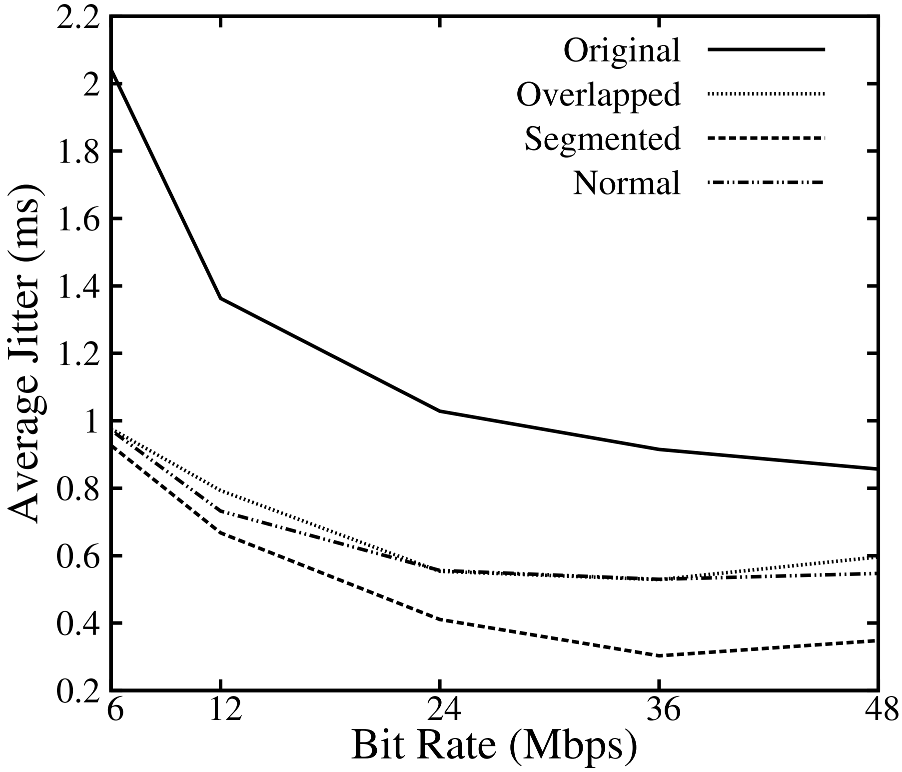

Figure 5.4: Average Jitter

have contention windows starting at “0”, the higher bit rate nodes may still be occasionally beaten by nodes at lower bit rates.

5.2 Impact of Hidden Terminal Problem

In this case, the network was configured to still have one access point and two client nodes with one at 54 Mbps and the other varying its bit rate, but the clients do not hear each other. RTS and CTS are disabled to fully stimulate the hidden terminal problem. Figure 5.10 illustrates the hidden terminal scenario in wireless networks. Node A and H are the client nodes and node B is the access point. Node A and H cannot hear each other because they are not in radio range but they can hear node B. If node A and H transmit frames, it will sense the channel first but cannot hear the frames from nodes hidden to each other. So both nodes attempt to transmit simultaneously and results in collisions which reduces the network

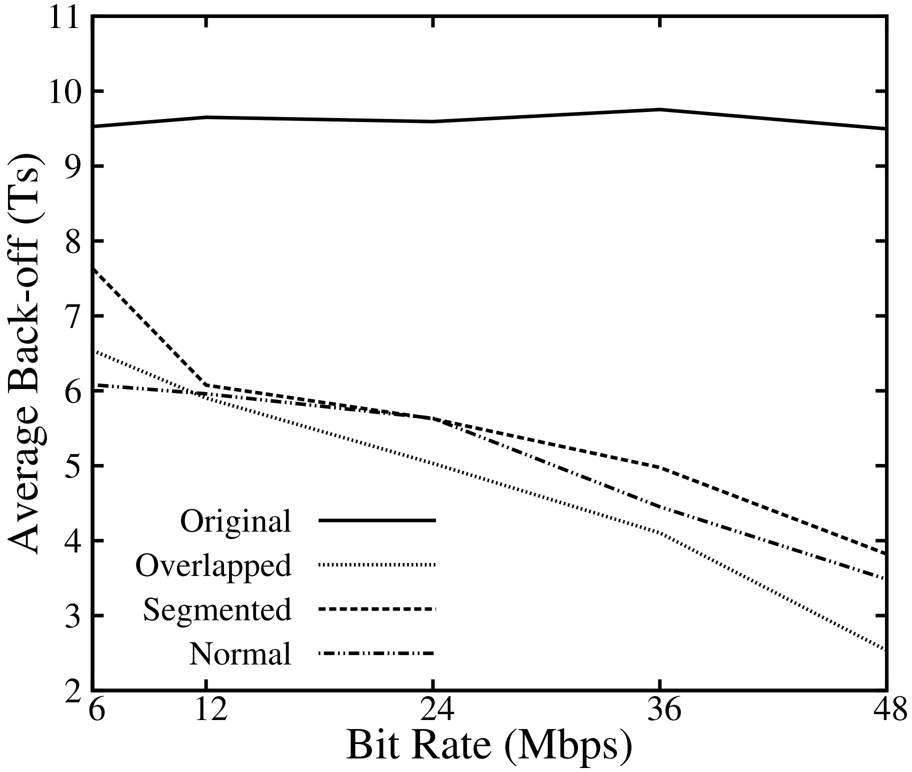

Figure 5.5: Average Backoff

performance drastically. Our opportunistic access schemes also have this hidden terminal effect but it has the probability of transmitting more frames over the traditional 802.11 MAC protocols and hence improve the network performance considerably. The performance results are discussed as follows: Figure 5.6 plots the measured throughputs at different rates. The hidden terminal problem does hurt the performance of all algorithms. The figure tells that the overall network throughput is still improved by the opportunistic access, although the improvement is reduced to some degree by the hidden terminal problem. To show more clearly the effect of hidden terminal, we further studied the percentage of packet loss ratio of the network. Packet loss ratio percentage is the difference between total transmitted packets and total received packets over the total number of transmitted packets. Figure 5.8 shows that packet loss ratio is considerably reduced in opportunistic access which explains the performance improvement of opportunistic access as compared to the original access.

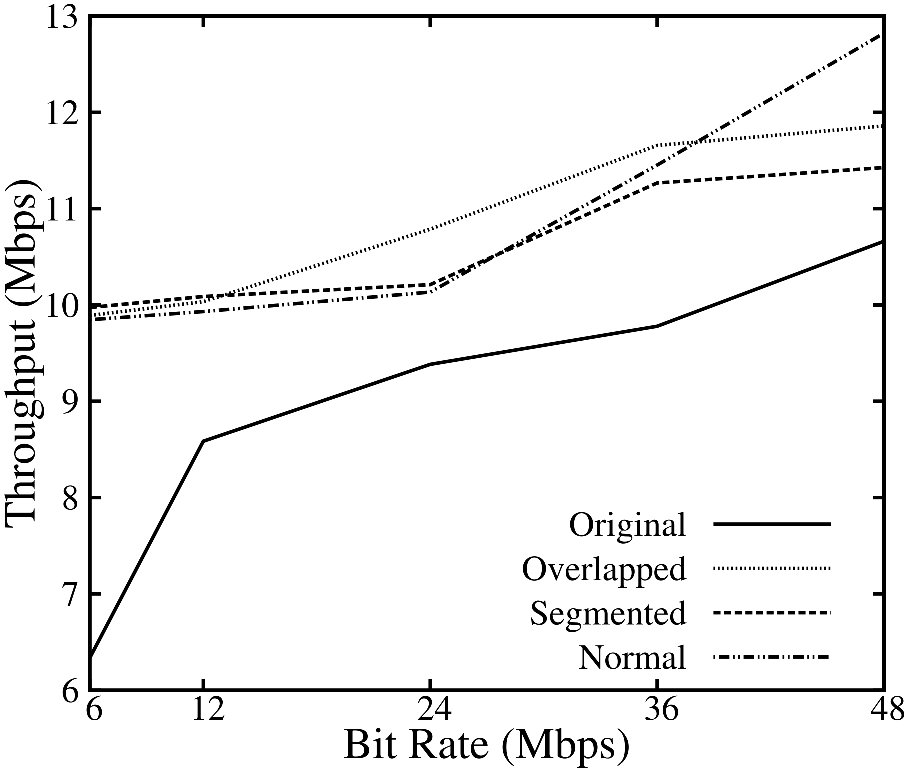

Figure 5.6: Hidden Terminal Problem

5.2.1 With RTSCTS

Although opportunistic access performs better than original one, the measured throughput performance is mainly due to high bit rate nodes in the presence of hidden terminal. This is because the high bit rate nodes win the channel more frequently due to its initial smaller contention window size, suppressing the channel access to lower bit rate nodes. Hence the channel should be reserved by nodes before its access to provide the fairness among the nodes. We have enabled the RTS/CTS reservation technique for this purpose. As expected, the opportunistic access outperforms the original one in throughput as shown in Figure 5.7 and gives the throughput proportional to its bit rates because of channel reservation technique and long term temporal fairness provided by our scheme. The packet loss ratio of our scheme is also considerably reduced in the presence of RTS/CTS channel reservation technique as

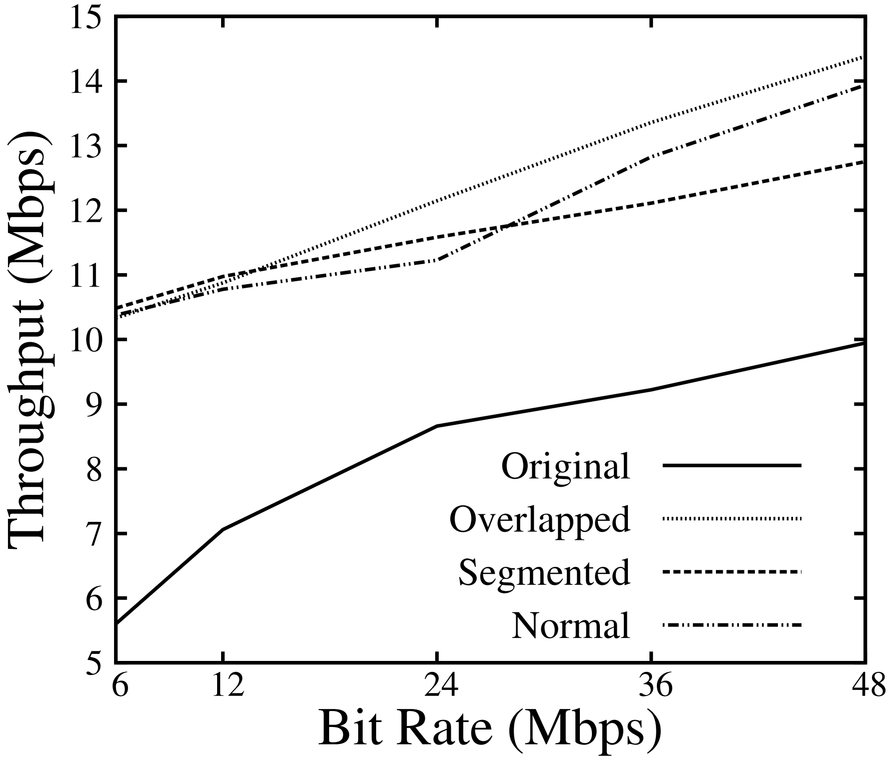

Figure 5.7: Hidden Terminal Problem with RTSCTS

shown in Figure 5.9 which increases the overall network performance of opportunistic access.

5.3 Comparison with Opportunistic Transmission under Mobility and Auto Rate

We also evaluated the performance in an infrastructure topology of multiple flows with mobility. We tested topologies with a different number of nodes varying from 2 to 6 nodes with one flow between each node and the access point. The maximum transmission range of a node was set to 30m and mobility was enabled such that each node would be moving randomly within the bounded area of 50m×50m at a speed of 5 m/s. The nodes sometimes move out of range and packet losses occur more frequently. Because of mobility, the supported bit rate has to be dynamically adapted. *RRAA* [20] rate adaptation algorithm was

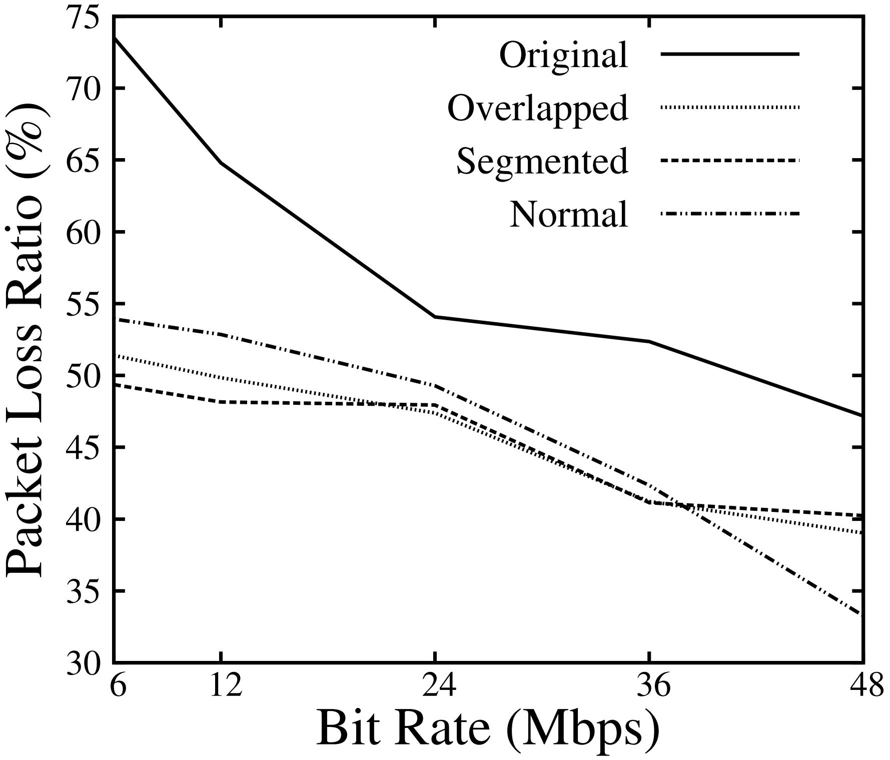

Figure 5.8: Packet Loss Ratio

enabled for this purpose. In addition, we also implemented Opportunistic Auto Rate (OAR) protocol as a representative of *opportunistic transmission* algorithms to compare with the opportunistic access in this experiment setting. Figure 5.11 shows the throughput performance of the opportunistic access algorithms, the original access and OAR with mobility and $RRAA$ in the case of multiple flows. The X-axis represents the number of flows and the Y-axis represents the throughput for the entire network. From the figure, the opportunistic access (our algorithms) and the opportunistic transmission (OAR) have close performance when the network only has a couple of nodes, but the opportunistic access gradually outperforms the opportunistic transmission as the number of mobile nodes increases. This is because of the difference in the opportunism between access and transmission. With the growing number of mobile users, the user diversity increases as well. OAR does not exploit user diversity and it uniformly selects a user to transmit. As a result, it does not favor the

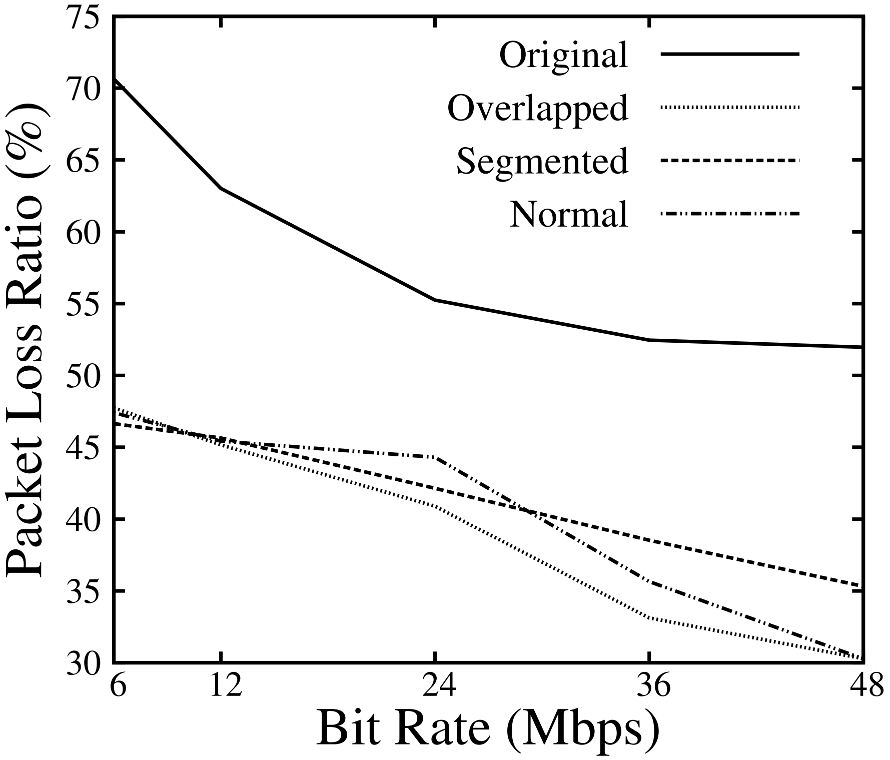

Figure 5.9: Packet Loss Ratio with RTSCTS

user with the best channel condition to use the channel each time. On the contrary, opportunistic access exploits user diversity. With more users, it is more likely that someone is at a very high bit rate. Because the opportunistic access always favors the user with the highest bit rate to use the channel, the overall network performance is improved. In addition, in this environment, the mobility and rate adaptation introduce fast channel variations. This may result in transmission failure when *OAR* opportunistically transmits a burst of frames if the channel degrades before the opportunistic transmission finishes. However, because the opportunistic access only transmits one frame per contention, its short transmission time is resilient to the fast variations. Moreover, the variations generate new user diversity in the network that facilities the opportunistic access to exploit for high network performance. The performance figure also shows that the overall throughput increases slowly when the number of flows grows because of the increasing contention among the flows.

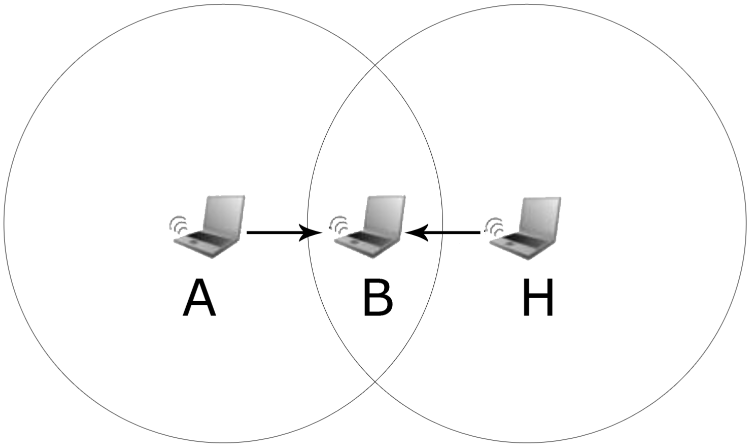

Figure 5.10: Illustration of Hidden Terminal topology

5.3.1 High Performance of Opportunistic transmission over Opportunistic access

In this case, the network is still configured with infra-structure topology of multiple flows but without mobility and auto rate algorithms. The number of flows is increased from 2 to 6 by gradually adding one node each time. All nodes transmit packets to the access point. Because of stable channel conditions and less network overhead, opportunistic transmission OAR protocol transmits multiple frames when it gains access to the channel whereas opportunistic access relies on one frame transmission per contention and network overhead is more comparatively. Although OAR protocol shows a high performance over opportunistic access scheme as shown in Figure 5.12, opportunistic access shows a better performance than default CSMA/CA method.

5.3.2 Fairness Index Measurement

Jain Fairness Index is the most commonly used metric to measure the fairness variation using the individual flow throughput over wireless networks. Basically Jain Fairness rates the individual throughput variation with respect to number of flows. If resources are allocated equally, then Jain fairness index will have the maximum value 1 and vice-versa. Jain Fairness

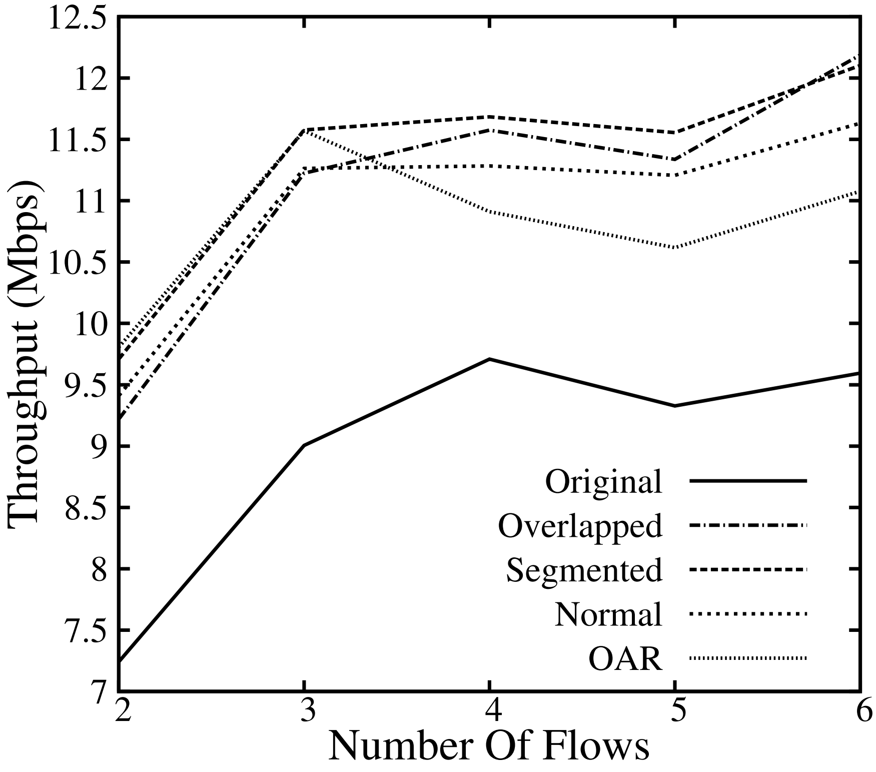

Figure 5.11: Mobility

Index is given by

$$I_J = \frac{(\sum_{i=1}^{n} r_i)^2}{n \sum_{i=1}^{n} r_i^2} \tag{5.1}$$

Where r_i and n are the allocated resources to user i and the total number of users respectively. Figure 5.13 shows that the fairness of opportunistic access scheme gets increased as the number of flows increases. This is because the opportunistic access actually reduces the contention time of high bit rate nodes, thereby giving opportunism to send more packets but the lower bit rate node remain in its regular channel access time. The fairness of opportunistic transmission is also compared with opportunistic access which shows that the resources are allocated equally over the long term.

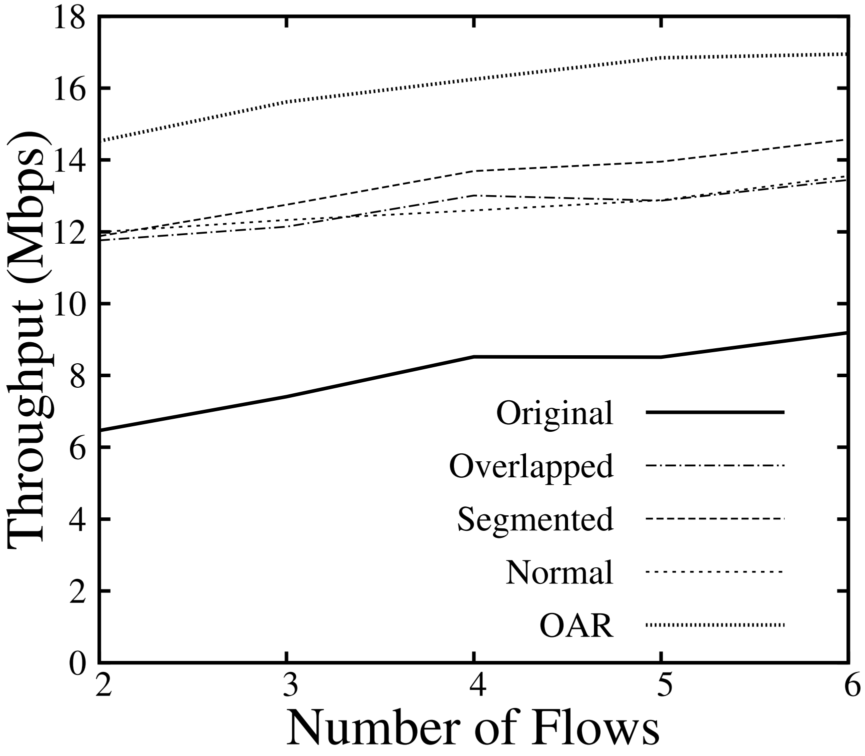

Figure 5.12: No Mobility

5.4 Multi-hop Mesh Topology

In this scenario, 30 nodes were randomly and statically distributed in a 150m×150m area and bit rates (12, 24, 36, 48, 54 Mbps) were assigned to the hops in a uniform distribution. Since the radio range was 30 m, these nodes form a multi-hop mesh network. Source and destination pairs of flows were preselected among the nodes and the number of flows was increased from 1 to 9. OLSR [32] protocol was used to route the packets over the network. The network throughput performance is plotted in Figure 5.14. The opportunistic access shows an average throughput improvement of up to 40% over the original access. This is because the original access takes the same initial contention window upper bound regardless of bit rates, but the opportunistic access obtains a smaller initial contention window upper bound than that in the original access if the bit rate is larger than the basic rate. As a result, the opportunistic access spends less overhead time on contention than the original

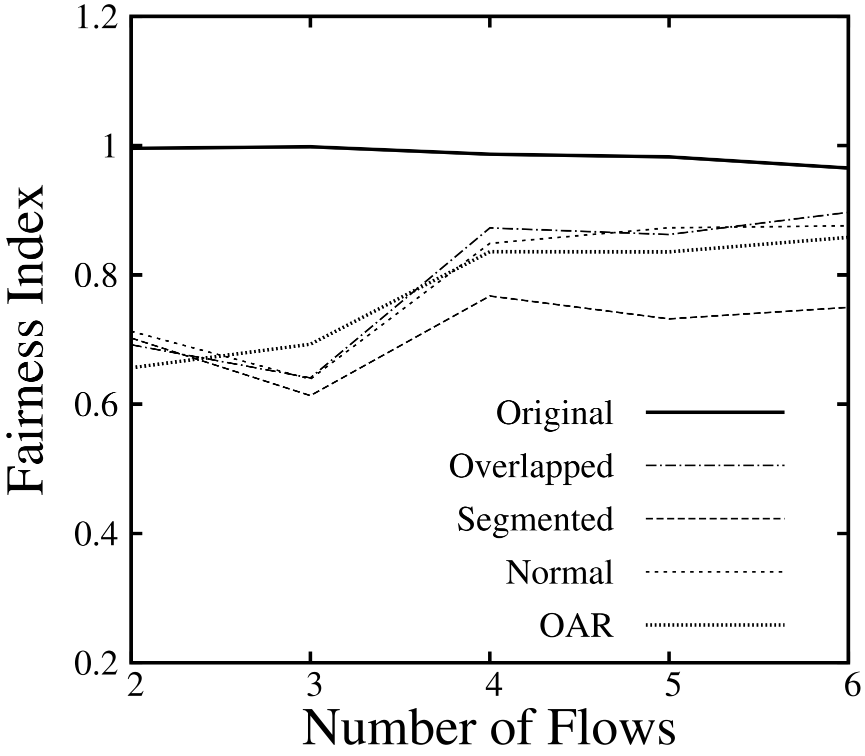

Figure 5.13: Fairness

access if the channel condition for the single flow is good. As the number of flows grows, the throughputs decrease because of the increased collisions among flows. The *Overlapped Contention* and the original access boost their throughputs in the case of 9 flows because their uniform selection of back-off from overlapping contention windows helps dilute the collision.

5.5 Discussion on Issues with Opportunistic Access

This section presents some issues with opportunistic access as observed during the performance evaluation. We also briefly discuss the tradeoff between the opportunistic transmission and access.

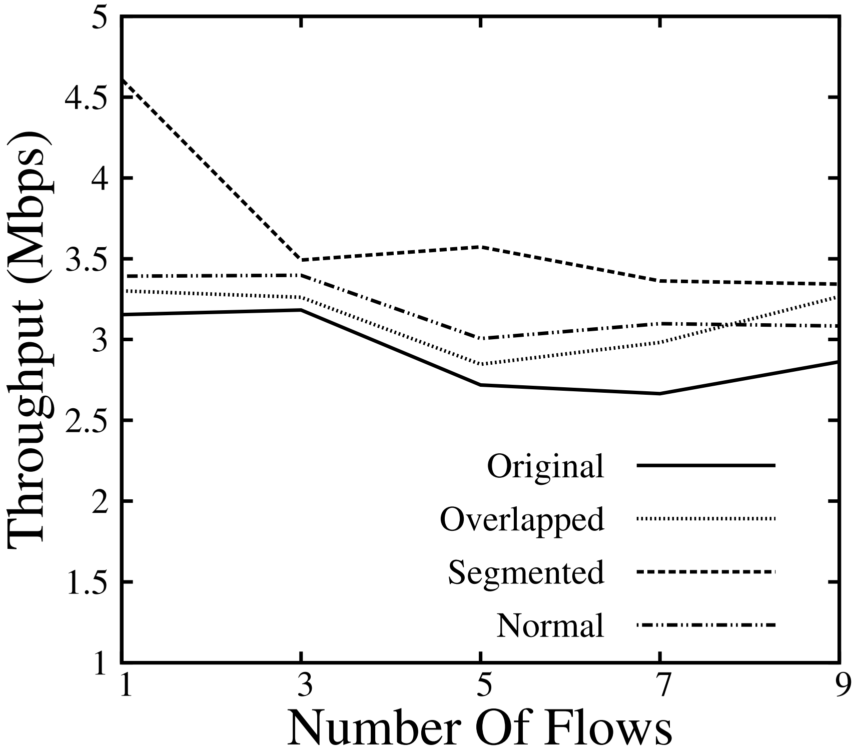

Figure 5.14: Multi-hop Mesh Topology

5.5.1 Performance Outage in Chain Topology

During the performance evaluation with simulation, we tested a 5-hop chain network where the sender and receiver were placed at the extremities of the chain with 4 nodes between. Each node had a buffer of 130 frames. The bit rates of these 5 hops were set in four different patterns as shown in Figure 5.15. Pattern A has ascending bit rates (12, 24, 36, 48, 54 Mbps) along the transmission path, B has descending bit rates (54, 48, 36, 24, 12 Mbps), C has hybrid ordering with lower rates first (12, 24, 54, 36, 48 Mbps), and D has hybrid ordering with high bit rates first (36, 48, 54, 12, 24 Mbps). Figure 5.16 plots the throughput performance of all algorithms in the four bit rate distribution patterns. From the figure, the opportunistic access is significantly outperformed by the original access in the decreasing order case (B) and slightly outperformed in the hybrid order that has high bit rates first (D). This performance outage problem occurs because the opportunistic access transmits

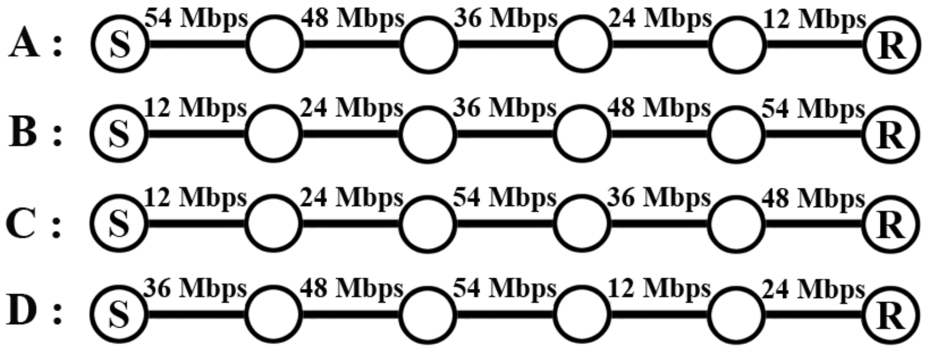

Figure 5.15: Four Chain Topologies

more packets in the early hops than what the low bit rate nodes in the downstream hops can drain out of the network. Therefore, many packets have to be dropped on the intermediate hops. This problem should exist to some degree whenever the bit rate bottleneck is in the downstream of a path, but opportunistic access or transmission exacerbates it.

5.6 Random Adhoc topology

In this experiment, we have evaluated the performance of random topology of 50 nodes placed initially in a random position bounded by 150m×150m area. The bit rates (12, 24, 36, 48, 54 Mbps) were assigned to the nodes in a uniform distribution and the radio range was 30m. Mobility is enabled such that the nodes are moving at a speed of 5m/sec in a random direction. Because of mobility, the auto rate algorithm (RRAA) is enabled to adapt dynamically the channel conditions and reduce loss due to hidden terminal problem. Preselected source and destination are configured such that the number of flows are increased from 1 to 10. OLSR protocol was used to route the packets. The opportunistic access performance is degraded considerably due to mobility and auto rate as shown in Figure 5.17. This is because opportunistic access doesn't give the OLSR protocol enough time to compute its MPR (Multi-point Relay) and routing table. Opportunistic access injects packets into the network more frequently due to its less contention time. The position of nodes also changes randomly over a wider area due to mobility which may sometimes lead to multi-hop routing

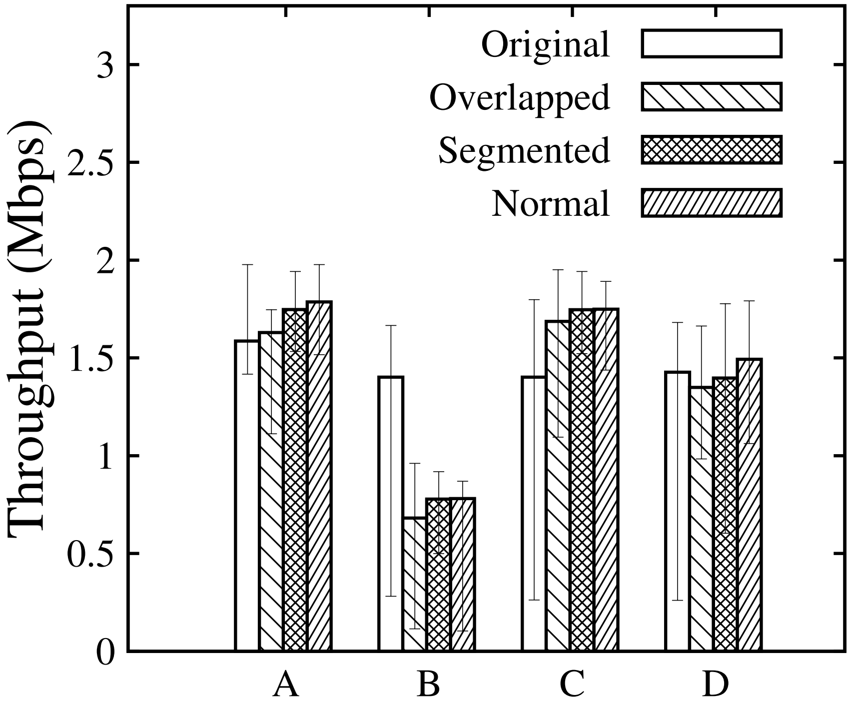

Figure 5.16: Throughput in Chain Topologies

of packets to reach the destination. Because of this two reasons, OLSR protocol not able to build its routing table in less time. So network congestion and packet losses occurs which leads to degradation in performance.

5.6.1 Increased Collision

In the proposed opportunistic access, high bit rate nodes tend to have small contention windows. Although the back-off values of these nodes are selected randomly, the initial contention window size for very high bit rate nodes is too small, which increases the probability for these nodes to select the same back-off value, especially when a network has many such nodes. Then, this exacerbates the collision because the back-off values at the nodes terminate at the same time. Although the binary exponential back-off mechanism can address this problem, the network efficiency is degraded with the channel resource wasted by frequent

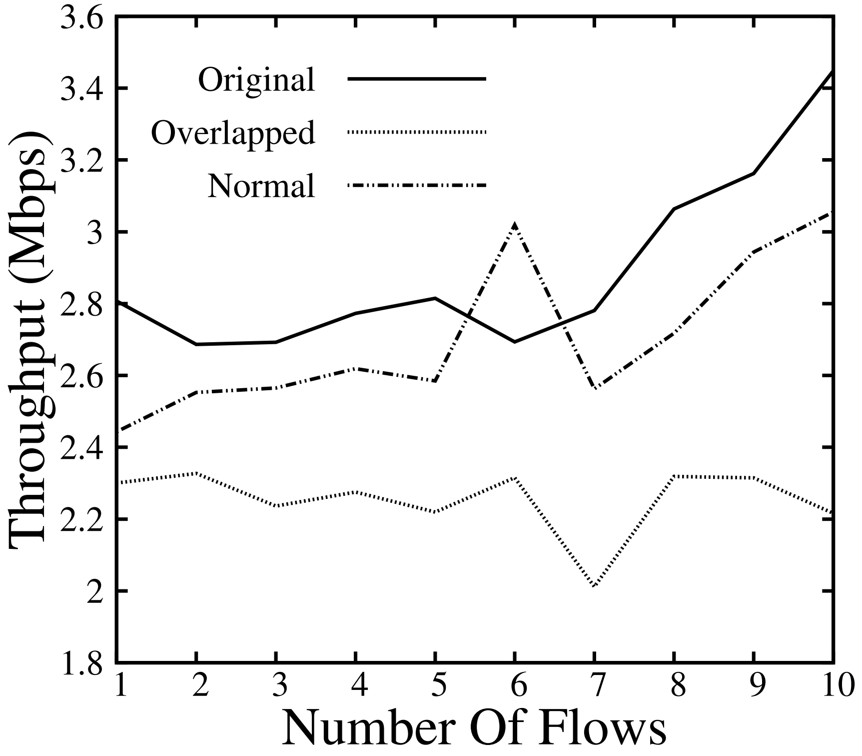

Figure 5.17: Random Adhoc Topology

collisions. The network throughput and delay will be hurt as well. Further effort is required to mitigate this problem.

5.6.2 Opportunistic Access and Transmission

Although the performance evaluation showed a case that the opportunistic access outperformed the opportunistic transmission OAR under fast channel variations due to mobility, the opportunistic transmission may perform better in some cases. One case is when the user diversity is light, then the opportunistic access does not make much difference from the original access. Since the opportunistic transmission sends multiple frames per contention period, it results in average smaller overhead per frame than the opportunistic access. Another possible case is when the channel is stable enough to sustain the completion of transmitting multiple frames in the opportunistic transmission.

Chapter 6

Concluding remarks

This thesis work proposes three opportunistic random access algorithms to exploit user diversity in wireless networks. These algorithms probabilistically or semi-deterministically enable the users to access the shared wireless channel based on their channel conditions such that the user at the highest achievable bit rate is favored. To avoid starving users with poor channel conditions, a slow filtering scheme are proposed to maintain temporal fairness among nodes. The proposed three opportunistic schemes are also derived and compared analytically between overlapped contention and segmented contention to prove that our opportunistic scheme performs better than original CSMA/CA scheme. With extensive experiments on the *NS3* network simulator, it shows that the proposed opportunistic access significantly improves the network performance in throughput, delay, and jitter.

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