Opportunistic Random Access with Temporal Fairness in Wireless Networks

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Technical Report

***Abstract*—User diversity arises when wireless users experience diverse channel conditions. This paper proposes three opportunistic random access algorithms that favor users with the best channel conditions in channel access. These algorithms operate on the contention mechanism of CSMA/CA and compute the contention window based on channel conditions. In one algorithm, the contention windows of all users share the same lower bound zero. In another, the contention windows of users with different channel conditions are segmented without overlapping. The third algorithm adopts a normal distribution to select the backoff value in the contention window. These algorithms are also enhanced to provide temporal fairness and avoid starving the users with poor channel conditions. We implemented a Linux-based testbed for a real world performance evaluation and also developed the algorithms into the *NS3* simulator to conduct comprehensive and controllable experiments. Extensive evaluations show that the proposed opportunistic access can significantly improve the network performance in throughput, delay, and jitter over the current default CSMA/CA method.**

I. Introduction

In wireless networks, channel conditions are determined by many factors such as fading, mobility, shadowing, and location. Because of spatial difference, wireless users often experience different channel conditions, which is referred as *user or spatial diversity* in wireless communication. Due to spatial diversity, a wireless user with excellent channel condition may be able to transmit data at the highest bit rate while another user with a poor link 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 variations of channel conditions are often considered detrimental in the traditional wireless communication because 1) they are unpredictable and 2) 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 [11], transmission [1], scheduling [12]–[14] and routing [15]–[18]. 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.

In this paper, we propose and evaluate three opportunistic media access schemes that exploit *user diversity* in random access wireless networks. These schemes enable the user with the best channel conditions in a random access wireless network to have the largest probability to access the shared channel at a certain moment, but they do not starve the users with poor links. In the long run, each user probabilistically obtains a throughput proportional to its channel conditions in terms of bit rate.

The main contributions of this work consist of:

- three distributed opportunistic random access algorithms
- the development of a Linux-based testbed through prototyping the algorithms into open source implementation
- extensive performance evaluation on the testbed and the *NS3* [25] simulator.

The rest of this paper is organized as follows. The related contention scheme of CSMA/CA is briefly reviewed in Section II. Then, Section III presents the problems that motivate this work. Next, Section IV discusses the three proposed opportunistic access algorithms. Section V presents the implementation of a testbed, experiment settings, and performance evaluations on the testbed and the *NS3* simulator. Some observations are discussed in Section VI followed by the related work in Section VII. Finally, Section VIII concludes this paper.

II. Overview of CSMA/CA

Nowadays, most random access networks such as IEEE 802.11 [6] 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. The contention is regulated by a *Binary Exponential Backoff* process. Each node maintains a contention window that has a lower bound of “0” and an upper bound of CW that starts with an initial value of CW_{min} and may exponentially increase up to a maximum of CW_{max}. Then, a node that is ready to transmit randomly selects a backoff value CW_{bf} from (0, CW] using a *uniform* distribution. The node will keep sensing the channel. If the channel is busy, the backoff value is frozen until the channel becomes idle. Otherwise, it is decremented by one at every (idle) time slot. When the backoff value reaches "0", the node starts its transmission. If the transmission fails, the current contention window upper-bound CW is doubled unless it has reached the maximum CW_{max}. Then another backoff procedure is repeated with the updated contention window.

III. 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 observed problems as described below.

A. 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*.

B. Equal Probability Access in CSMA/CA

From the brief review of CSMA/CA in Section II, regardless of the channel conditions, all nodes probabilistically have **equal** opportunities to access the channel because they **uniformly** select the backoff 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 III-A), 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.

C. 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.

IV. 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 backoff 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.

A. Contention Window Based Opportunistic Access

Two algorithms achieve opportunistic random access by determining contention windows based on channel conditions.

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 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 1 below whenever a node is ready to contend on the channel for a new transmission.

$$CW = \lceil \alpha \times \frac{R_b}{R_i} \times CW_{base} \rceil \quad (1)$$

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 backoff value from the contention window. Then, the computed *CW* can be used by the *Binary Exponential Backoff* procedure in the CSMA/CA to fulfill the opportunistic access.

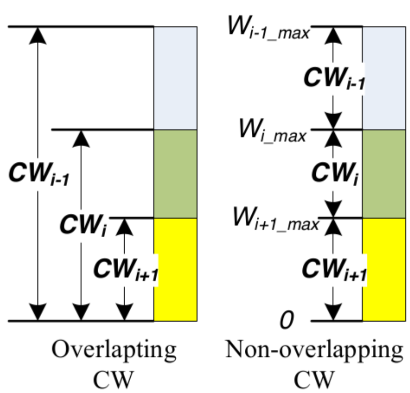

Fig. 1: Illustration of Contention Window

Note 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 backoff value because their contention windows have the same lower bound of "0".

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 1. In this approach, the initial contention window is still computed as in Formula 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 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 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 backoff 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 backoff value, but (2) the access of nodes at different rates is deterministically prioritized because the lower rate nodes can never get a smaller backoff 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 IV-C.

B. Normal Distribution Based Backoff 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 backoff value from its contention window. The third proposed opportunistic access approach consists of using a normal rather than a uniform distribution, in selecting the backoff 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 backoff value than a lower bit rate node. Systematically, the expectation of the normal distribution of a node at rate R is computed as below:

$$E = \lceil \frac{CW}{2} \rceil \quad (2)$$

where CW is computed as in Formula 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 backoff values as shown in Figure 2. As a result, in the long run, A will select a smaller backoff value than B because most likely the

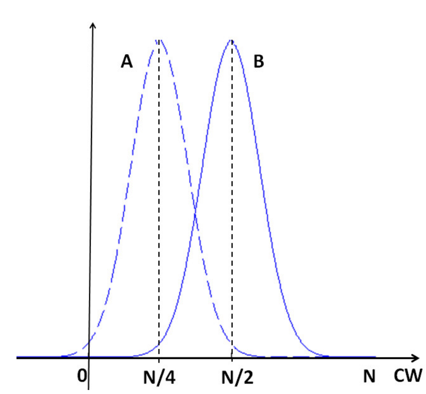

Fig. 2: Normal Distribution Backoff

selected values are near to the expectation in the normal distribution.

C. 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 III, 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:

$$T_{normalized}[k,m] = T_k[m]/R_k \tag{3}$$

This is used to compute the initial contention window. As a result, Formula 1 is accordingly updated as:

$$CW = \alpha \times T_{normolizd}[k,m] \times CW_{base} \tag{4}$$

The contention with Formula 3 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 3 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, 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: $T_k[m+1] = (1-\frac{1}{t_w}) \times T_k[m] + \frac{1}{t_w} \times \phi \times R_k[m]$.

V. Performance Evaluation

We extensively evaluated the performance of the proposed opportunistic access algorithms with both prototyping and simulation.

A. Evaluation with Prototyping

To evaluate the opportunistic access performance in real world, we implemented a Linux based testbed. The implementation includes only the first algorithm–*Overlapped Contention* because the other two require the modification of the lower bound of the backoff window that is "sealed" as 0 in the closed firmware to which we do not have access.

1) Implementation Platform and Experiment Settings: Our prototype testbed consists of six embedded computing nodes based on Alix 3dc SBC that has a 512 MHz AMD LX800 CPU, 256M RAM, and 8GB SD Card storage, and runs Linux kernel version 3.3.1. Each node is equipped with a miniPCI IEEE 802.11a/b/g/n WiFi adapter, MkroTik R52Hn, that is based on Atheros AR9220 chipset that is well supported by the open source Linux driver Ath9k [10]. Each interface is connected to a pair of external high gain antennas. The implementation is based on the Linux wireless modules [9].

The testbed were deployed in the second floor of the Bobby Chain Science Technology Building on campus with a floor plan as shown in Figure 3. The building consists of laboratories, offices and classrooms. Both infrastructure (WLAN) and infrastructureless (Ad-hoc) modes were evaluated. In infrastructure mode, one of the nodes was configured to work as the access point represented by the black triangle in Figure 3 and two client nodes were placed at the locations of circles A and B in the figure. The five hexagons in Figure 3 show the infrastructureless mesh topology. We conducted all our experiments at midnight to minimize the external surrounding interference such as walking people because all classes were dismissed and people were away from work. There are three non-overlapping channels(1, 6, 11) available in IEEE 802.11. We chose channel 1 since channel 6 and channel 11 were heavily used by surrounding networks. As for the software tools, we use iperf [26] to generate and collect UDP traffic from clients to the access point. We did not choose TCP traffic because we would focus on the evaluation of the MAC access performance. The network was set in the IEEE 802.11n mode with two transmission streams and 20MHz bandwidth. With

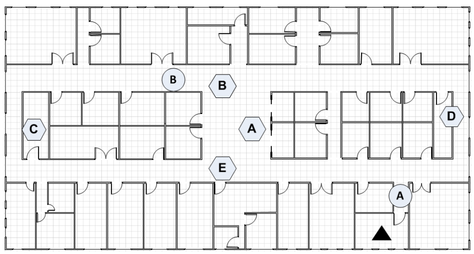

Fig. 3: Floor Plan

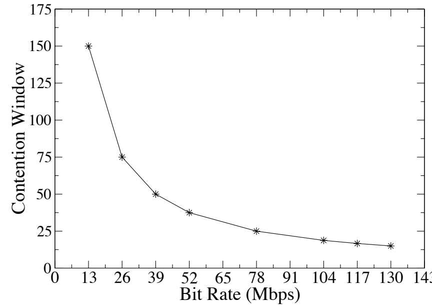

Fig. 4: Validation

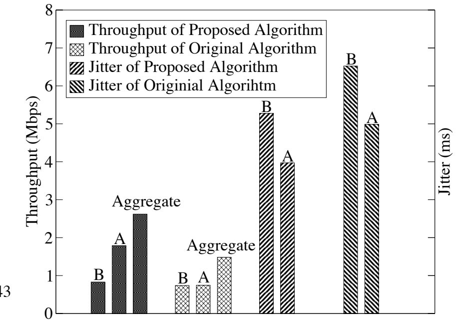

Fig. 5: Infrastructure

this configuration, the bit rate set consists of 13, 26, 39, 52, 78, 104, 117, and 130 Mbps. In our experiments, the basic rate was 13 Mbps when there were two streams enabled over 20 MHz bandwidth with short SGI disabled in IEEE 802.11n. In experiments, α in Formula 1 was set to 100 and the weighted window t_w for temporal fairness was set to 100 ms.

The traffic transmission lasted for 20 seconds for each run of experiment. The *iperf* manual reports that 10 seconds are enough to measure the network throughput. In order to eliminate the variation at the startup and completion of the experiment, we trimmed the 5 seconds at the beginning and the 5 seconds at the end of the measurement, so we still had 10 seconds of measurement. We repeated each scenario six times and the final data in the figures were averaged from the multiple runs.

2) Implementation Validation: We validated the correctness of our implementation as shown in Formula 1 by evaluating the initial contention window computed against the bit rate. Figure 4 shows in general the variation of contention window along with the bit rate. As can observed on this figure, the initial contention window shrinks as the bit rate increases. The figure shows that the implementation validation numerically matches the relation of the initial contention window and bit rate in Formula 1.

3) Infrastructure Mode: This experiment is designed to evaluate the performance of the proposed *Overlapped Contention* in infrastructure mode with an access point and two client nodes as in Figure 3. A supported 130 Mbps and B had 52 Mbps. The transmissions were from the clients to the access point. In this experiment, the access point was configured to run the *iperf* server to receive the UDP traffic from clients.

In this experiment, we measured the jitter and throughput of UDP packets reported by the *iperf* server. Jitter is defined as the latency variation. The results are shown in Figure 5. The left two plots respectively show the throughputs of the proposed algorithm and the original algorithm in CSMA/CA. The right two plots illustrate the jitter performance of these two algorithms. Two obvious observations are: 1) the proposed opportunistic access algorithm outperforms the original one in both throughputs and jitter in general, because the opportunistic access spent much less time on backoff with smaller contention windows than the original access when nodes were at bit rates higher than the basic rate, 2) although the clients A and B have identical throughputs in the original algorithm as expected, the opportunistic access enables them with different throughputs based on their channel conditions and the aggregate network throughput is thereof significantly improved, by more than 50% in the measured case.

4) Ad-hoc Mode: We also conducted performance evaluation on an ad-hoc topology as shown by the placement of the circles in Figure 3. In our experiments, all nodes used the default routing protocol implemented in the module of MAC 80211 in the Linux kernel. MAC 80211 is the wireless management layer in the Linux kernel. Two traffic flows went from C to D, and from B to E. C and D were so placed that they cannot hear each other and their flow had to be routed by A. The hops from C to D had bit rate of 52 Mbps and the hop from B to E was at 130 Mbps. As a result, the experimental topology resulted in a two-hop mesh network. In the experiments, the *iperf* flows started at B and C at the same time to transmit UDP traffic to D and E respectively. As in infrastructure topology, the jitter and throughput were measured.

Figure 6 shows the measurement results. The left part of the figure illustrates the aggregate network throughputs of the proposed opportunistic access and the original algorithm in CSMA/CA. It shows about 30% improvement of the throughput in this specific case. The right two plots on the figure depict the jitters of these two flows. As we can observe, when the opportunistic access was enabled, the jitter of flow $C \to D$ only slightly increased, but that of flow $B \to E$ significantly reduced because the channel condition of $B \to E$ was better than that of $C \to D$ and therefore transmitted more frequently.

5) Impact of t_w: As discussed in Section IV-C, the size of the weighted window, t_w, has a significant impact on the network performance. Actually, it determines the degree of opportunism in that if it is large, the contention metric will not be updated until after a long period and then the user with good channel conditions can opportunistically access the channel for long. But this is at the cost of delaying the users with poor conditions and may hurt real-time applications that require small delay and jitters. We numerically evaluated the impact of t_w on the throughput and jitter in the infrastructure mode with two clients: A at 130 Mbps and B at 39 Mbps. t_w took the values of 50, 80, and 100 ms in the evaluation.

Figure 7 shows the impact on throughput. When t_w was doubled from 50 to 100 ms, the throughput of A improved by about 40% while that of B reduced by about only 15% and the aggregate network throughput improved by about 20%. This is because, as the opportunism is increased along with t_w, A got more chance and B got less chance of using the channel.

Figure 8 shows the impact on jitter. The impact is opposite to that on throughput. When t_w was doubled, the jitter of A was reduced from 5 ms to about 3.5 ms while the jitter of B increased from 7.7 ms to 10 ms just because A got more chance and B got less chance of using the channel. However, both of their jitters are much lower than what is required for real-time applications.

B. Evaluation with Simulation

We developed all three proposed algorithms into the simulator *NS3* [25] 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 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 Backoff Selection*.

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 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 9 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 10 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 comparitively beacause of collision due to back-off terminate at the same time and the contetion window size gets doubled everytime when it encounters a collision. Yet the overall network performance in delay is improved significantly over the default CSMA/CA method. To show more clearly, we further studied the delay performance with increase in traffic rate Figure 11. 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 12 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 and the selected backoff 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.

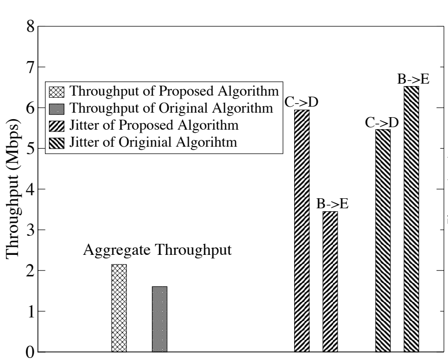

Fig. 6: Ad-hoc

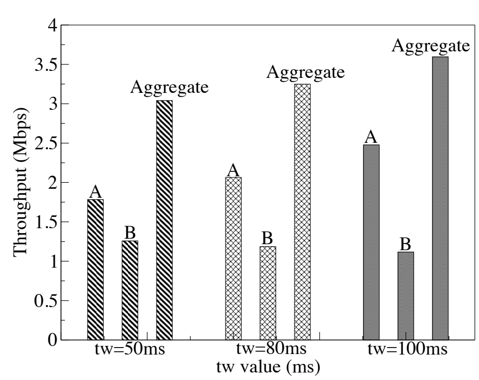

Fig. 7: Impact of t_w on Throughput

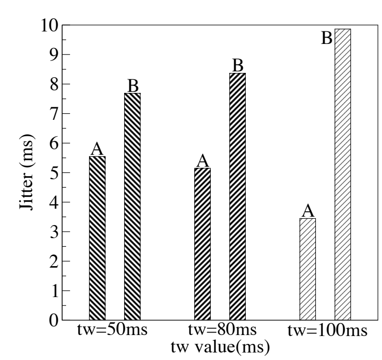

Fig. 8: Impact of t_w on Jitter

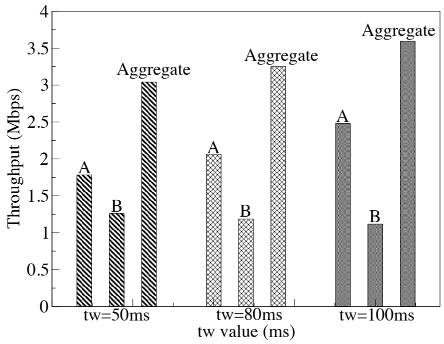

Fig. 9: Throughput

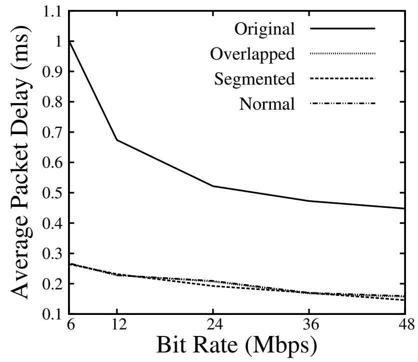

Fig. 10: Average Delay

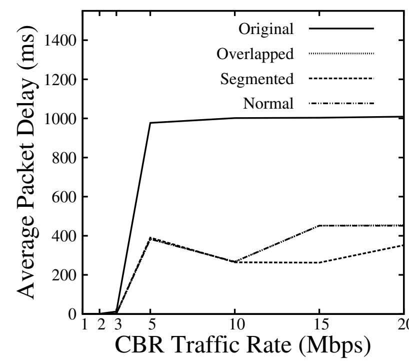

Fig. 11: Traffic Rate Vs Delay

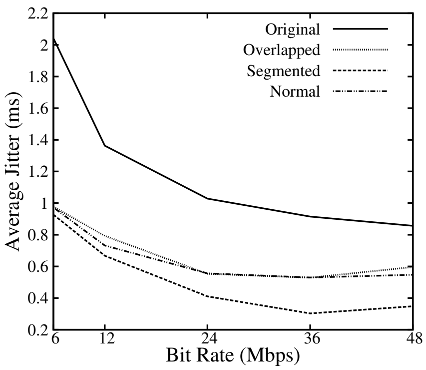

Fig. 12: Average Jitter

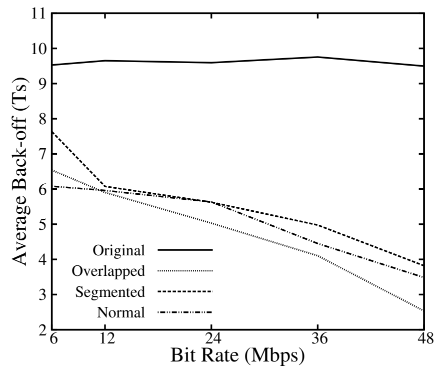

Fig. 13: Average Backoff

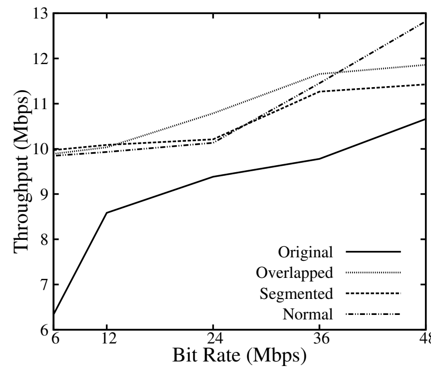

Fig. 14: Hidden Terminal Problem

Average Backoff Time: To further investigate how the opportunistic access improves the throughput and jitter, we collected the backoff time in terms of time slots of each transmission. Figure **??** shows the average backoff time per successful transmission for each access algorithm. Average backoff slot time per packet is calculated as the sum of individual packet backoff time slots over the total number of packets transmitted successfully. From the figure, the opportunistic access algorithms consume much less time in backoff than the original access, up to 400% less at 48 Mbps. The overall network performance improves because 1) the equal probability access in the original algorithm results in almost constant average backoff, and 2) the opportunistic access algorithms spend less time on backoff, namely contention.

Discussion on Opportunistic Access Algorithms: Among the proposed three opportunistic access schemes, the *Segmented Contention* yields in general the best performance from Figure 9 to **??**. 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 backoff value than the ones with higher bit rates. The *Overlapped Contention* and the *Normal Distribution Based Backoff* result in almost identical performance. This is because both of them have a similar expectation in selecting backoff values for the nodes at the same bit rate. Because they both have contention windows starting at “0”, the higher bit rate nodes may still be occasionally beaten by nodes at lower bit rates.

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 14 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 16 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.

3) 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 wins the channel more frequently due to its initial smaller contention window size, suppressing the channel acces 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 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 shown in Figure 17 which increases the overall network performance of opportunistic access.

4) 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$\times$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 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 **??** 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 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.

5) 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 are 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 comparitively.Although OAR protocol shows a high performance over opportunistic access scheme as shown in Figure 19, opportuinistic access shows a better performance than default CSMA/CA method.

6) 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 Jains 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 Index is given by

$$I_J = \frac{(\sum_{i=1}^{n} r_i)^2}{n \sum_{i=1}^{n} r_i^2} \tag{5}$$

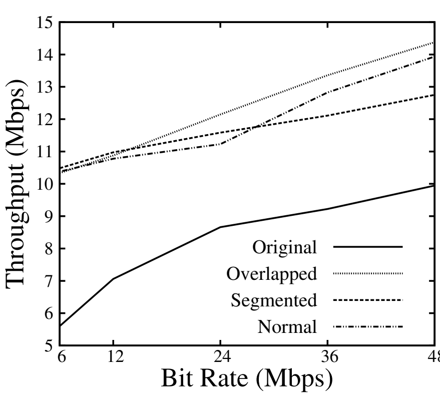

Fig. 15: Hidden Terminal Problem with RTSCTS

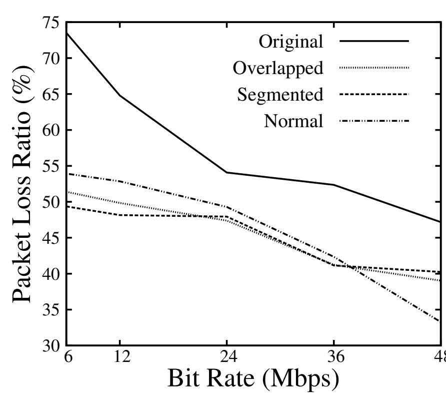

Fig. 16: Packet Loss Ratio

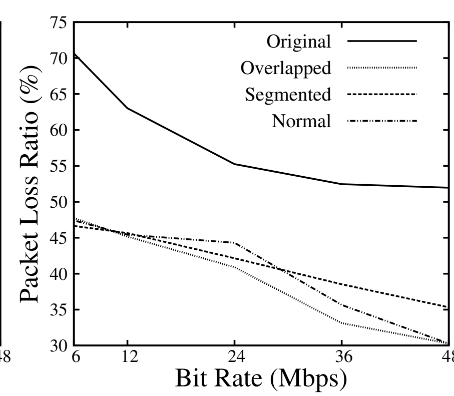

Fig. 17: Packet Loss Ratio with RTSCTS

Where r_i and n are the allocated resources to user i and the total number of users respectively.

Figure 20 shows that the 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.

7) Multi-hop Mesh Topology: In this scenario, 30 nodes were randomly and statically distributed in a 150m$\times$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 [27] protocol was used to route the packets over the network.

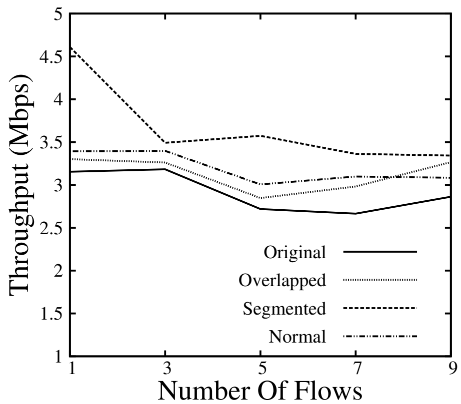

Fig. 21: Multi-hop Mesh Topology

The network throughput performance is plotted in Figure **??**. 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 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 backoff from overlapping contention windows helps dilute the collision.

VI. Discussion

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.

A. 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 22. 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).

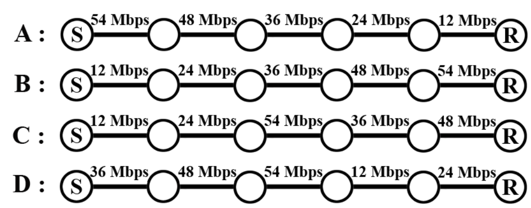

Fig. 22: Four Chain Topologies

Figure 23 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 more packets in the early hops

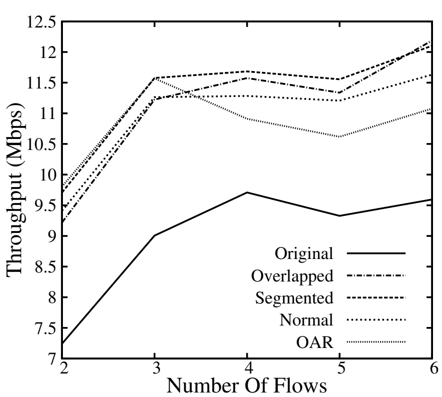

Fig. 18: Mobility

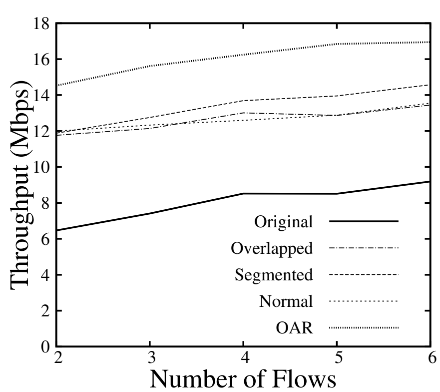

Fig. 19: No Mobility

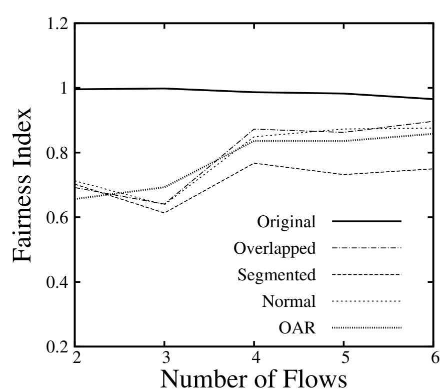

Fig. 20: Fairness

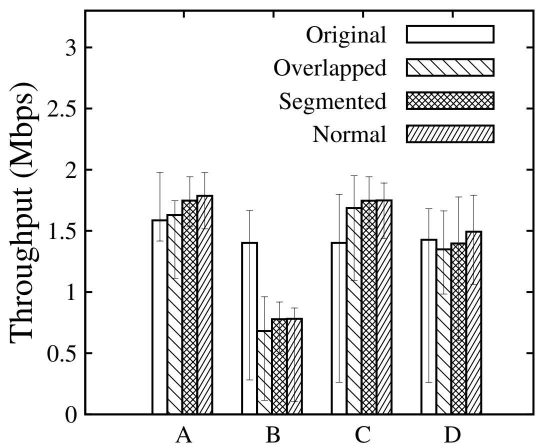

Fig. 23: Throughput in Chain Topologies

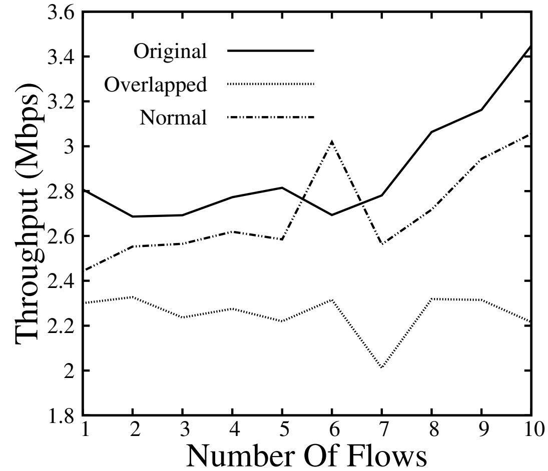

Fig. 24: Random Adhoc Topology

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.

B. 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. Pre-selected source and destination are configured such that the numbet of flows are increased from 1 to 10. OLSR protocol was used to route the packets. The opportunistic acces performance is degraded considerably due to mobility and auto rate as shown in Figure 24. 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 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.

C. Increased Collision

In the proposed opportunistic access, high bit rate nodes tend to have small contention windows. Although the backoff 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 backoff value, especially when a network has many such nodes. Then, this exacerbates the collision because the backoff values at the nodes terminate at the same time. Although the binary exponential backoff mechanism can address this problem, the network efficiency is degraded with the channel resource wasted by frequent collisions. The network throughput and delay will be hurt as well. Further effort is required to mitigate this problem.

D. 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.

VII. Related Work

Hwang and Cioffi [24] proposed an opportunistic CSMA/CA that also targets the user diversity in WLAN. Their algorithm instructs 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. Zhai *et al.* [11], [21] 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.

Opportunistic transmission based on multiple rates was demonstrated to yield a significant improvement of the network performance in IEEE 802.11 networks [1]–[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. Opportunistic transmission occurs after the contention of channel access that is still conducted with traditional non-opportunistic approach: equal probability access. It exploits the time diversity of a node, not the user diversity of a network.

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 the smallest size. In this way, the higher priority traffic has a chance to be delivered before the lower priority 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.

VIII. Conclusion

This 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 is proposed to maintain temporal fairness among nodes. With extensive experiments on a developed linux-based testbed and the *NS3* network simulator, the proposed opportunistic access significantly improves the network performance in both throughput, delay, and jitter.

IX. Acknowledgments

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