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Research Article

Channel MAC Protocol for Opportunistic Communication in Ad Hoc Wireless Networks

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Despite significant research effort, the performance of distributed medium access control methods has failed to meet theoretical expectations. This paper proposes a protocol named "Channel MAC" performing a fully distributed medium access control based on opportunistic communication principles. In this protocol, nodes access the channel when the channel quality increases beyond a threshold, while neighbouring nodes are deemed to be silent. Once a node starts transmitting, it will keep transmitting until the channel becomes "bad." We derive an analytical throughput limit for Channel MAC in a shared multiple access environment. Furthermore, three performance metrics of Channel MAC—throughput, fairness, and delay—are analysed in single hop and multihop scenarios using NS2 simulations. The simulation results show throughput performance improvement of up to 130% with Channel MAC over IEEE 802.11. We also show that the severe resource starvation problem (unfairness) of IEEE 802.11 in some network scenarios is reduced by the Channel MAC mechanism.

1. Introduction

An ad hoc wireless network is a collection of wireless mobile nodes that self-configure to construct a network without the need for any established infrastructure or backbone. The mobile nodes themselves handle the necessary control and data acquisition tasks through the use of distributed control algorithms. Significant research effort has been invested in designing protocols suited for ad hoc networks, with various objectives such as minimising energy consumption, throughput improvement, scalability, efficient self-configuration, fairness, and minimising delay.

The implementation of medium access control (MAC) protocols for ad hoc networks has been dominated by the IEEE 802.11 standard, which was initially implemented in the context of single-hop wireless local area networks (WLANs). Although often used in practical implementations of mobile ad hoc networks, IEEE 802.11 presents several drawbacks in the context of ad hoc networks, one of them being its poor throughput performance. Gupta and Kumar introduced a random network model for studying the throughput of wireless networks with fixed topologies and showed that the throughput per source-destination pair is $\Theta(1/\sqrt{n \log n})$ ($f(n) = \Theta(g(n))$ means $g(n)$ is an asymptotically tight bound of $f(n)$), where n is the number of nodes [1]. Grossglauser and Tse (2001) later showed that when nodes are mobile it is possible to have a constant throughput scaling per source-destination pair [2], independent of the number of nodes. However, the performance of ad hoc networks with MAC protocols such as IEEE 802.11 falls short of what is predicted by these theoretical models. This has been attributed to various factors including the inability of current MAC protocols to simultaneously take into account various effects such as fading channel conditions due to mobility, self-configuration issues, and unfairness in providing access to the common channel [3], [4, Chapter 16].

Throughput performance degradation of IEEE 802.11 in the presence of fading channels has been studied in detail in [5]. In this paper, authors quantitatively estimated the degradation of the network throughput due to fading. Figure 1 shows the degradation of network throughput versus the probability of the channel being "bad" for different

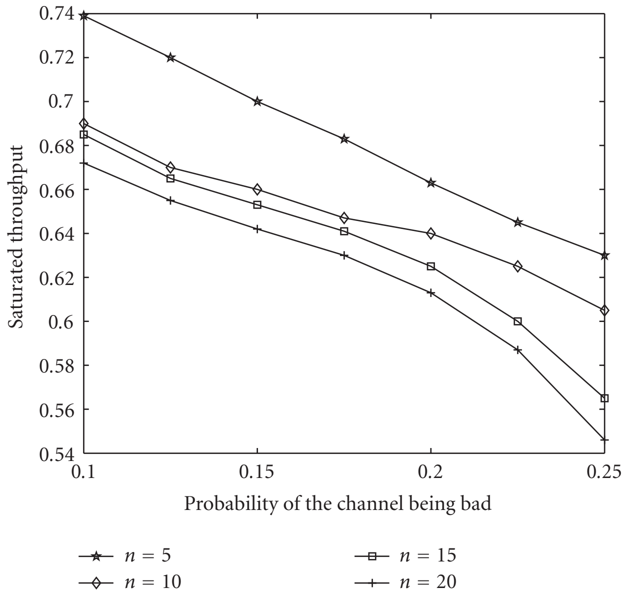

Figure 1: Throughput degradation in IEEE 802.11 DCF mode depending on probability of bad channel.

network sizes (n is the number of nodes in the network). This performance degradation is due to the MAC layer not receiving instantaneous notification of channel variations. When the channel goes into a "bad" state, the nodes continue sending packets, eventhough these packets are discarded due to the low received power. This results in a waste of bandwidth which could have been used by other nodes. In [5], the authors proposed to improve the performance of the IEEE 802.11 standard by utilising channel state information (CSI). The resulting MAC only transmits packets when the channel is such that the received signal will be above a predetermined threshold which ensures proper detection of the data at the receiver. Although this proposed scheme has improved performance when compared to that of the usual IEEE 802.11 standard, it is well below the channel capacity [4, Chapter 16].

The rest of the article is structured as follows. Section 2 describes related research in the field of opportunistic medium access control mechanisms and Section 3 follows with an explanation of the motivation for this study and the functionality of the proposed MAC protocol. Section 4 presents an analysis of the throughput performance of the Channel MAC mechanism. Section 5 discusses the network simulation to calculate, throughput, delay and fairness of the system, and the performance of Channel MAC is compared with its IEEE 802.11 counterpart. Finally, Section 6 concludes this work with future research objectives.

2. Related Work

Similar to the work in [5], a mechanism for deciding which node, from a set of nodes, should be allowed to transmit at a given time has been presented in [6]. The basic idea exploits the multiuser diversity principle at the MAC layer and relies on the fact that users are competing for the channel access experience peaks in their channels at different times, and at a given time the node with the best transmission conditions gets the opportunity to transmit. In [6], it was shown that if access to the medium is given in a centralised fashion to the user with the best channel, the throughput performance of the overall system is improved.

In [7], Qin and Berry considered a medium access control protocol, where each user possesses knowledge of their own channel gain. They introduced a channel-aware ALOHA protocol where users can still exploit multiuser gain in a decentralised way. A series of related works was published in [8–10]. It has to be pointed out that these proposed schemes, although exploiting diversity as a way to determine who has priority for transmission, still use a slotted system. Therefore, in the absence of a central entity which would determine who will transmit based on the "best" channel, collisions will still occur because all nodes with good channel conditions will compete for resources at the beginning of the slot.

The gain in throughput observed in these CSI based MAC protocols is due to two reasons: firstly, only a reduced number of nodes (those with a good channel) will be competing for the available bandwidth in a given time slot, which reduces the number of collisions and increases the throughput. Secondly, the allowed transmissions will be successful with a higher probability due to the high signal quality, which reduces the number of retransmission requests, as well as the amount of bandwidth wasted on unsuccessful transmissions. However, in a decentralised system, collisions can still occur unless spreading techniques are used [9] or other collision avoidance mechanisms are implemented, resulting in an increased number of control packets. This will reduce the throughput performance.

We proposed a new MAC paradigm, called Channel MAC in [11], which exploits the random nature of the fading channel to determine the channel access instances in a decentralised and distributed manner. In contrast to [6], where the user with the best channel is given access to a time slot, our proposal does not require a slotted access system. A centralised network where nodes are communicating to an access point is shown on the left side in Figure 2. In the literature, the multiuser diversity principle is generally applied to this scenario. In contrast, Channel MAC considers a decentralised network scenario shown on the right side of the figure where different transmitter-receiver pairs are communicating independently (i.e., without any centralised access point).

Channel MAC uses the randomness of the fading channel between transmitter-receiver pairs to decide which node should transmit at a given time in a distributed manner. The idea is that the node which has its channel becoming "good" at a given instance gets access to the channel provided that no one else is transmitting at that moment. This opportunity for transmission persists until the channel becomes "bad" again. Therefore, it is a time-asynchronous channel access mechanism. It should be noted here that Channel MAC merely gives channel access to a "good" channel at a given time, but not necessarily to the "best" channel.

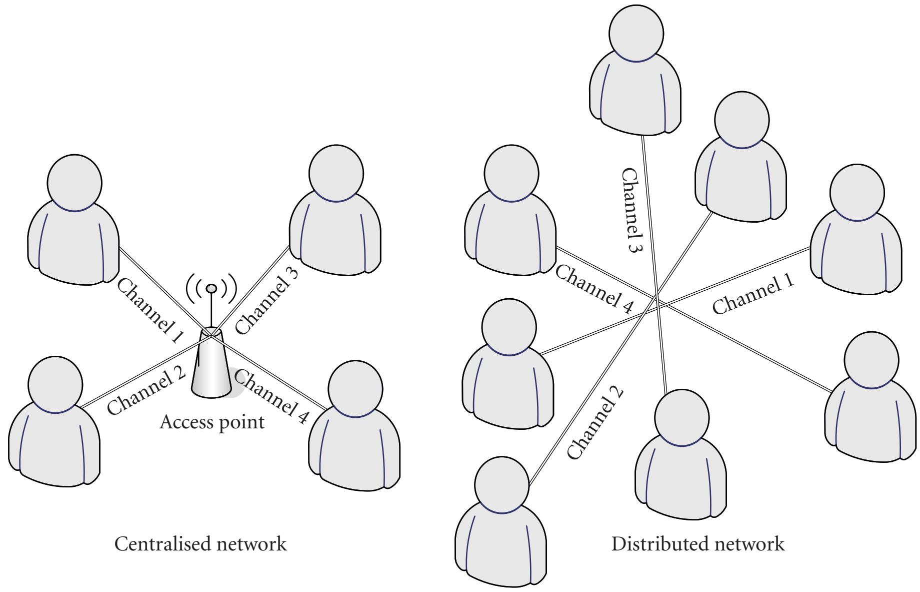

Figure 2: Centralised and distributed networks.

The objective of this paper is to evaluate the effectiveness of such a *fully-distributed, but nonoptimum* medium access control mechanism in various network environments. We will evaluate the performance of this MAC paradigm using analytical results as well as event-based simulation results.

3. The Channel MAC Mechanism

In the related work described in Section 2 [8–10], medium access is accomplished either in a centralised way or at each node with the knowledge of the channel states of other nodes. We use a fully distributed scheduling mechanism where each node determines its channel access irrespective of the channel conditions at other nodes.

3.1. Channel Prediction. Similar to other opportunistic communication-based systems, Channel MAC requires nodes to predict the fading channel [4]. As the objective of this paper is to investigate whether a distributed nonideal opportunistic access scheme exploiting the channel randomness can provide significant performance improvement, we do not suggest a particular prediction scheme to be used in conjunction with the Channel MAC protocol in this paper. We provide the following discussion on fading channel prediction to ascertain the existence of schemes that are suited for channel prediction in Channel MAC.

Fading generally occurs due to multiple reflections of the transmitted signal from objects in the environment. If an unmodulated carrier at frequency f_c is transmitted over a fading channel, the complex envelope of the received noiseless signal at time t, $c(t)$, is given by

$$c(t) = \sum_{n=1}^{N} A_n e^{j(2\pi f_n t + \theta_n)}, \quad (1)$$

where N is the number of scatterers. For the nth scatterer, f_n is the Doppler frequency, θ_n is the phase, and A_n is the amplitude. The parameters A_n, f_n, and θ_n vary slowly (on the order of 0.1 second [12]) and can be viewed as fixed over a few milliseconds. Channel prediction methods discussed in the literature can be broadly divided into three categories, according to the underlying channel model: autoregressive (AR), sum-of-sinusoids (SOS), and basis expansion algorithms (band limited process model-based, etc.) [13]. To allow for comparison between different schemes, the prediction range is often expressed in "wavelengths," λ (when the maximum Doppler shift is f_d, a prediction t seconds ahead corresponds to a prediction of $f_d t$ wavelengths). References [12, 14] provide overviews of long range prediction techniques for fading channels, which include several techniques capable of predicting a channel over more than 1 wavelength.

In the SOS model-based approach, if the parameters A_n, f_n, and θ_n in (1) remain fixed and are known perfectly, the individual complex sinusoids can be extrapolated and summed to produce a reliable prediction of the fading signal. ESPRIT [15] is an example of the SOS approach. With the ESPRIT prediction scheme, reliable prediction is feasible for about 1 wavelength [15]. At a speed of about 10 kmph, this corresponds to making predictions about 46 milliseconds ahead at 2.4 GHz. Assuming that the ratio of power threshold to root mean square (RMS) power of the received signal is 0.5, the level crossing rate for the above parameters (i.e., speed = 10 kmph, frequency = 2.4 GHz) is about 35 crossings per second. This leads to around 1.6 fades in 46 milliseconds. Hence, with the ESPRIT scheme it is possible to predict the channel gain for the next 1 or 2 fading cycles.

The modified covariance method discussed in [14] is capable of predicting the channel for up to 1.5 wavelengths.

For the same parameters discussed above, this corresponds to predicting the channel gain for the next 2 to 3 fading cycles.

The AR model-based methods are more appropriate for realistic channels. The AR model-based long range prediction (LRP) algorithm was discussed in [12]. In LRP, the low sampling rate increases the memory span and utilises the large side-lobes of the channel autocorrelation function to predict the channel for multiple fading cycles. For example, for a sampling frequency of 500 Hz, maximum Doppler frequency of 100 Hz and model order of 20, the memory span of channel prediction becomes 30 milliseconds at high accuracy, compared to a memory span of 0.76 millisecond at a higher sampling frequency of 25 KHz with the aforementioned channel configuration. (In time series analysis, "model order" is defined as the number of previous samples used to predict a future value.)

Band-limited process model-based prediction algorithms are investigated in [16–18]. In these methods, the basis functions of the subspace of time-concentrated and band-limited sequences are determined using the AR function of the fading channel. The extrapolated basis functions are then used to construct predicted fading coefficients. Although band-limited process model-based algorithms demonstrate reliable performance for synthetic channels with stationary parameters, performance, and complexity, investigations for realistic channels have not been carried out for these methods.

Based on the above cited literature, we assume that it is possible to accurately predict the channel fading for the next multiple fading cycles as required by the Channel MAC protocol. However, with increasing number of nodes the required prediction range increases as we illustrate through the following simple example.

Assuming a constant data transmission interval l for each transmitter-receiver pair, n transmitter-receiver pairs and fair access the shared channel, a transmitter should access to the channel every nl seconds. This requires a transmitter to predict at least nl time ahead in a single-hop network environment. In other words, if the prediction range is t, a maximum of $\lfloor t/l \rfloor$ number of transmitter-receiver pairs can be accommodated in the single-hop system. Hence, the size of the network is bounded by the prediction range. However, in practice, if the required prediction range is very large (in case of large number of users), either multistep (predicting the full length in a single step) or iterated one-step predictions can be applied [19, Chapter 12]. Although, iterated one-step prediction is preferable in terms of calculation efficiency and accuracy in general time series analysis, this technique may suffer from the problem of exponential divergence. However, in a large interval, correlation in samples becomes negligible [20]. In such systems, the mean value is considered the best prediction as only minimal multistep errors are observed [19, Chapter 4, Chapter 12].

As the objective of this paper is to evaluate potential performance improvement (throughput, delay, and fairness) resulting from the proposed access paradigm, we do not focus on the actual mechanisms used in the channel prediction scheme or the potential scalability problems as discussed in the previous paragraph. Instead, we consider a prediction inaccuracy model, presented in [21], and evaluate the effect of such prediction inaccuracies on the overall performance in Section 5.1.1.

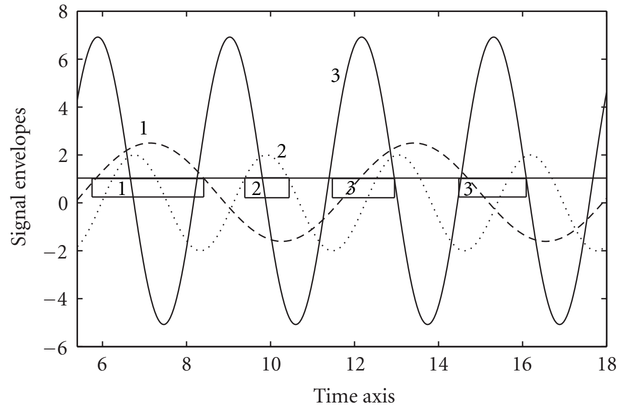

Figure 3: Data transmission using Channel MAC.

3.2. Channel MAC Protocol. In Channel MAC, a node prearranges the instances at which it will send data packets based on the predicted channel gain between the node and the intended receiver and a signal amplitude threshold (P_{th}) for transmission. We also consider constant transmission power in the network. When the predicted signal amplitude goes above the P_{th} threshold, the corresponding node can potentially start transmission. However, before sending data, a node will sense whether the channel is busy or not. If the channel is idle, that is, no other node is currently transmitting, the node starts transmission and continues until the signal envelope goes below the P_{th} threshold (i.e., the channel goes into a fade). The number of packets transmitted during a good channel period depends on the packet size and the duration of the good channel period. If any other channel becomes good during transmission, the corresponding node will sense the channel is busy and will not transmit. It should be noted here that the carrier-sensing threshold of the nodes is set to a much lower value than the receiving threshold. Hence, the transmitters should sense the medium is busy even if the channel gain between a transmitter and an interfering node is low.

Given that each transmitter-receiver pair is likely to have an independent fading channel, the probability of two or more channels crossing the transmission threshold on a positive slope exactly at the same instance is assumed to be negligible. An instance is considered as a very small interval on the order of 1 picosecond or less. Channel detection time is considered negligible for a channel of size 200 KHz or more as in [22]. However, due to finite propagation delay, collisions can occur, decreasing the throughput. A comprehensive analysis of collision probability in Channel MAC and the reason why it is negligible is given in the appendix. In case of collisions, colliding packets will be retransmitted.

The detailed principles of Channel MAC are explained in Figure 3. As soon as *Channel 1* (represented by 1 in the figure) goes above the threshold, transmission for node 1 starts. Transmission is terminated as soon as the signal amplitude goes below the threshold. Next, *Channel 2* (2 in the figure) goes above the threshold and starts transmission. During the transmission at node 3 (its channel is 3 in the figure), *Channel 2* and *Channel 1* become good but both node 1 and node 2 will sense the channel busy and defer transmission.

It should be noted that the Channel MAC does not rely on a random backoff mechanism to randomise access to the shared medium. Instead, Channel MAC uses the random fluctuation of channels between different pairs of nodes to randomise channel access. The decision to transmit is taken at each node without explicit knowledge of the channel gain between other nodes in the neighbourhood. Therefore, the system is totally distributed.

3.3. Practical Considerations. In this section, we briefly describe some issues in implementing the Channel MAC paradigm.

3.3.1. Start-Up Phase. To start the communication, a node needs to predict the channel gain at the intended receiver. To predict the channel gain, a node requires a few samples of the previous channel gains. This can be obtained through the received powers recorded on the acknowledgment (ACK) packets or by sending periodic beacons. Whenever a node needs to send a packet to a new node (i.e., start-up session of any new transmitter-receiver pair), a series of beacon messages can be used to measure and predict the channel to the new node. At the start, these beacons need to be sent randomly when the channel is idle. Once sufficient measurements have been obtained, nodes can predict the channel and start data transmission. A similar procedure needs to be performed when there is a long period of inactivity between two nodes. It should be noted here that initially the predictions will be inaccurate and hence there will be a period of low throughput until the prediction accuracy becomes sufficiently high.

3.3.2. Mean Received Power Calculation. The widely used radio signal-based distance estimation (RSS) provides high accuracy in location measurements on the order of a meter or better [23]. Conversely, the mean received power can be measured if the distance information is available. We assume each node uses the GPS or a similar scheme to estimate its location and transmit the location, antenna gain, and relevant information using a field in the packet. Thus each transmitter-receiver pair knows the relative distance from each other and can approximate the mean received power for a constant transmitter power value. The information required for this calculation can be sent using a field of either control or data packets.

3.3.3. Power Threshold Selection. After measuring the mean received power, each transmitter-receiver pair calculates the *threshold* power level for the packet transmission and reception based on the probability of a good channel, P. P is the probability that the channel gain H_i is above a certain threshold $H_{\hat{T}}$, given by [24]

$$P = \exp\left(-\frac{H_{\hat{T}}^2}{h_0^2}\right), \tag{2}$$

where h_0 is the average channel gain. Note that keeping approximately the same P across all channels maintains fair throughput in the network [11]. We assume all nodes in the network agree on the same value of P for data transmission. Hence, once the mean received power is estimated, a node will estimate the channel gain threshold $H_{\hat{T}}$, using (2).

3.3.4. Acknowledgments. Once the receiving node receives the packet, the received signal strength is estimated and sent to the transmitting node in an ACK packet. If the estimated received power in the current ACK packet is higher than the threshold, the sender sends another packet to the receiver. Otherwise, the sender defers packet transmission and predicts the start of the next transmission instance (i.e., the time predicted signal strength crosses the threshold in an upward direction).

4. Throughput Analysis of Channel MAC

In this section, the analytical throughput equations for Channel MAC are derived and validated using a simple Monte-Carlo simulation.

4.1. System Model. Let us define a neighbourhood of $2n$ nodes, where $N_T \in (1, 2, \ldots, n)$ are the transmitters and $N_R \in (1, 2, \ldots, n)$ are the receivers. For symmetry, let us assume that each transmitter $i \in N_T$ is communicating with receiver $j \in N_R$.

4.2. Channel Model. We consider a simple two-state channel model. It has either a nonfade state "ON" with gain 1 or a fade state "OFF" with gain 0. The (ith) nonfade duration of the $\overline{n}$th channel, denoted as $l_{\overline{n}i}$, is an arbitrary distributed random variable with mean l (i.e., average nonfade duration (ANFD) is l), where $\overline{n} \in n, i \in \mathbb{R}$. Afterwards, the channel goes into a fade with an arbitrary distributed fade duration as shown in Figure 4. The instantaneous (ith) fading time of the $\overline{n}$th channel, denoted as $\Theta_{\overline{n}i}$, is a random variable with the mean Θ, where $\overline{n} \in n, i \in \mathbb{R}$. Θ is also known as average fade duration (AFD) of the channel. Hence, the probability of good channel, P, can be calculated as follows:

$$P = \frac{l}{l + \Theta}. \tag{3}$$

We assume that all the channels in the network have the same P value.

When the number of users in the network is 1 node pair (this system is termed 1-user pair Channel MAC), the resulting transmission pattern of the network is identical to the channel model.

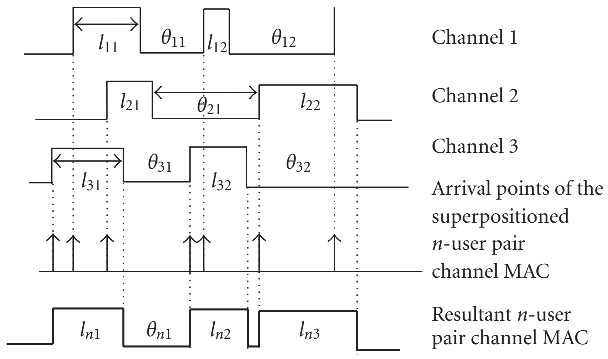

Figure 4: Two-state channel model.

We define the expected period of 1-user pair Channel MAC, T_p, in terms of the number of arrival points per unit time period (i.e., level crossing rate, r) as follows:

$$T_p = \frac{1}{r} = t + l, \tag{4}$$

where t is the expected idle time for 1-user pair Channel MAC.

4.2.1. Arrival Points of n-User Pair Channel MAC. We define the "Superpositioned n-user pair Channel MAC" as the superposition [25, pages 101–104] of arrival points of n independent channels. We assume that, at each instance, exactly one channel becomes good (i.e., transitions from OFF to ON). The corresponding node can then transmit data given that no one else is transmitting at that instance. Following the operation of Channel MAC, we can identify the transmission periods and idle periods of the network with n user pairs, which we term as "Resultant n-user pair Channel MAC" system.

Note the difference between *Resultant* and *Superpositioned* n-user pair Channel MAC. In Resultant n-user pair Channel MAC, the number of arrival points (i.e., transition from OFF to ON) cannot be greater than the number of arrival points in the Superpositioned n-user pair Channel MAC. This is due to the fact that some of the arrival points of the Superpositioned n-user pair system may not contribute to throughput in Channel MAC operation as they may occur while another node is transmitting.

We further assume that in Superpositioned n-user pair Channel MAC, arrival points of individual channels are "sparse." That is, in any particular set $\overline{A}$ of arrival points occurring in a random and large time interval, there will be with high probability, at least one point from each process. In addition, no arrival points from one channel dominate over others. Hence, an approximately equal number of arrival points from different channels should be present in a large enough time interval. These assumptions will be satisfied if all the channels use the same P values as is the case with Channel MAC.

4.3. Superposition of Point Processes. It is known that the superposition of two independent renewal processes is itself a renewal process if and only if both processes are Poisson [26]. It is also known that the superposition of independent and uniformly sparse processes converge to a Poisson process as the number of processes and the sparseness increase. Such convergence results were first examined by Palm in 1943 and Khinchin in 1955 under rigid assumptions [27]. A general Poisson limit theorem for independent superpositions was obtained by Grigelionis in 1963 [28]. This theorem states that if the points of each individual processes are (a) suitably sparse and (b) no one process dominates the rest, the distribution of the point process is close to Poisson. Corresponding results for point processes generated by mixing Poisson and compound Poisson process can be found in [29]. Similarly, practical applications such as the superposition of arrival processes in a "single server queuing model" consider approximation-based approaches, where the superimposed point process is approximated as a Poisson process [30]. All these works conclude that a Poisson process is often a good approximation for a superposition process if many processes are being superposed. Based on our assumptions above, we assume that the arrival points of the Superpositioned n-user pair Channel MAC converge asymptotically to a Poisson process.

4.4. Expected Idle Time of Resultant n-User Pair Channel MAC. It can be observed that the expected idle time, $E[I]$, of the system decreases with the increasing number of channels. As per our assumptions, the Superpositioned n-user pair Channel MAC is approximated by a Poisson point process.

Since the arrival points are memoryless, we derive

$$\begin{aligned} F_I(x) &= P(I \le x) = 1 - e^{-nrx} \\ \therefore E[I] &= \frac{1}{nr}. \end{aligned} \tag{5}$$

4.5. Throughput Estimation. The expected period of arrival point process for the Resultant n-user pair Channel MAC $\hat{T}_p$ is the summation of the expected duration of successful transmission l and expected idle time $E[I]$. The average channel utilisation or throughput S of Channel MAC is given by the ratio of l to the expected period of the Resultant n-user pair Channel MAC [22]:

$$S = \frac{l}{\hat{T}_p} = \frac{l}{l + E[I]}. \tag{6}$$

4.6. Model Validation. In this section, we use two distinct channel models to verify the accuracy of the above throughput estimations.

4.6.1. Simulation 1: Fixed l and Exponential Fade Duration. We assume arbitrary distributions for both nonfade and fade durations. As a special case, we consider fixed l for nonfade duration and exponentially distributed fade duration with mean $(1/r - l)$. The simulation approach we use is to generate n independent channels with the same l and average fade duration $1/r - l$. When one or more channel "ON" periods

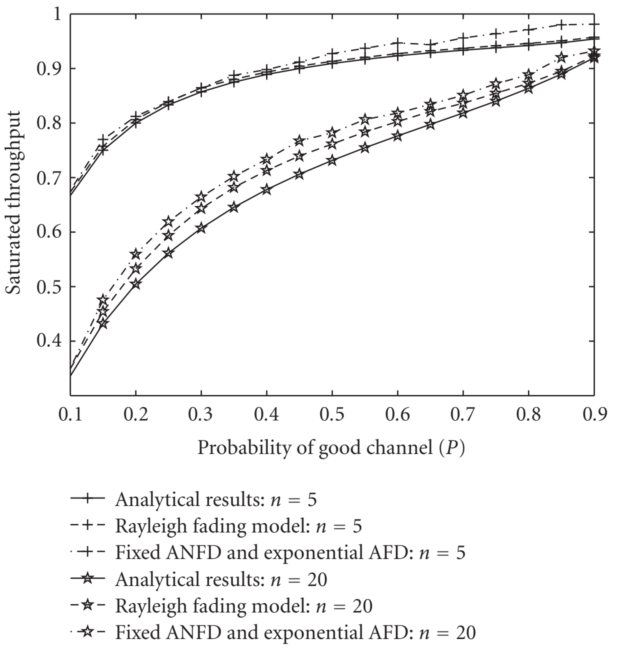

Figure 5: Throughput versus P for different number of node pairs.

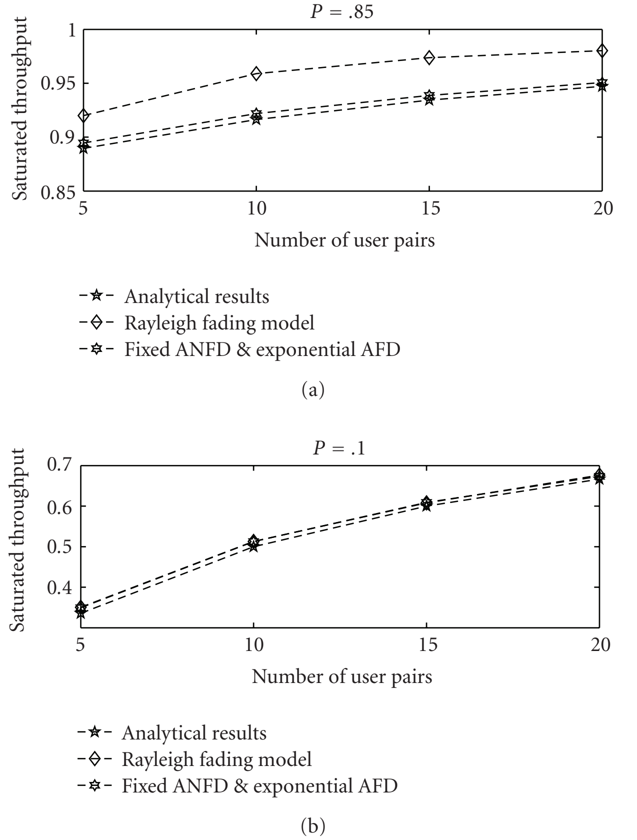

Figure 6: Throughput versus numbers of node pairs for $P = .1$ and $P = .85$.

overlap, only the first channel to go to "ON" after a nonzero idle period contributes to the throughput.

4.6.2. Simulation 2: Rayleigh Fading Model. In the second simulation, we generate a set of "ON" and "OFF" intervals based on a Rayleigh fading channel. P which is equivalent to the probability that the envelope amplitude of the received signal H_i is above a certain threshold $H_{\hat{T}}$, is given by (2).

In the simulation, for a given P value, we derive the signal envelope threshold, $H_{\hat{T}}$. Then, we generate a channel model, covering a time period $\hat{T}$, in the form of a set of time intervals, $\mathbf{\Lambda} = \{\lambda_1, \lambda_2, \ldots, \lambda_i, \ldots\}$, where the signal envelope is above the threshold $H_{\hat{T}}$. These $\mathbf{\Lambda}$ time periods are the transmission intervals of a node when the probability of good channel is P. For n node pairs, n sets of independent $\mathbf{\Lambda}$ time intervals were generated. In case of overlapping transmission intervals from different nodes, only the first transmission interval in the overlapping group contributes to the throughput. We assume the same P for all nodes.

Throughput performance of the aforementioned models for Channel MAC is presented in Figure 5. The results are shown for a different numbers of node pairs ($n = 5$ and 20) at different probabilities of good channels. It can be observed that the analytical results largely agree with the simulation results for different n values over the range of channel conditions. Furthermore, in Figure 6, the throughput versus the number of nodes in Channel MAC using all three models is shown at $P = .1$ and .85. It can be noted that, as expected, the discrepancy between the simulation and the analytical model decreases with increasing number of node pairs.

5. Network Simulation Using NS2

In this section, we evaluate the performance of the proposed Channel MAC protocol through an event-based simulation. The objective of this simulation study is to show that the proposed fully-distributed medium access control mechanism provides significant performance gains over the widely used IEEE 802.11. The simulations in this paper are conducted using NS2 version 2.27. We assume the fading between different nodes is Rayleigh. However, it should be noted here that the results can be extended to other flat fading channels such as the Ricean channel. In this simulation study, instead of using channel prediction we derive the start and end of transmission periods for each channel as follows. We generate a Rayleigh distributed fading within a narrowband signal envelope according to the "dent model" proposed in [31]. In the model, the carrier frequency is set to 2.4 GHz, symbol rate is 19.2 Ksps, and node velocities are set to 10 kmph (which corresponds to pedestrian speeds over short time periods). The probability of good channel, P, which is equivalent to the probability that the signal envelope H_i is above a certain threshold, $H_{\hat{T}}$, is given by (2). Transmission intervals for all nodes in the network are calculated as described in Section 4.6.

Nodes communicate using half-duplex radio based on the Channel MAC mechanism at 1 Mbps. The transmission range of a node is set to 250 m and the carrier sense threshold is set to 550 m. A packet interframe space (PaIFS) is used just before transmitting a packet. PaIFS is similar to DIFS of IEEE 802.11 DCF mode. Between receiving a packet and sending the ACK, a short interframe space (SIFS) is used. PaIFS, SIFS, ACK, and MAC-PHY header values of Channel MAC use similar values of IEEE 802.11 (basic access mode) for comparison purposes (the MAC-PHY header and ACK sizes are 400 and 240 bits, resp., PaIFS and SIFS durations are 128 and 28 microseconds, resp.). The sensing delay for each node pair is set to 0.01% of the packet transmission time. This finite sensing delay and propagation delay will lead to collisions. Generally, the next DATA transmission of a node starts after getting an ACK. In the case of a collision (i.e., no reception of ACK/timeouts), the node stops further transmissions. For the 802.11 simulation, the basic access method is used.

Generally, channel quality-based packet schedulers introduce unfairness among the users. We assumed the same probability of good channel P for all transmitters. Correspondingly transmitter-receiver pairs fix the thresholds according to (2) based on different mean received powers. This provides the same average nonfade durations of the channels, which are the opportunities for packet transmission [32, Chapter 5]. Hence, the level-crossing rates (i.e., the number of times the signal envelope crosses the threshold in positive direction [32]) of the different channels are the same for all node pairs. In [33], Tse and Hanly showed that such selection of thresholds leads to fair channel access among all nodes. Later, in a single-hop simulation setting, we measure the throughput fairness in respect to the wireless nodes and confirm the fairness of the Channel MAC protocol.

For the IEEE 802.11 simulation, we have used the fading simulator extension [34] for NS2 to consider the time-correlation of the channel based on P. The extension aids in identifying the rms signal of the channel, R_{rms}, using the two-ray ground method. The packet reception threshold (R_{th}) based on P is derived using (2). Finally, we accept or discard a received packet comparing its received power to the packet reception threshold.

5.1. Simulation Scenarios and Results. In this section, we describe the simulation scenarios and present corresponding results. In all scenarios, we compare the throughput and delay performance of the Channel MAC protocol with the IEEE 802.11 protocol. We also evaluate the fairness of the proposed protocol in a single-hop scenario and a number of well-known multihop scenarios such as the flow-in-the-middle scenario. In these scenarios, we calculate the fairness measures for IEEE 802.11, Ideal MAC (collision-free), and Channel MAC.

5.1.1. Single-Hop Scenario. In a single-hop simulation scenario, we consider $2n$ nodes, where n nodes are transmitters and the other n nodes are receivers, randomly distributed in a one-hop neighbourhood. That is, each node can reach all the other nodes in a single hop. In the simulation, we consider $n = 5, 10, 20$. Each source node generates 1000 bytes UDP packets at a data rate of 1 Mbps and the data rate of the channel is also set to 1 Mbps. This leads to a saturated network (i.e., every node has a packet to send at every instance) at this offered load. The MAC queue size is set to 15 packets in both cases.

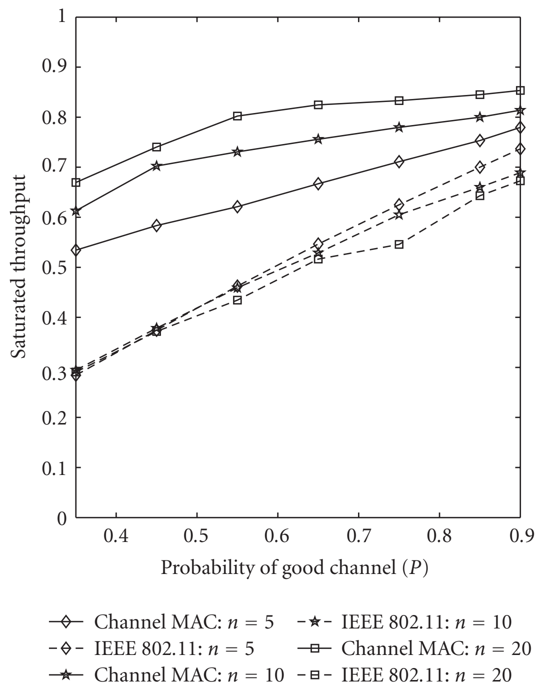

Figure 7: Throughput performance in single-hop scenario.

The saturated throughput (throughput achieved in a saturated network) of Channel MAC for different probabilities of good channels under Rayleigh fading is presented in Figure 7. The performance of IEEE 802.11 under Rayleigh fading is also shown in this figure for comparison. End-to-end packet delay versus P for both Channel MAC and IEEE 802.11 in single-hop case is shown in Figure 8. In a single-hop scenario, Channel MAC outperforms IEEE 802.11 for all values of P and all numbers of nodes. It can be noted that for higher numbers of nodes, Channel MAC achieves higher throughput at lower P values, increasing the potential operating range. Furthermore, the total throughput of the network increases with increasing number of nodes due to multiuser diversity, contrary to the performance of IEEE 802.11. In other words, with increasing number of nodes, the probability of finding at least one good channel at a given time increases, which improves the transmission opportunities.

It should also be noted that increasing the number of nodes leads to more collisions, which have a detrimental effect on the throughput. However, it is evident from the throughput result in Figure 7 that the increase in throughput due to multiuser diversity is more than the decrease in throughput due to collisions. At $n = 5$, Channel MAC outperforms IEEE 802.11 by 17%, and the improvement grows to 41% for $n = 20$.

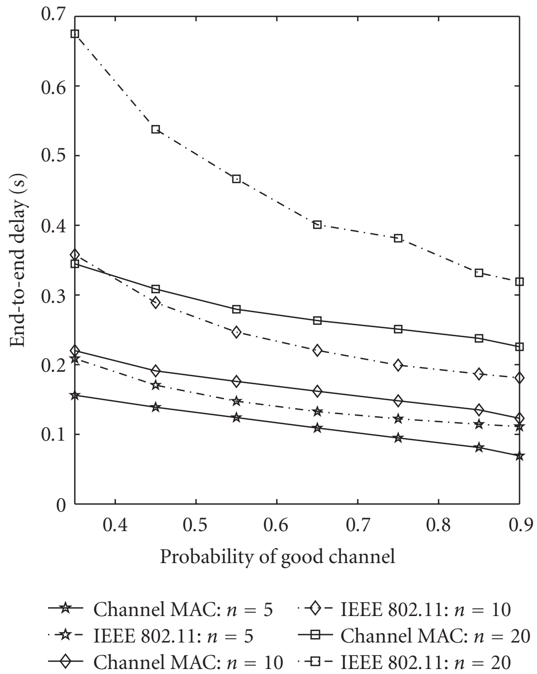

Figure 8: Delay performance in single-hop scenario.

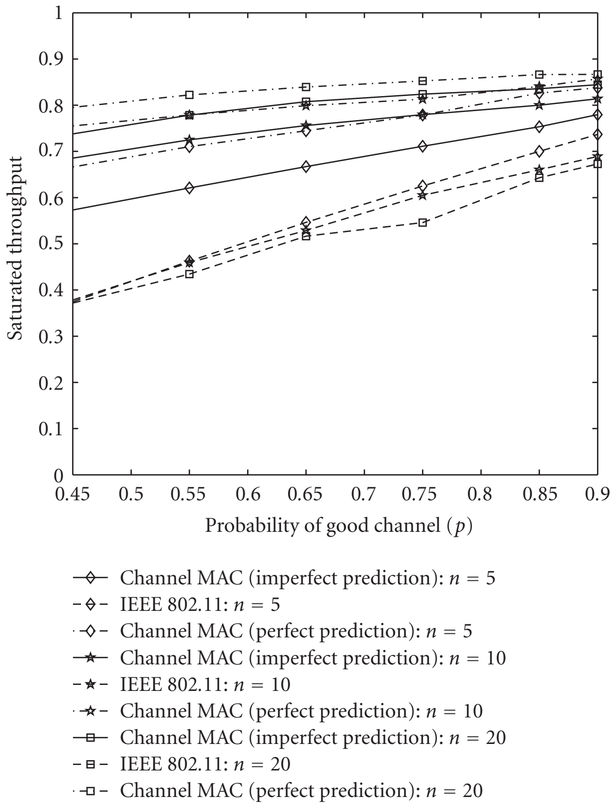

Figure 9: Throughput performance in a single-hop scenario considering channel prediction inaccuracy.

Similar performance improvements are observed in terms of delay. In this simulation scenario, the major contributor to packet delay is queuing delay at the nodes. With higher throughput, Channel MAC serves packets faster, reducing the queuing delay, thus the reduction of packet delay with the Channel MAC scheme.

Next, we observe the fairness performance in a single-hop Channel MAC scenario. The fairness in resource sharing of the wireless transmitters $x_i \mid i \in n$ in a single hop can be calculated using the popular Jain fairness index [35] as

$$f(x_1, \ldots, x_n) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \sum_{i=1}^{n} x_i^2}, \tag{7}$$

where x_i is the throughput of ith node.

We observe the fairness index to be above 0.98 for every case, which is almost equal to that of IEEE 802.11 in the similar settings. Therefore, by keeping the same probability of good channel among every Tx-Rx pair, a fair throughput share can be maintained in a single-hop network. IEEE 802.11 also maintains fairness which is preserved in a single hop network.

5.1.2. Channel Prediction Inaccuracy. As we discussed earlier, Channel MAC assumes that the channel can be predicted accurately based on past channel values. In this section, we use the model described in [21] to evaluate the effect of channel prediction inaccuracies on system performances. We define prediction accuracy as the percentage of predicted values within a fixed prediction range/horizon. Consistent with [5], we use a prediction accuracy of 90% in our simulations. Figure 9 shows the throughput degradation of Channel MAC at different node numbers due to prediction inaccuracies. It can be observed that Channel MAC still outperforms IEEE 802.11 for all possible values of n in case of imperfect predictions.

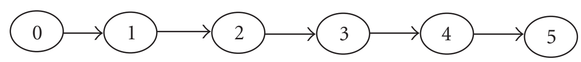

Figure 10: Per-hop throughput of a 6-node multihop scenario.

5.1.3. Linear Chain Scenario. We use a 6-node linear chain (i.e., 5 intermediate link/channels) (Figure 10) as an example to illustrate the throughput performance of Channel MAC in a multihop topology. The distance between consecutive nodes is 245 m. The reception range and the carrier-sensing range of the simulation are 250 m and 550 m, respectively. Node 0 sends UDP traffic (packet-size of 1000 bytes) to node 5. The probability of good channels P is set to .85.

With an *ideal MAC* protocol (i.e., all flows are coordinated to avoid collisions completely), the above linear chain network can achieve a maximum utilisation of 1/4 [36]. However, in most practical MAC protocols, nodes in the middle of the chain suffer more from contention and interference than nodes at the end of the linear chain. Hence, source nodes inject more packets into the chain than what the next nodes can forward. As a result, packets are dropped in

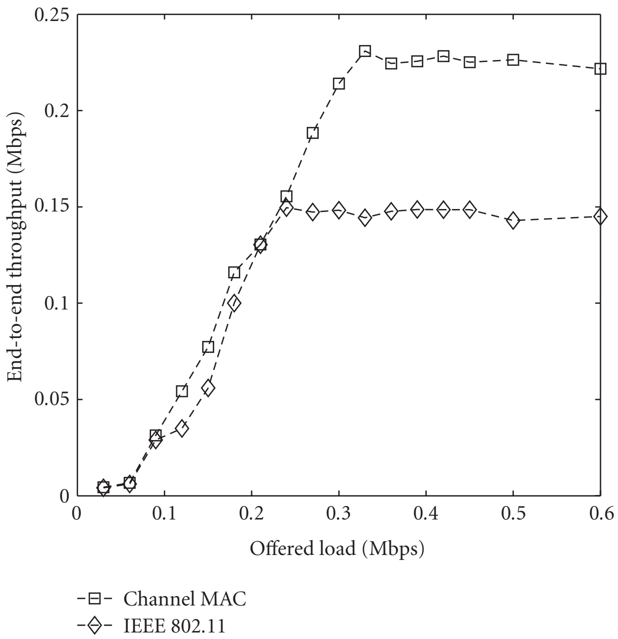

Figure 11: Offered load versus end-to-end throughput (Mbps) in the chain network at $P = .85$.

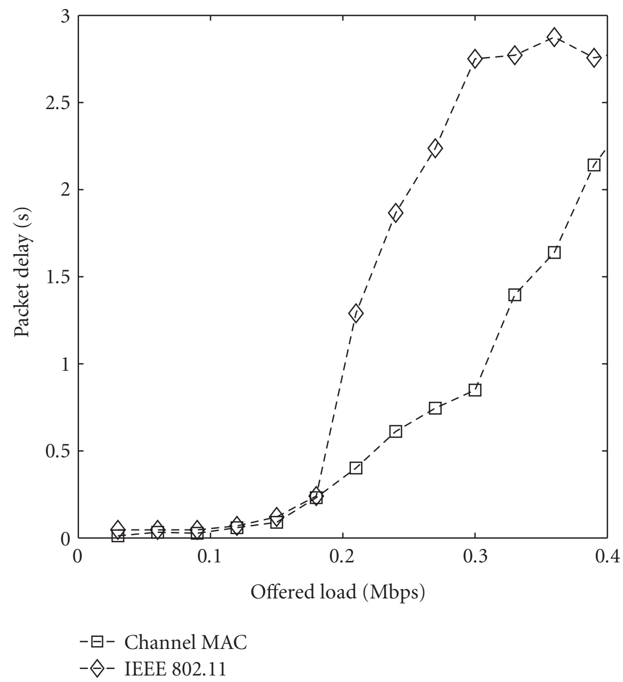

Figure 12: Offered load versus packet delay in the chain network at $P = .85$.

the middle of the chain wasting the resources used to forward them. The end-to-end throughput of a linear chain is hence equal to the minimum throughput of all the intermediate nodes [37].

In this simulation, we vary the offered load and measure the end-to-end throughput and delay at $P = .85$. The offered load versus end-to-end throughput graph for the linear chain scenario is shown in Figure 11. IEEE 802.11 achieves a saturation throughput of around 0.15 Mbps, compared to a saturation throughput of 0.23 Mbps for Channel MAC. It can be observed in Figure 11 that, at all values of offered loads, Channel MAC provides better throughput than IEEE 802.11. The impact of the offered load on the end-to-end packet delay is shown in Figure 12. As expected, the packet delay increases with increased offered load due to the increasing queuing delay. In Channel MAC, we observe a relatively lower delay than IEEE 802.11 at all offered loads. This is due to shorter queue delays at intermediate nodes due to higher throughput with Channel MAC. In Figure 13, the saturation throughput at different values of the probability of good channel is given. It can be observed that the throughput of Channel MAC is higher than that of its IEEE 802.11 counterpart for all channel conditions.

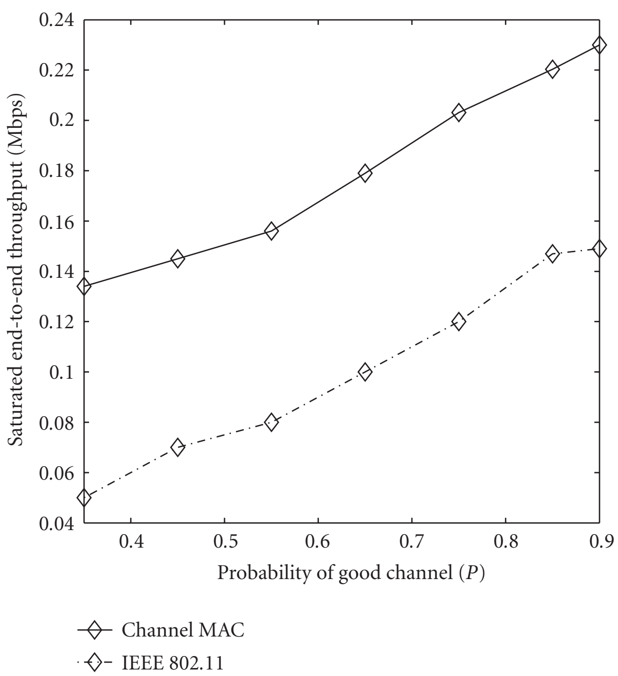

Figure 13: Saturated throughput at all P values.

As shown in [36], IEEE 802.11 backoff mechanism is unsuitable for ad hoc forwarding. For example, during a transmission from node 3 to 4 (channel 4), node 0 (as it is not aware of the transmission from node 4 to 5) may send data to node 1 (channel 1). But node 1 will not respond with an ACK to node 0 due to collision. As a result, node 0 will backoff and retry. For the duration of node 3's transmission, all attempts by node 0 will fail, resulting in a large increase of the backoff window. Therefore, after completion of node 3's transmission, node 0 may remain in backoff for a long time, thus missing transmission opportunities. Furthermore, channel fading decreases effective throughput. On the other hand, under Channel MAC, due to the same level crossing rate (i.e., same fading statistics), both channel 1 and 4 can capture the medium uniformly. Therefore, node 0's unnecessary idle

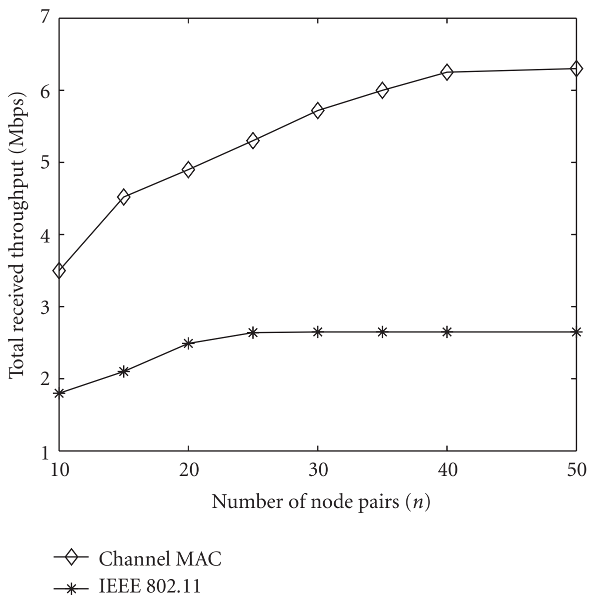

Figure 14: Channel MAC and IEEE 802.11 throughput for the random network.

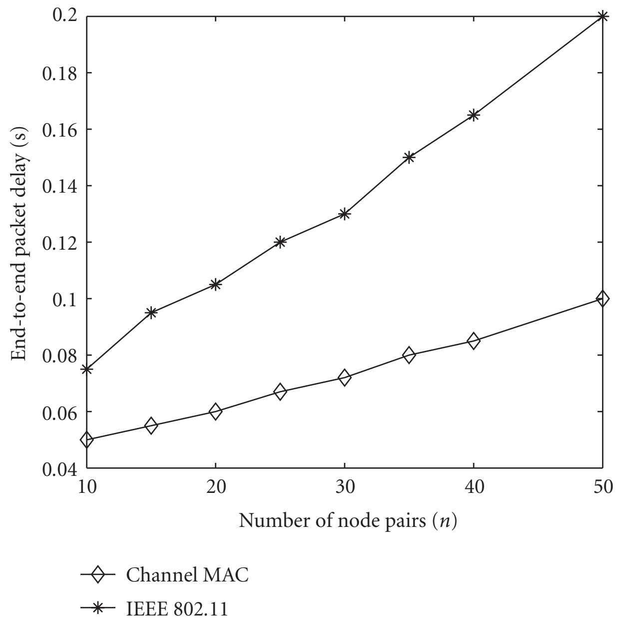

Figure 15: Channel MAC and IEEE 802.11 end-to-end packet delay for the random network.

times due to large backoff delay are eliminated. Eventually, the resultant throughput (0.23 Mbps at $P = .9$) reaches a level close to the maximum possible *ideal MAC* throughput of 0.25 Mbps.

5.1.4. Random Network Topology. In a random network scenario, we consider nodes randomly distributed in an area of $1500\times1500\,\mathrm{m}^2$. We only consider single-hop flows in these simulations. The data generation rate is 1 Mbps per node, which generates enough data to saturate the network. The reception and sensing range for all nodes are set to 250 m and 550 m as before and P is set to .85. We average a large number of simulation results to derive the throughput for a number of nodes.

Figure 14 shows the average received throughput for both Channel MAC and IEEE 802.11. With the number of nodes, the received throughput increases rapidly in Channel MAC as compared to IEEE 802.11. For $n = 10$, Channel MAC outperforms IEEE 802.11 by about 100%. The improvement in throughput grows to around 130% for $n = 50$. This improvement is again due to the multiuser diversity gain. In Figure 15, the end-to-end packet delay for different number of nodes is presented. As expected, the packet delay in Channel MAC is much lower than that of IEEE 802.11 in the random network scenario. This is due to the fact that with higher throughput at each node, packets are served faster with Channel MAC, reducing the queuing delay, which is the major contributor to delay in this scenario.

5.1.5. Flow-in-the-Middle Topology. Carrier sense multiple access (CSMA)-based protocols like IEEE 802.11 can lead to large differences between the observed throughput in neighbouring nodes [38, 39]. This fact can be demonstrated using the flow-in-the-middle topology as shown in Figure 16, with three flows (flow 1 to 3) across the nodes separated by 245 m. The capture threshold, denoted as CPThreshold, is set to 10 dB, which corresponds to 445 m of signal interference region (suppose a packet is received by a node in an interval. If another packet transmission starts during that interval so that the latter packet reaches the node with a power which is CPThreshold below the received power of the first packet, the node will be able to successfully receive the first packet. Otherwise, both packets will not be properly received). Sources of two neighbouring flows are separated by more than the signal interference region but less than the carrier sense region (550 m). Hence, flow 1 and 3 are out of carrier-sensing range from each other. Flow 2 has a chance to capture the medium when the other flows are idle. Therefore, both flows 1 and 3 compete with flow 2, resulting in throughput starvation of flow 2. This problem is known as the flow-in-the-middle (FIM) problem. The probability of good channel condition P is set to .75 across the entire network in this experiment.

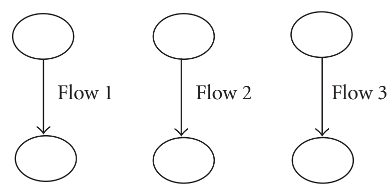

Figure 16: Flow-in-the-middle (FIM) topology.

In Figures 17 and 18 we show the throughput of each flow under IEEE 802.11 and Channel MAC. In IEEE 802.11 the middle flow (flow 2) receives very low throughput

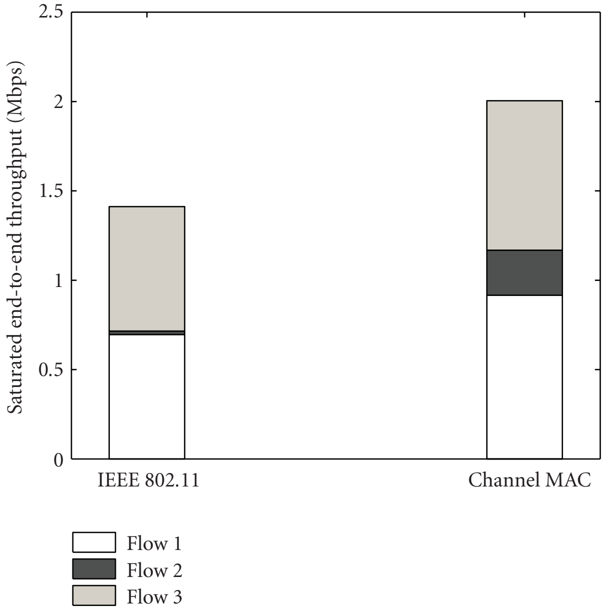

Figure 17: FIM throughput with IEEE 802.11 and Channel MAC for $P = .75$.

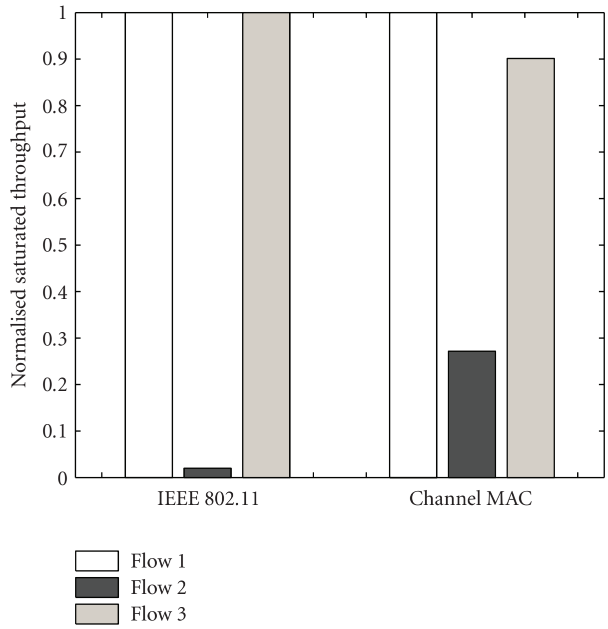

Figure 18: FIM normalised throughput with both IEEE 802.11 and Channel MAC for $P = .75$.

(almost zero), while the outer flows (flow 1 and 3) receive throughput close to the maximum. The reason of this disparity was widely investigated in the literature, for example, in [40]. In the *ideal situation*, the middle flow should contend with the two outer flows, whereas flow 1 and 3 contend only with flow 2. Hence, the effective capacity of flow 2 ideally is upper bounded by 1/3 of its maximum capacity. But the capacity of each outer flow can grow up to 2/3 of its maximum capacity. In the case of IEEE 802.11, each unsuccessful transmission by flow 2 increases its waiting period exponentially. Moreover, node 2 freezes its transceiver most of the time since the outer flows capture the medium frequently. Even when flow 2 wins a contention, packets may be lost due to channel fading, further reducing the throughput.

On the other hand, the end-to-end throughputs of the flows increase in Channel MAC as compared to IEEE 802.11 due to the opportunistic channel diversity principle. In Channel MAC, nodes try to capture the medium with equal probability, resulting in a close to equal share of resource usage for each flow. Therefore, the severe unfairness among the saturated chains decreases in Channel MAC by maintaining the same probability P of good channel condition across the network. Due to the fairness in medium access, Channel MAC operates closer to the ideal situation.

5.2. Multiple Chain Networks. In this section, we study the interactions among multiple flows considering an $N \times M$ lattice network as shown in Figure 19. In each chain, nodes are separated by 245 m. CPThreshold was set to 10 dB. Nodes of two immediate chains are separated by 500 m. Hence, we observe the flow-in-the-middle starvation problem [40], where the middle chain starves due to an increased carrier

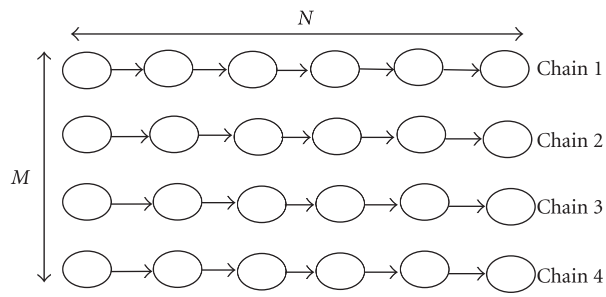

Figure 19: Multihop networks.

sensing impact. Each chain consists of 6 nodes (i.e., $N = 6$). Each left-most node is transmitting data to the right-most node of its chain. Incorporating subsequent chains (e.g., $M = 2, 3$, etc.), we investigate the end-to-end throughput and fairness of different chains for different lattice structure (i.e., different values of M).

The capacity of such a regular lattice structure using an *ideal MAC* is given in [36]. Due to the placement of parallel chains, every second chain can operate without interchain interference, potentially giving 1/4 of the link capacity. The two outer chains can use 2/3 of the link capacity, whereas the internal chains can use 1/3 of the link capacity. Furthermore, due to intrachain interference, the capacities of each outer flow and internal flows finally become 1/6 and 1/12 of the link capacity, respectively. However, in the case of two parallel chains, each flow can use 1/2 of its link capacity.

Figures 20, 21, 22, and 23 show the end-to-end throughput for subsequent chains for different lattice structures. The source of a chain injects more packets than the forwarding capability of internal nodes. This is due to the fact that

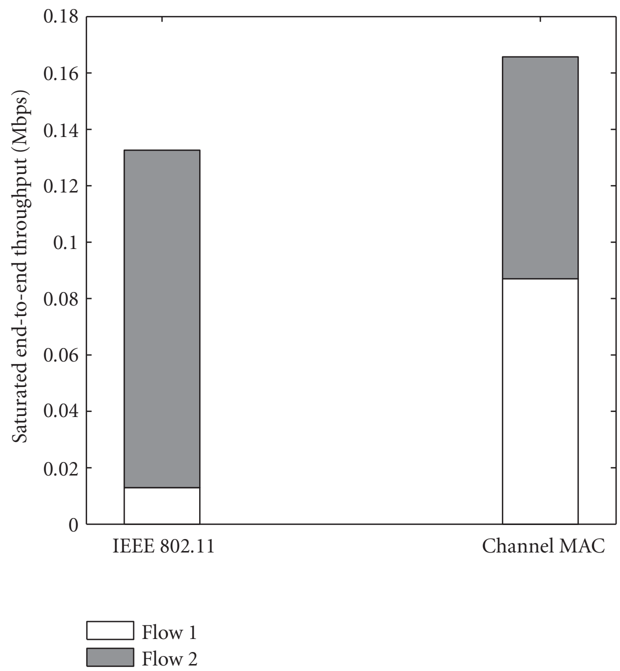

Figure 20: Channel MAC and IEEE 802.11 throughput for the multihop network at $P = .9$: $N = 2$.

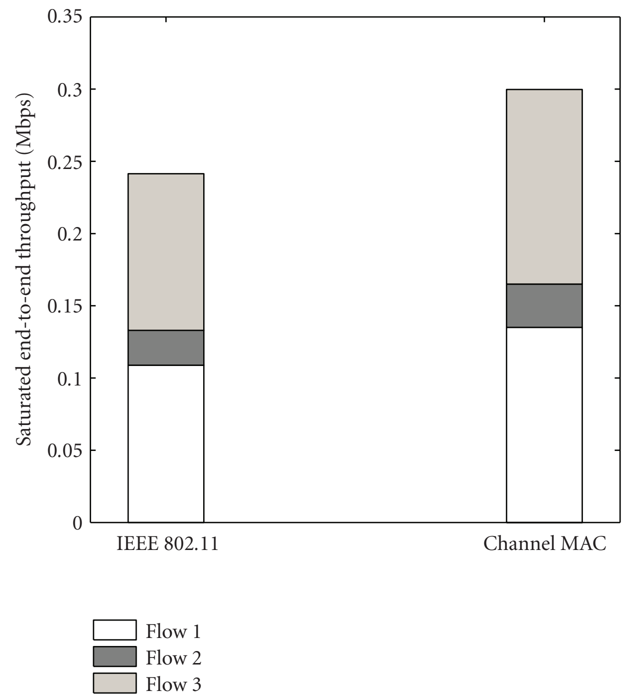

Figure 21: Channel MAC and IEEE 802.11 throughput for the multihop network at $P = .9$: $N = 3$.

forwarding rates of internal nodes are limited due to the increased neighbour interference. This rate discrepancy leads to higher packet loss and retransmissions in IEEE 802.11. While these extra packets are transmitted, other nodes in the interference range cannot transmit, leading to even lower efficiency. Hence, the exponential backoff of IEEE 802.11 is unsuitable for such ad hoc forwarding of packets, which is also shown in [36]. Lastly, the fading channel leads to more throughput losses. On the other hand, the end-to-end throughputs of the chains increase in Channel MAC in every case as compared to IEEE 802.11.

Furthermore, we observe much reduced discrepancies between saturated throughput for different flows with Channel MAC as compared to IEEE 802.11. For example, consider the end-to-end saturated throughput for the lattice structure for $M = 5$ as shown in Figure 23. In IEEE 802.11, we observe that the end-to-end throughput diminishes to zero in chains 2 and 4, whereas other chains attain higher throughput than the mean. In contrast, this severe unfairness among the saturated chains decreases in Channel MAC by maintaining the same probability P of good channel condition across the network. A comparison of the throughput for each flow in ideal MAC, IEEE 802.11, and Channel MAC is given in Table 1. Due to the opportunistic and fair communication paradigm of Channel MAC, the throughput of each flow is close to the ideal MAC throughput.

Table 1: Saturated throughput (Mbps) of each flow when $M = 4$.

Flow	Ideal MAC ($P = 1$)	IEEE 802.11 ($P = .9$)	Channel MAC ($P = .9$)
1	0.17	0.15	0.14
2	0.083	0	0.08
3	0.083	0.15	0.08
4	0.083	0	0.07
5	0.17	0.15	0.14

6. Conclusion

The goal of the Channel MAC protocol is to use opportunistic communication principles in a distributed manner to improve the performance of ad hoc networks. In this paper, we model and simulate Channel MAC and show that Channel MAC can achieve higher performance than IEEE 802.11 in distributed wireless networks. Furthermore, the throughput in Channel MAC increases with increasing number of nodes, due to the multiuser diversity of the system. It is also shown that, in a linear chain topology of 5 nodes, Channel MAC can increase the saturation throughput by around 50%. In addition to the increased throughput, a significant drop in the end-to-end delay is observed.

Furthermore, we investigated the starvation problem (fairness issue) for typical network scenarios, for example, the flow-in-the-middle topology and the chain topology (single and multiple) under IEEE 802.11 and Channel MAC. We have shown that by using the same P (probability of good channel condition) in the network, the severe starvation problem is reduced. The exponential backoff of IEEE 802.11 is unsuitable for packet forwarding in a chain network. This problem is reduced in Channel MAC due to the channel diversity as shown in both the single chain and multiple chain

Table 2: Parameters used to calculate the probability of collision in the Channel MAC.

Symbol	Parameter
a	Propagation delay
$\overline{a}$	Normalised propagation delay with respect to packet transmission time
n	Number of nodes
l	Average nonfade duration of the channel, equivalent to transmission time
r	Normalised level crossing rate (LCR) of the channel with respect to packet transmission time
p_{coll}	Probability of collision
ρ	Normalised threshold level with respect to rms signal level
d_{tx}	Transmission range of the sender
f_{m}	Maximum Doppler frequency

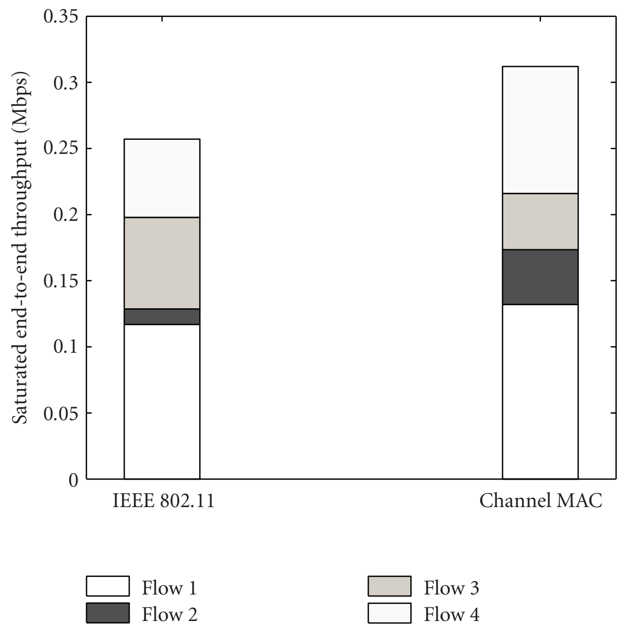

Figure 22: Channel MAC and IEEE 802.11 throughput for the multihop network at $P = .9$: $N = 4$.

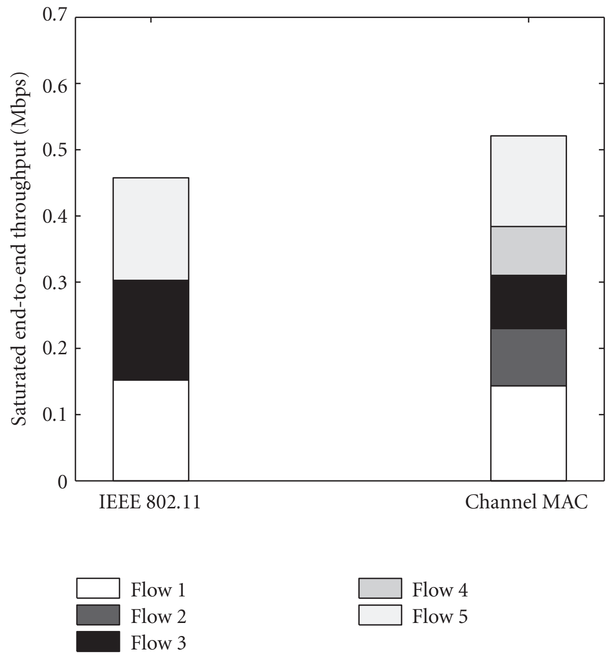

Figure 23: Channel MAC and IEEE 802.11 throughput for the multihop network at $P = .9$: $N = 5$.

(lattice) structure. It results in a higher total throughput as compared to IEEE 802.11 for any lattice structure. The throughput of individual chains also becomes close to the ideal MAC throughput.

Furthermore, we show that in a large random network scenario, up to 130% throughput improvement can be observed, as compared to IEEE 802.11. Therefore, we argue that the nonideal, distributed paradigm based on the opportunistic communication principle can significantly improve the performance of distributed wireless networks compared to IEEE 802.11.

In this paper, we consider a single-rate data transmission. However, a number of rate adaptive mechanisms [20, 41] at the MAC layer have been proposed to exploit the multirate transmission capability based on the underlying channel conditions. We intend to address the issue of rate and power adaptation in the context of Channel MAC in the future. Furthermore, in this paper we assume the existence of perfect prediction schemes. In the future, we will investigate the integration of prediction schemes with Channel MAC and other implementation issues such as initialisation of the network, packet headers, and channel information exchange.

Table 3: Analytical P_{coll} at n pair of Tx-Rx.

n	Approximate P_{coll} in all P range of good channel
10	.001
20	.002
30	.003
50	.004

Table 4: Simulation results of P_{coll} at n pair of Tx-Rx.

n	d_{tx} = 10 m	30 m	50 m	70 m	90 m	110 m	250 m	550 m	1000 m
5	0	0	0	0	0	0	0	0	.001
10	.0	.004	.004	.0042	.0044	.0045	.0046	.0048	.0049
20	.0006	.0008	.002	.004	.005	.005	.006	.0064	.0066
30	.0008	.002	.003	.004	.005	.008	.009	.01	.022

Table 5: IEEE 802.11 collision probability results for different window sizes (W) and node numbers (n).

n	$W = 8$	$W = 16$	$W = 32$
10	.47	.38	.29
20	.58	.5	.38
30	.62	.55	.45
50	.74	.63	.55

Appendix

Collision Probability in Single-Hop Channel MAC

In this appendix, we calculate the collision probability of Channel MAC in a single-hop network, and show why the collision probability of Channel MAC is negligible compared to that of IEEE 802.11.

The instance of the predicted signal amplitude crossing the threshold in the positive direction is termed as an arrival point in Channel MAC. We assume that the arrival point process of a channel is Poisson. Theoretically, the probability of arrival points for 2 or more nodes occurring at the same instance reaches zero. However, collisions can still occur at the receiver due to the finite propagation delays in the network [22]. We consider constant propagation delay, equal to the largest possible value in the network, leading to pessimistic bounds on performance. Furthermore, due to numerical precision error of the sensing circuitry, more than one arrival point from different nodes can simultaneously occur within a short interval η. In other words, η is the precision limit. In our calculations, we assume up to 15 decimal points of precision; hence $\eta = 10^{-15}$ second. We measure the probability of collision based on Poisson arrival points by different nodes within a distance of 250 m.

The parameters used for the calculations are collected in Table 2. Transmission range of the sender is assumed to be 250 m and the maximum Doppler frequency is set to 20 Hz. Furthermore, the arrival points are assumed to be Poisson distributed. The average nonfade duration of the channel (packet transmission interval) and level-crossing rates are estimated assuming the Rayleigh fading as in [32, Chapter 5]. The propagation delay and the level crossing rates are normalised to the packet transmission interval. Then, the probability that at least one arrival occurs within the normalised propagation delay of an on-going transmission is equal to the probability of collision in the system.

The results from the analytical model of (A.6) are given in Table 3;

$$\alpha = \frac{d_{tx}}{3 \times 10^8} = \frac{250}{3 \times 10^8} \text{ second}, \tag{A.1}$$

$$\rho = \sqrt{-\log(p)}, \tag{A.2}$$

$$l = \frac{1}{\rho f_m \sqrt{2\pi}} = \frac{1}{\rho 20 \sqrt{2\pi}}, \tag{A.3}$$

$$r = \sqrt{2\pi f_m \rho p} \times l, \tag{A.4}$$

$$\overline{a} = \frac{a}{l}, \tag{A.5}$$

$$P_{coll} = 1 - e^{-n r \overline{a}}. \tag{A.6}$$

From (A.6), if $\overline{a} \to 0$, then $P_{coll} \to 0$. The collision probabilities for different network sizes at transmission range 250 m are given in Table 4 and similar results for NS2 simulations for different transmission ranges and network sizes are given in Table 4. The small differences in collision probabilities between the analytical and simulation results are due to the Poisson approximation of the arrival point process of the Rayleigh faded channels in (A.6). Furthermore, we compare the results obtained above to the collision probability observed in IEEE 802.11 given in Table 5. The results for IEEE 802.11 are taken from [42]. This shows a significantly higher order collision probability in IEEE 802.11. Hence, we can ignore packet collision in Channel MAC.

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The 2011 European Signal Processing Conference (EUSIPCO-2011) is the nineteenth in a series of conferences promoted by the European Association for Signal Processing (EURASIP, www.eurasip.org). This year edition will take place in Barcelona, capital city of Catalonia (Spain), and will be jointly organized by the Centre Tecnològic de Telecomunicacions de Catalunya (CTTC) and the Universitat Politècnica de Catalunya (UPC).

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- Signal detection and estimation.
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