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On Concurrent Transmissions in Multi-hop Wireless Networks with Shadowing Channels

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Abstract— **In this paper, we study the exposed terminal problem in multi-hop wireless networks with log-normal shadowing channels. Assuming that location information is known, we first calculate the success probability for the concurrent transmissions from exposed nodes. We then propose a new MAC protocol which schedules concurrent transmissions in the presence of log-normal shadowing, thus mitigating the exposed terminal problem and increasing network throughput. The performance of the proposed protocol is evaluated with ns-2 simulations, and it is shown to achieve considerable improvements in both end-to-end throughput and delay over the IEEE 802.11 MAC.**

I. Introduction

It has been shown that IEEE 802.11 MAC suffers low throughput performance in wireless ad-hoc networks [1]. In particular, "exposed terminal problem" deteriorates the network throughput, and it is highly important to solve or alleviate this problem. There has been considerable research effort on this aspect. For example, MAC protocol requiring additional hardware or PHY capacities are shown to be helpful [2]. In addition, there have been proposals on tuning the carrier sensing range [3], controlling the transmit power [4] and modifying the behavior of the IEEE 802.11 MAC [5]. However, these studies are performed with the deterministic wireless propagation models, where path loss is determined by the distance between the transmitter and the receiver *deterministically*. However, due to obstacles, multi-path propagation, and mobility, randomness exists in most real wireless networks and should be considered in protocol design.

Factors such as reflection, diffraction, and scattering impact the propagation in a wireless network. In addition to power attenuation, "large-scale shadowing" and "small-scale fading" are usually experienced by radio signals. Small-scale fading describes the rapid fluctuation of the signals over a short period of time or distance. On the other hand, large-scale shadowing represents a random effect which occurs over a large number of measurement locations which have the same distance between the transmitter and the receiver, but have different levels of obstacles on the propagation path. It has been known that the log-normal shadowing propagation model captures this characteristic. Some researchers have studied the connectivity problem in presence of log-normal shadowing [6]. To the best of our knowledge, there is no related work considering log-normal shadowing in studying the exposed terminal problem.

In this paper, we study the problem of how to mitigate the exposed terminal problem in the presence of shadowing channels. We first derive an analysis on the success probability of concurrent transmissions from exposed nodes. Here we assume location information for the nodes. Note that such an assumption is reasonable since GPS is becoming more and more accessible. There are also many localization schemes from the literature that can be adopted in case GPS service is not available. We describe a new MAC protocol based on this analysis, aiming to schedule concurrent transmissions in the presence of log-normal shadowing. Such concurrent transmissions can considerably improve the end-to-end throughput and delay performance of multi-hop wireless networks over the IEEE 802.11 MAC, as observed in our ns-2 performance study of the proposed location-assisted MAC protocol.

The rest of this paper is organized as follows. In Section II, we describe the log-normal shadowing propagation model and derive the success probability of a concurrent transmission. We present the proposed MAC protocol in Section III. Our simulation studies are presented in Section IV. Finally, Section V concludes the paper.

II. Success Probability of a Concurrent Transmission under Shadowing

A. Log-normal Shadowing Propagation Model

In real wireless networks, the variations in the received power measured at different locations with the same distance from the transmitter, are random and independent [7]. It means that the real transmission range is NOT circular. Fig. 1 illustrates the transmission ranges of the two-ray ground reflection model (left) and the log-normal shadowing propagation model (right), respectively. The variation seen in the right figure is nicely described by the log-normal random variable, and it is incorporated in the log-normal shadowing propagation model.

Consider a pair of transmitter and receiver where the distance between them is d. According to the log-normal shadowing propagation model, the received power of the intended signal at the receiver in dB, $P_{r,dB}$, is represented by

$$P_{r,dB} = -10\beta \log\left(\frac{d}{d_0}\right) + X_r, \qquad (1)$$

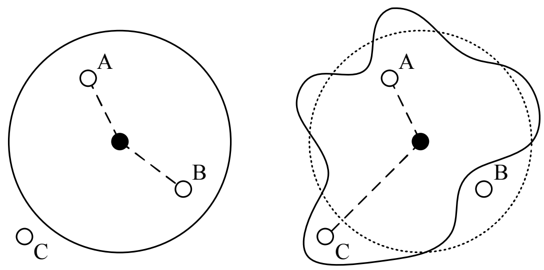


Fig. 1. Transmission ranges: Two-ray ground (left) and shadowing (right).

where β represents the path-loss exponent, d_0 represents the reference distance, and X_r represents a normal random variable with zero mean and variance $\sigma_{dB}^2 (= \sigma^2/(0.01(\ln 10)^2))$. The received power consists of two parts: the deterministic part depending on the distance between the transmitter and the receiver, and the probabilistic part X_r. The variation of the received power is determined by the standard deviation σ_{dB} or σ. Note that the standard deviation σ_{dB} typically ranges from 4 dB to 8 dB. The probabilistic part X_r makes the transmission range not circular, as shown in Fig 1. The received power can be expressed in unit of watts as follows:

$$P_r = P_0 10^{-\beta \log\left(\frac{d}{d_0}\right) + 0.1 X_r} = C\frac{Y_r}{d^\beta}, \tag{2}$$

where P_0 is the reference power measured at d_0, $C = P_0 d_0^\beta$ is a constant, and $Y_r = 10^{0.1X_r}$ represents a log-normal random variable with zero mean and variance σ^2.

B. Success Probability of the Concurrent Transmission

Suppose that there are N (active) interfering nodes around a receiver, and that the distance between interfering node i and the receiver is r_i. Similar to (2), the interference by interfering node i, P_i, is represented by

$$P_i = C\frac{Y_i}{r_i^\beta}, \tag{3}$$

where Y_i is a log-normal random variable with zero mean and variance σ^2. From (3), the cumulative interference P_I measured at the receiver amounts to

$$P_I = \sum_{i=1}^{N} P_i = \sum_{i=1}^{N} C\frac{Y_i}{r_i^\beta}. \tag{4}$$

From (2) and (4), we obtain that

$$\frac{1}{SIR} = \frac{P_I}{P_r} = \frac{\sum_{i=1}^{N} C\frac{Y_i}{r_i^\beta}}{C\frac{Y_r}{d^\beta}} = \sum_{i=1}^{N}\left(\frac{d}{r_i}\right)^\beta \frac{Y_i}{Y_r}. \tag{5}$$

In order to receive the packet successfully, the signal-to-interference ratio (SIR) should be greater than a threshold T_{SIR}. Thus, we calculate the probability that SIR is greater than a certain threshold T_{SIR}.

$$P_s = \Pr[SIR > T_{SIR}] = \Pr\left[\frac{1}{Y_r}\sum_{i=1}^{N}\left(\frac{d}{r_i}\right)^\beta Y_i < \frac{1}{T_{SIR}}\right]. \tag{6}$$

Let $U_i = \left(\frac{d}{r_i}\right)^\beta Y_i$. Note that U_i is a log-normal random variable with mean $\mu_i = \ln\left(\frac{d}{r_i}\right)^\beta$ and variance σ^2. Furthermore, let $V = \sum_{i=1}^{N} U_i$. Since U_i's are independent, with the help of Fenton-Wilkinson method [8], V can be approximated by a log-normal random variable W with the following mean μ_w and variance σ_w:

$$\begin{cases} \mu_w = \log(\sum_{i=1}^{N} e^{\mu_i}) + \sigma^2 - \frac{\sigma_w^2}{2} \\ \sigma_w^2 = \log\left[(e^{2\sigma^2} - 1)\frac{\sum_{i=1}^{N} e^{2\mu_i}}{(\sum_{i=1}^{N} e^{\mu_i})^2} + 1\right]. \end{cases} \tag{7}$$

Finally, $\frac{W}{Y_r}$ is a log-normal random variable with mean μ_w and variance $(\sigma_w^2 + \sigma^2)$.

By utilizing the *logistic distribution* for CDF (cumulative distribution function) of the log-normal distribution [9], $F(x;\mu,\sigma) = \left[\left(\frac{e^\mu}{x}\right)^{\pi/(\sigma\sqrt{3})} + 1\right]^{-1}$, we finally obtain that

$$P_s = \left[(T_{SIR} e^{\mu_w})^{\frac{\pi}{\sqrt{3(\sigma_w^2+\sigma^2)}}} + 1\right]^{-1}. \tag{8}$$

C. The Case of a Single Interfering Node

When an IEEE 802.11-like MAC is used, the area around the transmitter and receiver is reserved by the RTS/CTS handshake. In addition, the carrier sensing range is usually much larger than the transmission range. As a result, the number of interfering nodes around a receiver should be small. Let's consider the case of a single interfering node. Equation (6) reduces to

$$P_s = \Pr\left[\frac{Y_i}{Y_r} < \frac{1}{T_{SIR}}\left(\frac{r}{d}\right)^\beta\right] = \Pr\left[Z < \frac{1}{T_{SIR}}\left(\frac{r}{d}\right)^\beta\right] \tag{9}$$

where Z represents a log-normal random variable with zero mean and variance $2\sigma^2$. Using the logistic distribution, we find the success probability to be

$$P_s = \left[\left(T_{SIR}\left(\frac{d}{r}\right)^\beta\right)^{\pi/(\sigma\sqrt{6})} + 1\right]^{-1}. \tag{10}$$

Figure 2 shows the success probability P_s for different σ's by evaluating (10). The parameters are selected as $T_{SIR} = 10$, $d = 20$m, $r = 35.6$m, and $\beta = 4$. The mean interference range $R_I = d\sqrt[\beta]{T_{SIR}} = 35.6$ m. We find that P_s is a decreasing function of σ when $r > R_I$, but an increasing function of σ when $r < R_I$. For example, consider the two extreme cases $\sigma = 0$ and $\sigma = \infty$. When $\sigma = 0$, (10) tends to be a *step function* as $P_s = \begin{cases} 0, & r < R_I \\ 1, & r > R_I. \end{cases}$ It is the deterministic disk model used in many prior studies. On the other hand, when $\sigma = \infty$, the success probability tends to be $\frac{1}{2}$ in all cases. It means that the success probability is no longer dependent on the distances d and r.

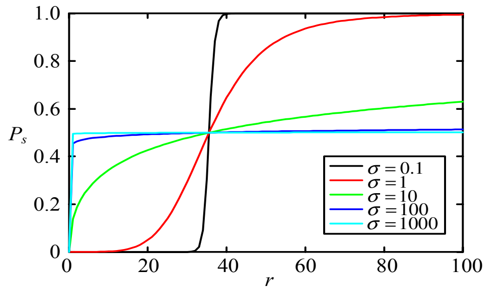


Fig. 2. P_s versus r when $T_{SIR} = 10$, $d = 20$m, and $\beta = 4$.

Procedure validate_schdTx()

calculate P_{DATA1}, P_{DATA2}, P_{ACK1}, *and* P_{ACK2};
if ($P_{DATA1} > P_{th}$ **AND** $P_{DATA2} > P_{th}$ **AND** $P_{ACK1} > P_{th}$ **AND** $P_{ACK2} > P_{th}$)
return 1; *// the scheduled transmission is allowed*
else
return 0; *// the scheduled transmission is cancelled*
endif

Fig. 3. Validation procedure.

III. MAC Protocol for Concurrent Transmissions in the Presence of Log-normal Shadowing

In this section, we describe a MAC protocol which schedules concurrent transmissions under log-normal shadowing channels.

A. Validating a Scheduled Transmission

Suppose that a node (called "free transmitter") wins the channel and is transmitting to a one-hop neighbor (called "free receiver"). When a node near the free transmitter identifies itself as an exposed terminal, the feasibility of its transmission can be tested probabilistically based on location information.

When testing the feasibility of concurrent transmission, we focus on the case of two (free and scheduled) transmitters and two (free and scheduled) receivers.[1] Assume that all parameters such as β and σ are known.[2] The following four probabilities should be evaluated:

- P_{DATA_1} – the success prob. of the free DATA frame;
- P_{DATA_2} – the success prob. of the scheduled DATA frame;
- P_{ACK_1} – the success prob. of the free ACK frame;
- P_{ACK_2} – the success prob. of the scheduled ACK frame.

Each probability can be calculated using (10). Fig. 3 shows the validation procedure of the proposed algorithm, where P_{th} is a prescribed threshold. In order to schedule the concurrent transmission, each of the above probabilities should be greater than P_{th}. As P_{th} increases, the number of the allowed scheduled transmission decreases.

[1]This simplification can be justified by the fact that usually carrier sensing range is much larger than transmission range. The chance of having multiple free transmitters in the neighborhood of the scheduled receiver is small.

[2]β and σ_{dB} can be estimated like this; (1) can be categorized as the ANOVA model I [10]. According to the least squares criterion, we can obtain the estimators which minimize the error. We omit the detail for the brevity.

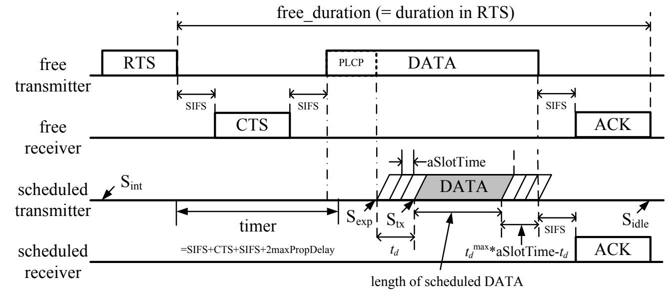


Fig. 4. A time-line illustration of the proposed protocol.

B. The Complete Protocol

In the proposed scheme, the RTS frame format is modified to piggyback the locations of the sender and its target receiver. When a node overhears an RTS, it extracts the location information, and stores them in a *location table*.

The operation of the proposed protocol is illustrated in Fig. 4. An exposed node is identified by examining the PHY PLCP frame header, which contains the frame length information, and by double-checking the delay between the RTS and the following DATA frame, which should be $(SIFS + CTS + SIFS)$. Once an exposed node is identified, it will try to validate its concurrent transmission, by executing the validation procedure shown in Fig. 3.

If this test is passed, the exposed node will attempt its scheduled transmission as follows. First, $schdTx\_margin$ is calculated as follows:

$$schdTx\_margin = \text{free\_duration} - \text{SIFS} - \text{CTS} - \text{SIFS} - \text{PLCP\_reading\_time} - \text{schd\_data\_duration} - \text{SIFS} - \text{ACK} - \text{round-trip\_prop\_delay} \quad (11)$$

where $free\_duration$ is the value in the *duration* field of the preceding RTS frame. If $schdTx\_margin$ is negative, the scheduled transmission will be canceled. That is, the concurrent DATA transmission cannot be aligned with the free DATA transmission. Otherwise, in order to avoid the case of multiple scheduled transmissions in a small neighborhood, a random delay t_d is introduced:

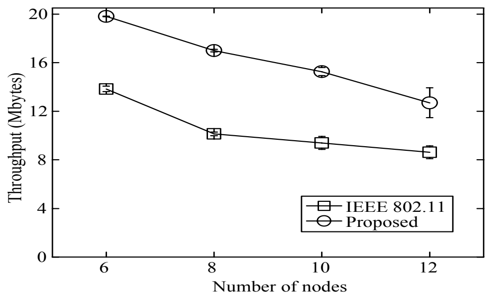
$$t_d = (random\_integer \ \% \ t_d^{max}) \times aSlotTime, \quad (12)$$

where $t_d^{max} = \lceil schdTx\_margin/aSlotTime \rceil$.

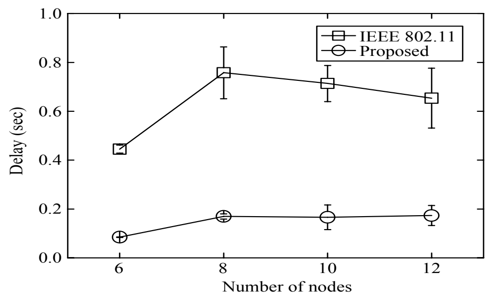
During the back-off period t_d, the exposed node will keep on detecting if there is a single transmission (i.e., the free transmission) or multiple transmissions (e.g., a scheduled transmission from another exposed node with a smaller t_d value, in addition to the free transmission). If the latter case is detected, the exposed node will not attempt the concurrent transmission; otherwise, it will start sending its DATA frame, which carries the information T_{info}, defined as

$$T_{info} = t_d^{max} - t_d/aSlotTime. \quad (13)$$

When a scheduled transmission is received, the scheduled receiver will return an ACK after a delay of $SIFS + T_{info} \times aSlotTime$, in order to align its ACK with the ACK from the free transmission. For more detail, refer to [5].

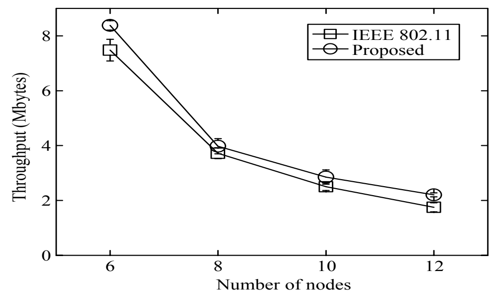


(a) Throughput performance

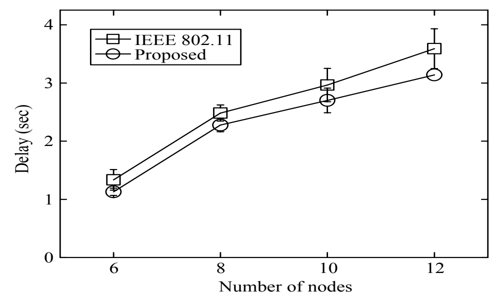


(b) Delay performance

Fig. 5. Simulation results for chain networks when $\sigma_{dB} = 0.01$.



(a) Throughput performance



(b) Delay performance

Fig. 6. Simulation results for chain networks when $\sigma_{dB} = 4$.

IV. Simulation Studies

We implemented the proposed MAC protocol using the `ns-2.30` simulator. Throughout the simulation studies, P_{th} is fixed to 0.5. We assume that $\beta = 4$ and $\sigma_{dB} = 0.01$ or 4. The ns-2 module "Propagation/Shadowing" is used as propagation model. The channel rate is set to 1 Mb/s. Antenna parameters are set to the default values in `ns-2.30`. In the simulations, the number of bytes successfully transmitted at the "agent" level (i.e., the end-to-end throughput) and the average end-to-end delay are measured. In each simulation run, all flows start to transmit at $t = 10$ second and each simulation lasts for 15 minutes. Each simulation is repeated five times. The averaged results of five trials are presented with 90% confidence intervals.

A. Chain Networks

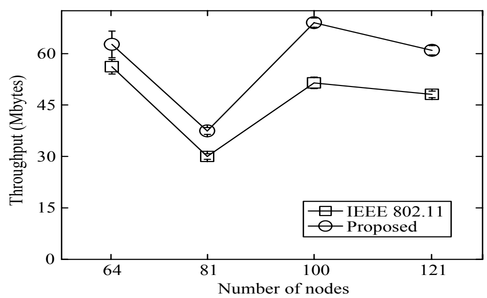
The first simulation study is performed with chain networks. The distance between two adjacent nodes is set to 20m. The forward flow (from Node 1 to Node N) is a CBR session with 1000-byte packets, while the backward flow (from Node N to Node 1) is a CBR session with 700-byte packets. The data rates are set to 90Kb/s, 80Kb/s, 70Kb/s, and 60Kb/s for the 6-, 8-, 10-, and 12-node chain networks, respectively. Note that the mean transmission range is equal to 26.9m, while the mean carrier sensing range is equal to 59.3m. When the distance between the transmitter and the receiver is equal to 20m, the mean interference range is equal to 35.6m.

Consider first the case that $\sigma_{dB} = 0.01$. In this case, the received power is almost the same as the mean value. Thus, a transmitter hardly reach the nodes except for their one-hop neighbors. For example, when $d = 20$ and $r = 40$, the success probability of the concurrent transmission is $P_i \approx 1$, where i can be $DATA_1$, $DATA_2$, ACK_1, or ACK_2.

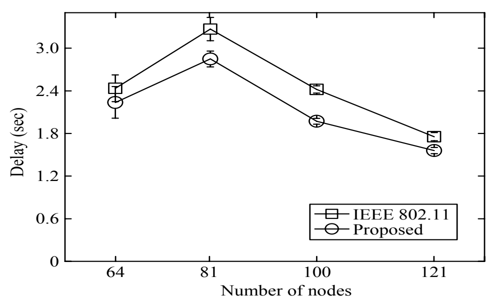
Figure 5 shows the simulation results. We observe considerable throughput improvements achieved by the proposed protocol. Specifically, 43.2%, 67.7%, 62.4%, and 47.3% normalized throughput improvements are achieved for the 6-, 8-, 10-, and 12-node chain networks, respectively. In addition, the average end-to-end delay is also drastically reduced for all the cases. From Fig. 5(b), we find that the ratios of the average delay of the proposed MAC to that of the IEEE 802.11 MAC are 19.1%, 22.4%, 23.3%, and 26.5%, respectively.

We next consider the case of $\sigma_{dB} = 4$. Since the average distance between the transmitter and the receiver gets longer, the distance between the receiver and the interfering node should also be longer to prevent the collision. Even if the distance between the transmitter and the receiver is small, the success probability decreases due to large σ_{dB}. For example, when $d = 20$ and $r = 40$, the success probability is $P_i = 0.5376$, where i can be $DATA_1$, $DATA_2$, ACK_1, or ACK_2. It is smaller than that when $\sigma_{dB} = 0.01$. Consequently, there are fewer feasible concurrent transmissions when σ_{dB} is large.

Figure 6 shows the results for $\sigma_{dB} = 4$, where the normalized throughput improvements are 12.0%, 6.9%, 14.1%, and 25.7%, respectively. From Fig. 6(b), we find the ratios of the average end-to-end delays are 84.7%, 91.7%, 91.1%, and 87.5%, respectively. Compared to the case of $\sigma_{dB} = 0.01$, the number of scheduled transmissions are reduced. However, the proposed MAC protocol still achieves considerable improvements in end-to-end throughput and delay.

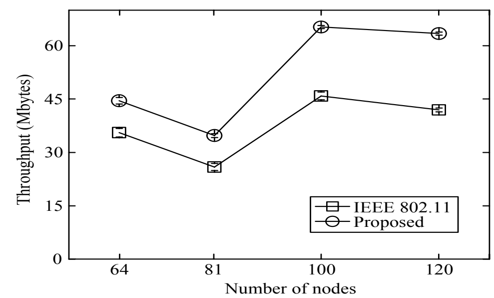


(a) Throughput performance

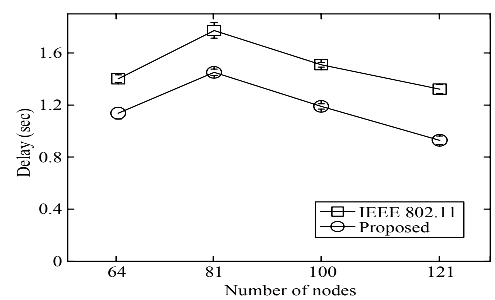


(b) Delay performance

Fig. 7. Simulation results for random networks when $\sigma_{dB} = 0.01$.



(a) Throughput performance



(b) Delay performance

Fig. 8. Simulation results for random networks when $\sigma_{dB} = 4$.

B. Random Networks

We also study the proposed MAC protocol using networks with random topologies. Node locations and traffic flows are randomly generated as follows: $2n$ nodes are selected as the sources for n^2-node random network. A half of sources transmit a CBR traffic of 1000-byte packets, while the rest of sources transmit that of 700-byte packets.

Simulation results for the case of $\sigma_{dB} = 0.01$ are plotted in Fig. 7. From Fig. 7(a), we find that normalized throughput improvements of 11.6%, 24.8%, 34.1%, and 26.7% are achieved. In addition, we find from Fig. 7(b) that the ratios of the average end-to-end delay with the proposed MAC to that of the IEEE 802.11 MAC are 91.8%, 87.2%, 81.4%, and 88.8%, respectively. The simulation results for the case of $\sigma_{dB} = 4$ are presented in Fig. 8. We find that normalized throughput improvements of 25.3%, 34.1%, 42.2%, and 51.2% are achieved. We also find from Fig. 8(b) that the ratios of the average end-to-end delay with the proposed MAC to that of the IEEE 802.11 MAC are 81.1%, 81.8%, 78.8%, and 70.3%, respectively. The proposed MAC protocol achieves considerable improvements in both throughput and delay for the random networks.

V. Conclusion

In this paper, we study the problem of improving the throughput of multi-hop wireless networks with log-normal shadowing channels. We first derived the success probability for the concurrent transmissions from exposed terminals, and then proposed a location-assisted MAC protocol, which validates the feasibility of the concurrent transmission based on the calculated success probability and a prescribed threshold value. Our ns-2 simulation results showed that the proposed protocol can effectively leverage spatial reuse, and thus improve the throughput and delay performance for IEEE 802.11 based multi-hop wireless networks.

Acknowledgments

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