Exploiting Location Information for Concurrent Transmissions in Multihop Wireless Networks

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***Abstract*—In a multihop wireless network environment, it has been shown that IEEE 802.11 media access control (MAC) suffers from a low-throughput problem, which is largely due to the inefficiency in carrier sensing and spatial reuse. In this paper, we present a location-assisted MAC protocol that schedules "feasible" concurrent transmissions in a multihop wireless network. A simple procedure based on location information is adopted in the proposed MAC to validate the feasibility of a concurrent transmission. Our simulation results show that the proposed scheme can effectively increase the throughput and reduce the average end-to-end delay of multihop wireless networks.**

***Index Terms*—Concurrent transmissions, exposed terminal, media access control (MAC), multihop wireless networks.**

I. Introduction

IEEE 802.11 is becoming the most popular protocol for wireless networks [1]. It uses the so-called virtual carrier sensing mechanism to resolve the hidden-terminal problem. However, the so-called "exposed-terminal" problem still remains. An exposed terminal, i.e., a node located within the request-to-send (RTS) range but not in the clear-to-send (CTS) range, is refrained from transmitting, even if its transmission will not interfere with the other receiver. The exposed-terminal problem hinders spatial reuse and is a key problem for network throughput in a multihop wireless network.

Considerable effort has been made to mitigate the exposed-node problem (see Section V). For example, it has been found that the carrier sensing range is an important parameter for spatial reuse, whereas using the optimal carrier sensing range will certainly help reduce the number of exposed nodes [2]–[6]. In addition, researchers also exploited efficient power control for leveraging spatial reuse [7]–[11]. In the so-called MACA-P protocol [12], a control gap is introduced between the RTS–CTS exchange and the subsequent DATA–ACK exchange, such that exposed nodes can transmit RTS–CTS in this control interval to schedule their concurrent DATA frame transmissions. Additional control messages, which are called request-to-send-simultaneously (RTSS) and clear-to-send-simultaneously (CTSS), are also used for scheduling concurrent transmissions in a recent work [13].

In this paper, we propose a new approach to improve spatial reuse in multihop wireless networks. This approach exploits location information to schedule concurrent transmissions. The objective is to allow an exposed node to schedule concurrent transmissions to improve network throughput and delay performance. We assume that each node has its location information, either through the Global Positioning System or many available localization algorithms [14]–[16]. We further assume that each node is able to exchange location information with its neighbors.

We present a location-assisted media access control (MAC) protocol that exploits location information to validate potential concurrent transmissions. Such a scheduled transmission should not interfere with the current transmission, and it should not be corrupted by the current transmission. We first present a simple analysis of the feasible region for target receivers of an exposed node and then use these constraints for validating a feasible transmission from an exposed node. We incorporate this idea into a new MAC protocol for single or multihop wireless networks. Compared with existing approaches, the proposed MAC protocol only introduces marginal control overhead (e.g., exchanging location information with one-hop neighbors when a node moves). The scheduling of concurrent transmissions is transparent to the current sender–receiver pair, making it backward comparable with the original IEEE 802.11 MAC. We further implement this proposed protocol on the `ns-2` simulator. Through extensive simulation studies, we find that the proposed scheme can improve throughput and delay performance for various multihop wireless networks.

The remainder of this paper is organized as follows: In Section II, we explore the feasible region of target receivers of an exposed node. Section III presents the proposed location-assisted MAC protocol, with simulation results given in Section IV. Section V reviews related work, and Section VI concludes this paper.

II. Feasible Region Analysis

In this section, we find the region where an exposed node's transmission can successfully be completed. Throughout this

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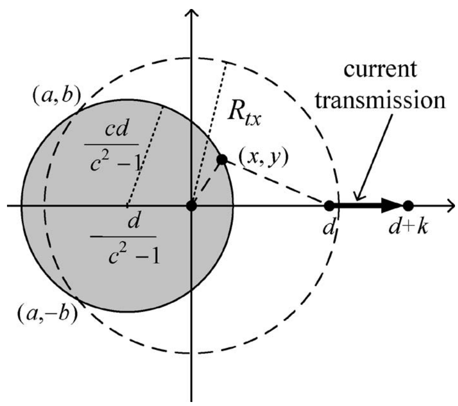


Fig. 1. Feasible region of scheduled receivers.

paper, we call a transmission that comes in first the channel *current transmission*. The transmitter and receiver of the current transmission are termed *current transmitter* and *current receiver*, respectively. On the other hand, a concurrent transmission from an exposed node, which is opportunistically scheduled to coexist with the current transmission, is termed *scheduled transmission*. The transmitter and receiver of the scheduled transmission are termed *scheduled transmitter and scheduled receiver*, respectively.

All nodes are assumed to have the same type of radio and identical transmit power. We consider the *two-ray ground propagation model* [17]. Under this model, the relation between the transmit power P_t and the received power P_r is $P_r = P_t G_t G_r (h_t^2 h_r^2)/(d^4)$, where G_t and G_r are the gains of the transmit and receive antennas, respectively; h_t and h_r are the heights of transmit and receive antennas, respectively; and d is the distance between the transmitter and the receiver.

For a target receiver, let P_r and P_i denote the received transmit power (with a distance of d_T from the receiver) and the received interference power (from an interfering source at a distance of d_I from this receiver), respectively. For successful reception, the signal-to-interference ratio (SIR) at the receiver should be greater than a threshold T_{SIR}, i.e.,

$$\mathrm{SIR} = P_r/P_i \geq T_{\mathrm{SIR}} > 1. \tag{1}$$

From the two-ray ground model and (1), the transmission of a node located within a distance of $d_T \sqrt[4]{T_{\mathrm{SIR}}}$ from the target receiver can interfere with the current transmission. Therefore, the interference range R_i is defined as [18]

$$R_i = d_T \sqrt[4]{T_{\mathrm{SIR}}}. \tag{2}$$

Without loss of generality, let the coordinates of the current transmitter, the current receiver, the scheduled transmitter, and the scheduled receiver be $(d, 0)$, $(d + k, 0)$, (0, 0), and (x, y), respectively, as shown in Fig. 1. We focus on the feasible location of the scheduled receiver to show *when* a scheduled transmission is allowed. Based on (2), boundary points of the area within which the scheduled transmission will not be interfered by the current transmission can be calculated from $c\sqrt{x^2 + y^2} = \sqrt{(x - d)^2 + y^2}$, where $c = \sqrt[4]{T_{\mathrm{SIR}}} > 1$. Rearranging the aforementioned equation, we obtain

$$\left(x + \frac{d}{c^2 - 1}\right)^2 + y^2 = \frac{c^2 d^2}{(c^2 - 1)^2}. \tag{3}$$

That is, this region is a *disk* centered at $(-d/(c^2 - 1), 0)$ with a radius $cd/(c^2 - 1)$, which is shown as the shaded area in Fig. 1. On the other hand, the scheduled receiver should be located within the scheduled transmitter's transmission range to correctly receive the frame, i.e.,

$$R_{\mathrm{tx}}^2 \geq x^2 + y^2 \tag{4}$$

represented by the dashed disk in Fig. 1. Nodes that are out of the dashed circle cannot successfully decode the scheduled transmission, even if the current transmission is absent. Therefore, the feasible region of a scheduled receiver, which is termed *feasible region* and denoted as F, is finally the overlapped portion of these two disks.

When R_{tx} is larger than or equal to $d/(c - 1)$, the dashed disk covers the entire solid disk. On the other hand, when $d < R_{\mathrm{tx}} < d/(c - 1)$, the two disks partially overlap each other. In this case, there exist two intersection points, and their coordinates are (a, b) and $(a, -b)$, respectively (see Fig. 1), where

$$a = \frac{d}{2} - \frac{c^2 - 1}{2d} R_{\mathrm{tx}}^2$$
$$b = \sqrt{-\frac{d^2}{4} + \frac{c^2 + 1}{2} R_{\mathrm{tx}}^2 - \frac{(c^2 - 1)^2}{4d^2} R_{\mathrm{tx}}^4}.$$

Let ρ be the ratio of the feasible region to the transmission region, termed *feasible ratio*. We have (5), shown at the bottom of the next page, where

$$\begin{cases} \theta_1 = 2 \arctan(-b/a) \\ \theta_2 = 2 \arctan(b/a) \\ \varphi_1 = 2 \arctan\left\{-b/\left[d/(c^2 - 1) + a\right]\right\} \\ \varphi_2 = 2 \arctan\left\{b/\left[d/(c^2 - 1) + a\right]\right\}. \end{cases}$$

Equation (5) allows us to evaluate the impact of the network parameters on the feasible region F and feasible ratio ρ. Generally, the larger the F or ρ, the higher the chance of allowing a feasible scheduled transmission. Fig. 2(a) plots ρ for increased R_{tx}. We find that ρ is a strictly decreasing function of R_{tx}, since larger R_{tx} will cause more severe interference at the scheduled receiver. To schedule more concurrent transmissions, it may be desirable to reduce the transmission range (if allowed by the network connectivity requirement). Fig. 2(b) plots ρ for increased d (i.e., the network gets sparser). As d gets larger, the feasible region of the scheduled receiver also increases. This result is as expected since the current transmitter is an interferer to the scheduled receiver. Increasing d means that the interfering node becomes further away, and the interference becomes smaller.

III. Location-Assisted MAC Protocol

We now present a location-assisted protocol to enhance the IEEE 802.11 MAC for concurrent transmissions within a

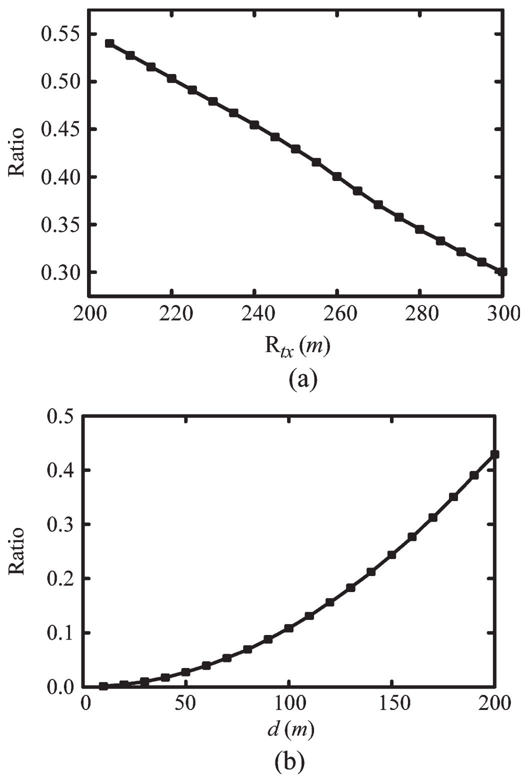


Fig. 2. Impact of network parameters on the feasible ratio ρ ($T_{\mathrm{SIR}} = 10$). (a) Transmission range R_{tx} ($d = 200$). (b) Distance between the two transmitters d ($R_{\mathrm{tx}} = 250$).

neighborhood. We first discuss the key steps in the proposed scheme and then present the complete distributed protocol.

A. Identifying an Exposed Terminal

When a node first overhears an RTS and then a DATA frame from the same transmitter, it can be identified as an exposed terminal with regard to the overheard transmission. In practice, however, information such as frame type will only be available at the MAC layer after the entire frame is received and verified by checking the frame check sequence trailer. When a node recognizes itself as an exposed terminal in this manner, it will be too late to schedule any concurrent transmission. To schedule concurrent transmissions, exposed terminals should be identified *before* the current DATA frame transmission begins.

We adopt a cross-layer approach to identifying exposed terminals, which exploits PHY frame header information for early DATA frame identification. The IEEE 802.11 PHY frame structure is shown in Fig. 3 for direct spread-spectrum sequencing (DSSS).

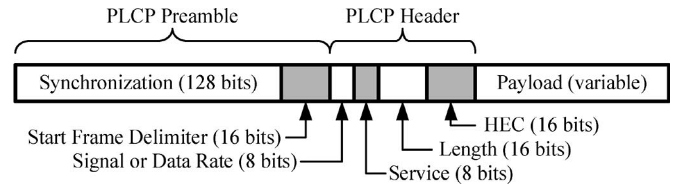


Fig. 3. IEEE 802.11 PHY frame structure when DSSS is used.

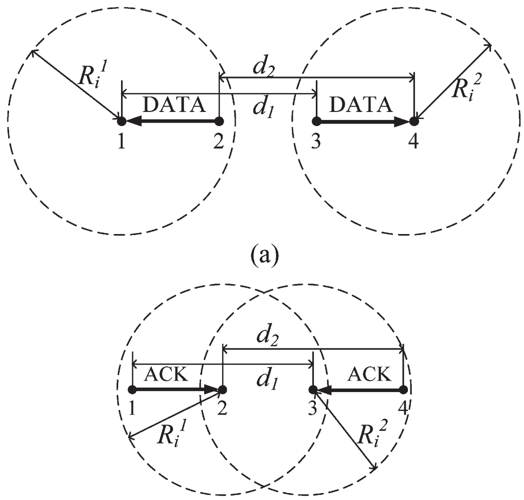
As soon as the physical-layer convergence protocol (PLCP) header, which precedes the current MAC DATA frame, is completely received and verified (by checking the header error check (HEC), a 16-bit cyclic redundancy check code), the exposed node will know the MAC protocol data unit length. The exposed node can determine if the MAC frame is DATA from the length information since DATA frames are always longer than control frames (i.e., RTS, CTS, and ACK). By comparing the *Length* value with that in the preceding RTS, the exposed node can infer if the RTS and the DATA frame are from the same sender. It can further validate its inference if the interval between the DATA frame and the RTS is (short interframe space (SIFS) + CTS + SIFS) plus some propagation delay.

B. Validating a Scheduled Transmission

When a node is identified as an exposed terminal, its transmission should first be validated. Such validation is necessary since a scheduled transmission may not always be feasible, as discussed in Section II. By exploiting location information, we can correctly identify scheduled transmissions that will not be interfered by the current transmission [see Fig. 4(a)]. Furthermore, for both DATA frames to be successfully delivered, the corresponding ACK transmissions should not interfere with each other either. In the case of ACK transmission, the roles of transmitter and receiver are switched, as shown in Fig. 4. Therefore, to prevent collisions between the two ACK frames, the current receiver should be out of the interference range of the scheduled transmitter, and the scheduled receiver should be out of the interference range of the current transmitter [see Fig. 4(b)].

Fig. 5 presents procedure `validate_schdTx()`. It evaluates the feasibility of a scheduled transmission by considering both DATA and ACK frames. Recall that the location information of a node's neighbors is available, which is used in the validation procedure. In Fig. 5, d_1 is the distance between the scheduled transmitter and the current receiver, whereas d_2 is the distance between the current transmitter and the scheduled receiver. These can easily be computed from the

$$\rho = \begin{cases} \frac{c^2 d^2}{R_{\mathrm{tx}}^2 (c^2-1)^2}, & \text{for } R_{\mathrm{tx}} \geq \frac{d}{c-1} \\ \frac{\theta_1}{2\pi} - \frac{\sin\theta_1}{2\pi} + \frac{c^2 d^2}{R_{\mathrm{tx}}^2 (c^2-1)^2}\left(1 - \frac{\varphi_1}{2\pi} + \frac{\sin\varphi_1}{2\pi}\right), & \text{for } \frac{\sqrt{c^2+1}}{c^2-1} d \leq R_{\mathrm{tx}} < \frac{d}{c-1} \\ \frac{\theta_1}{2\pi} - \frac{\sin\theta_1}{2\pi} + \frac{c^2 d^2}{R_{\mathrm{tx}}^2 (c^2-1)^2}\left(\frac{\varphi_2}{2\pi} - \frac{\sin\varphi_2}{2\pi}\right), & \text{for } \frac{d}{\sqrt{c^2-1}} \leq R_{\mathrm{tx}} < \frac{\sqrt{c^2+1}}{c^2-1} d \\ 1 - \frac{\theta_2}{2\pi} + \frac{\sin\theta_2}{2\pi} + \frac{c^2 d^2}{R_{\mathrm{tx}}^2 (c^2-1)^2}\left(\frac{\varphi_2}{2\pi} - \frac{\sin\varphi_2}{2\pi}\right), & \text{for } d < R_{\mathrm{tx}} < \frac{d}{\sqrt{c^2-1}} \end{cases} \quad (5)$$



(a)

(b)

Fig. 4. DATA and ACK transmissions for the current transmission from Node 2 to Node 1 and the scheduled transmission from Node 3 to Node 4. (a) DATA frame transmission. (b) ACK frame transmission.

```
Procedure      validate_schdTx()
calculate d1 and d2 ;
estimate Ri^1 and Ri^2 ;
if (d1 > Ri^1 AND d2 > Ri^2 AND d1 > Ri^2 AND d2 > Ri^1)
    return 1 ; // the scheduled transmission is allowed
else
    return 0 ; // the scheduled transmission is cancelled
endif
```

Fig. 5. Procedure validating a scheduled transmission. The variables d_1, d_2, R_i^1, and R_i^2 are shown in Fig. 4.

coordinates of these nodes. Furthermore, R_i^1 and R_i^2 are the interference ranges of the current receiver and the scheduled receiver, respectively; R_i^1 and R_i^2 are also the interference ranges of the current transmitter and the scheduled receiver, respectively. These interference ranges can be estimated using a proper propagation model, e.g., (2). Note that condition (4) is automatically satisfied since the scheduled transmitter and receiver are one-hop neighbors of each other. The first two conditions in Line 3 test the feasibility of the concurrent DATA transmission, whereas the last two conditions in Line 3 check the feasibility of the concurrent ACK transmission. An exposed node will not proceed to schedule a concurrent transmission if either of the aforementioned conditions is violated.

C. Scheduling a Concurrent Transmission

If the validation is passed, the exposed terminal will try to schedule its concurrent transmission. Fig. 6 provides an example. The starting time of a scheduled transmission is determined as follows: First, the value $schdTx\_margin$ is computed as

$$\begin{aligned} schdTx\_margin = &\text{current\_duration} - \text{SIFS} - \text{CTS} - \text{SIFS} \\ &- \text{(PLCP reading time)} \\ &- \text{(scheduled data duration)} \\ &- \text{SIFS} - \text{ACK} \\ &- \text{(round-trip propagation delay)} \end{aligned} \tag{6}$$

where current_duration represents the duration carried in the preceding RTS of the current transmission.

Suppose that there are multiple nodes near the current transmitter, then more than one node can be identified as exposed terminals. Since we are developing a fully distributed protocol, each exposed node may start to transmit, and there may be collisions among themselves. To play on the safe side, we take a conservative approach to introduce a random delay to differentiate the starting times of potential concurrent transmissions. A random value t_d is generated similar to the backoff mechanism

$$t_d = (random\_integer \,\%\, t_d^{max}) \times aSlotTime \tag{7}$$

where $t_d^{\max}$ is an upper bound for t_d, computed as $t_d^{\max} = \lceil schdTx\_margin/aSlotTime \rceil$. Note that the random delay is a multiple of aSlotTime (20 μs in IEEE 802.11b [1]). If $schdTx\_margin$ is negative, the scheduled transmission cannot fit into the current data transmission period, and it will not be scheduled. Otherwise, the scheduled data frame may be transmitted following the received PLCP preamble and header after an additional delay t_d. If $t_d^{\max}$ is sufficiently large, the probability that multiple scheduled transmissions concurrently start will be negligible.

Once an exposed terminal gets a positive $schdTx\_margin$ value, it will start a timer with a value t_d after detecting the beginning of the current DATA frame transmission. During the interval, it will keep on detecting if there is a scheduled transmission from another exposed terminal (in addition to the current transmission).[1] If it detects a scheduled transmission, it will cancel its timer. Otherwise, when the timer times out, it will start to schedule its concurrent transmission.

Due to the introduction of the random delay t_d, two ACKs for the current and scheduled transmissions may not be aligned. To let the scheduled receiver know when to transmit ACK, we introduce a new frame type for the scheduled DATA. The new frame type has one extra field, which is termed T_{info}, to carry the random delay value $(t_d^{\max} - t_d/aSlotTime)$. We can use the reserved value of Type and Subtype, e.g., value "11" for these types of frames [1]. When a normal DATA frame is received, an ACK frame is sent after SIFS. When a DATA frame of type "11" is received, ACK is sent after SIFS plus $(T_{\text{info}} \times aSlotTime)$.

It is worth noting that with the aforementioned mechanism, concurrent transmissions from exposed nodes will not collide with the current transmission. However, there is still a slight chance for multiple scheduled transmissions to collide with each other due to the multihop characteristics of the network and the fully distributed nature of the proposed scheme. In Section IV, we show via extensive simulations that the amount of such collisions is generally negligible. To avoid such collisions, multiple rounds of signaling are necessary, which will

[1]We assume that the radio device of an exposed node can detect such events. For example, a concurrent transmission from another exposed node (with a smaller timer value) can be detected by a sudden increase in the instant received signal-strength indicator [1]. The exposed node can also decode the received current DATA frame (rather than discarding it). It can infer the presence of a concurrent transmission when the PHY bit error rate suddenly increases.

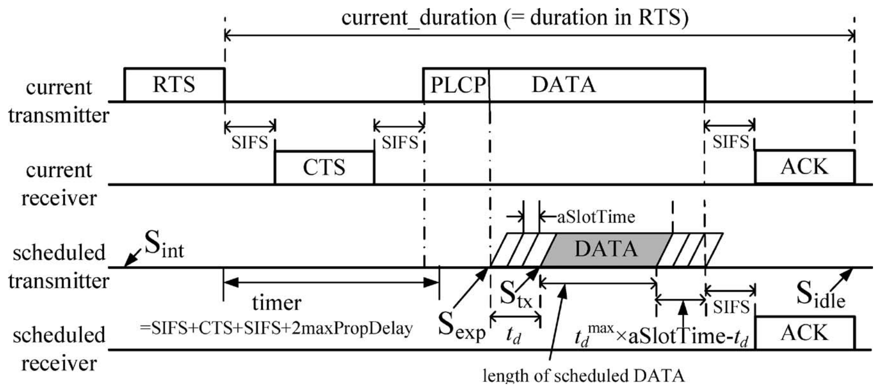


Fig. 6. Timeline illustration for the operation of the proposed protocol.

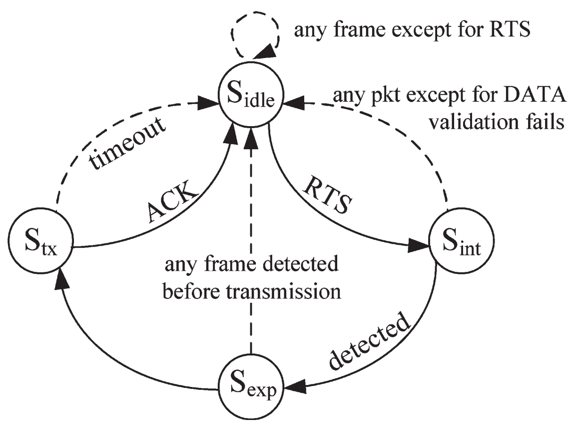


Fig. 7. State-transition diagram of the location-assisted MAC protocol, which has four states: 1) the initial state S_{idle}; 2) the intermediate state S_{int}; 3) the exposed-terminal state S_{exp}; and 4) the scheduled transmission sate S_{tx}.

incur higher control overhead. Such a tradeoff will be an interesting problem for further investigation.

D. Distributed Protocol

We are now ready to put all the pieces together. The basic operation of this MAC protocol resembles that of IEEE 802.11 MAC. By incorporating the identification, validation, and scheduling procedures previously described, it can schedule concurrent transmissions from exposed nodes, thus leveraging spatial reuse and improving network throughput.

The state-transition diagram of the proposed protocol is given in Fig. 7, where the solid arrows indicate the state transition path of a successfully scheduled transmission. First, based on the frames overheard from the medium, a node may identify itself as an exposed terminal. Specifically, after receiving an RTS destined to some other node, the node enters the intermediate state S_{int}. If a DATA frame from the same sender is detected as discussed, the node enters state S_{exp}. However, only nodes passing the validation process of the scheduled transmission will remain in S_{exp}. The validation process determines the following conditions: 1) whether the scheduled transmission will collide with the current transmission by running procedure `validate_schdTx`(), as shown in Fig. 5 and 2) whether the scheduled data frame can fit into the transmission period of the current data frame. That is, if $schdTx\_margin$ is nonnegative.

A timer with a value t_d will start if and only if both conditions are satisfied. However, the timer could be canceled if multiple concurrent transmissions (i.e., the current transmission and other scheduled transmissions) are detected before it expires, as indicated by the vertical dash arrow in Fig. 7. Otherwise, the scheduled DATA frame will be transmitted when the timer expires. The loop is closed when the scheduled receiver successfully returns an ACK to the scheduled transmitter. Otherwise, the scheduled sender will time out and try to retransmit the DATA frame. It is worth noting that although the scheduled transmission does not use an RTS to reserve the scheduled receiver, the scheduled receiver should not be involved in an ongoing transmission. This is because otherwise, the scheduled transmitter should have overheard a CTS from the scheduled receiver (since it is a one-hop neighbor) in response to an earlier RTS from some other transmitter.

IV. Simulation Results

To demonstrate the performance of the proposed protocol, we implement it with ns−2.30 and perform extensive simulation studies. In addition to the proposed protocol, a companion mechanism is also implemented to distribute location information. In this implementation, each node maintains a table storing its location information and that of its one-hop neighbors. We modify RTS to piggyback the coordinates of the sender itself and its target receiver.

An alternative approach is to adopt a special control message. A node broadcasts its location to its one-hop neighbors using the control message when it moves to a new location. Once a node's location table is updated, it will also send the updated entries to its neighbors, such that every node obtains locations of its two-hop neighbors. Note that this approach does not change the RTS frame of IEEE 802.11 MAC and is more suitable for networks with low mobility. We adopted the piggybacking approach instead of the broadcasting approach in our simulations.

Throughout this section, the antenna parameters are set to the default values in ns−2.30, i.e., $R_{\text{tx}} = 250$ m and $R_{\text{cs}} = 550$ m.[2] The channel rate is set to 1 Mb/s. In all the simulations,

[2]Such default settings allow cross-examination of our results with that reported in the literature (e.g., throughput results presented in [19]). All our IEEE 802.11 MAC simulation results are consistent with those in the literature.

data flows start at $t = 10$ s and last for about 15 min (simulated time). For throughput, we focus on the number of bytes successfully transmitted at the "agent" level (i.e., excluding protocol overhead; end-to-end throughput rather than one-hop throughput). Each simulation is repeated five times with different random seeds. Each result reported in this section is the average of the corresponding five trials, with 90% confidence intervals plotted. Other simulation parameters will be given when the results are discussed.

A. Chain Networks

The first simulation study is performed with the chain network topology, where the distance between any two adjacent nodes is set to 200 m. In the simulation, the forward flow (from Node 1 to Node N) is a constant-bit-rate (CBR) session with a stream of 1000-byte frames, whereas the backward flow (from Node N to Node 1) is a CBR session with a smaller packet size.

We first plot the throughput versus offered load for an eight-node chain network in Fig. 8(a). For both schemes, we find that the throughput first increases with offered load in the underload region, due to the more data available for transmission. In the overload region, however, the throughput decreases with offered load due to congestion. We find that both MACs achieve the largest throughput when offered load is 80 kb/s. Similar results are obtained for other chain networks with different sizes, but are omitted here. We choose the offered load that achieves the largest throughput for a chain network in the following simulations.

The simulation results for chain networks with various packet sizes for the backward flow are plotted in Fig. 8(b). Here, the data rates of the flows for the 6-, 8-, 10-, 12-, and 14-node chain networks are set to 90, 80, 70, 55, and 55 kb/s, respectively. These data rates are chosen according to the simulations presented in [19]. We define a performance measure, i.e., *normalized throughput improvement*, as

$$\alpha = \frac{throughput\_proposed - throughput\_802.11}{throughput\_802.11}.$$

We have $\alpha = 67.89\%$ for the eight-node chain when the frame size of the backward flow is 750 bytes. For the 6-, 10-, 12-, and 14-node chain networks, the normalized improvements achieved by the proposed scheme are found to be 52.93%, 58.26%, 27.25%, and 39.27%, respectively. When the packet size of the backward flow is reduced, the improvement ratio tends to be smaller. For example, when the packet size of the backward flow is 500 bytes, the throughput improvement ratio ranges from 24.94% to 61.22% for chain networks with increasing number of nodes. When the packet size of the backward flow is 250 bytes, the throughput improvement ratio ranges from 13.47% to 56.18% for the chain networks.

We also plot the average end-to-end delay in Fig. 8(c). We observe significantly reduced average end-to-end delays when the proposed MAC is used. Let β denote the ratio of the end-to-end delay of the proposed MAC over that of IEEE 802.11 MAC, i.e.,

$$\beta = \frac{delay\_proposed}{delay\_802.11}.$$

In the six-node chain with a 750-byte backward flow, we have $\beta = 18.36\%$. Significant delay improvement is also achieved for other chain networks we examined. When the packet size of the backward flow is equal to 750 bytes, the β values are 17.68%, 26.48%, 29.13%, and 33.06% for the 8-, 10-, 12-, and 14-node networks, respectively.

We next examine the microscopic behavior of the proposed protocol. Fig. 8(d)–(f) plots the results related to scheduled transmissions. We find that most of the concurrent transmissions are successful. For example, when the packet size of the backward flow is 750 bytes, the failure percentages (defined as the number of failures divided by the number of scheduled transmissions) are 3.21%, 7.92%, 2.87%, 0.22%, and 0.62%, respectively, for chain networks with different numbers of nodes.

B. Double-Ring Networks

We next study the performance of the proposed protocol under a double-ring network topology, where nodes are aligned on two circles with the same center. The distance between two adjacent nodes in the inner ring is set to 200 m, and the radius of the inner ring is

$$200 \Big/ \sqrt{2\left(1 - \cos\left(\frac{2\pi}{N}\right)\right)}$$

where N represents the number of nodes in the inner ring. For example, if there are six nodes in the inner ring, the radius is equal to 200 m. The radius of the outer ring is larger than that of the inner ring by 100 m. Same number of nodes are located in the outer ring, aligned with the nodes in the inner ring. All the inner-ring nodes are sources, whereas all the outer-ring nodes are one-hop receivers. Odd-indexed nodes transmit a CBR flow consisting of 1000-byte packets, whereas even-indexed nodes transmit a CBR flow consisting of 750-byte packets. The data rate is set to 850 kb/s in all the simulations. The maximum one-hop throughput is given in [19].

Fig. 9(a) shows the number of bytes successfully transmitted for both IEEE 802.11 and location-assisted MACs. The proposed scheme achieves considerable throughput improvements in all cases, with α values of 39.67%, 32.43%, 117.85%, and 20.67%, respectively. The average end-to-end delay results are shown in Fig. 9(b). The ratios of the end-to-end delay achieved by the proposed protocol to that of the 802.11 MAC, i.e., β, are 64.16%, 67.80%, 43.50%, and 73.74%, respectively. During the simulations, there are, on average, 49 902.4, 41 686.6, 139 600.4, and 57 579 scheduled transmissions, and all scheduled transmissions are successful.

We also performed simulations with the grid network topology, with horizontal and vertical flows. We observed similar improvements in throughput and delay achieved over the IEEE 802.11 MAC, but we omitted this set of results for brevity.

C. Random Networks

Finally, we use random network topologies in our simulation. In this setting, 64, 81, 100, and 121 nodes are randomly located

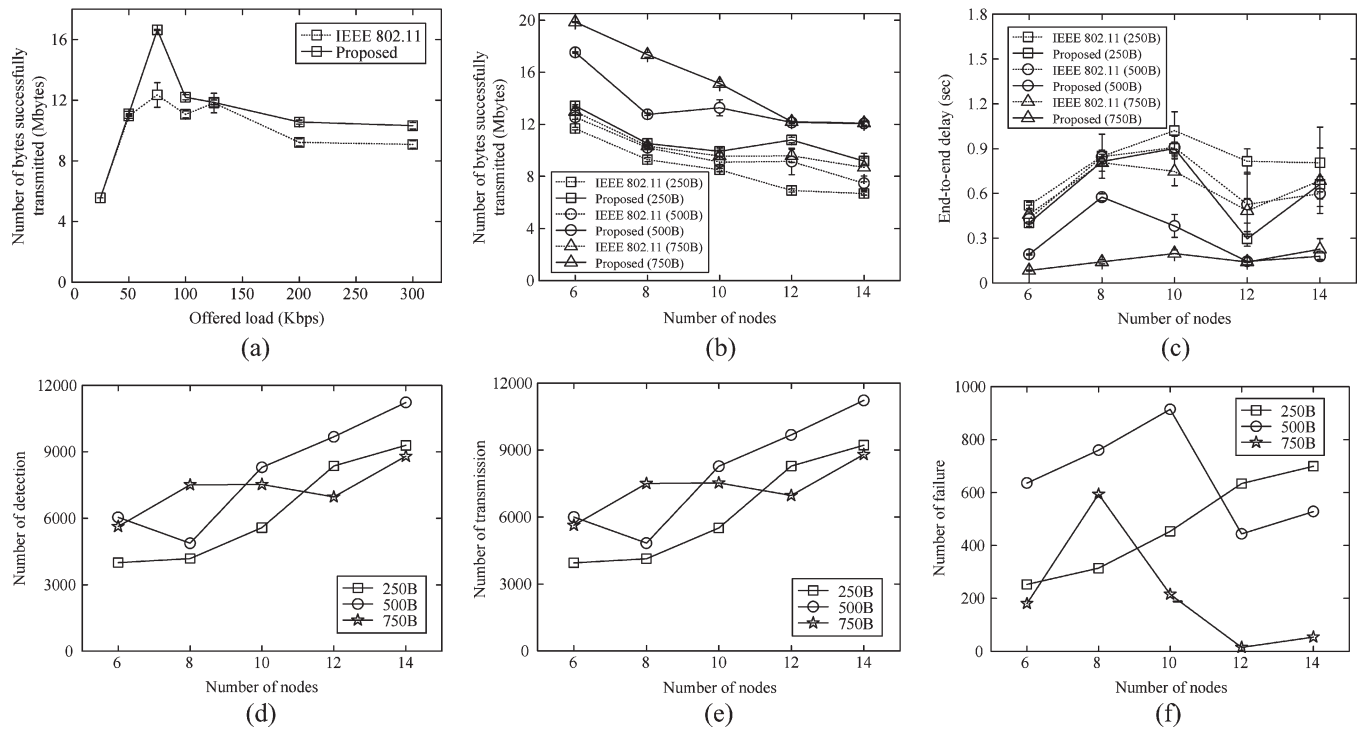


Fig. 8. Simulation results for chain networks. (a) Throughput versus offered load. (b) Number of bytes successfully transmitted over an 890-s interval. (c) Average end-to-end delay. (d) Number of detected exposed nodes. (e) Number of scheduled transmissions. (f) Number of failed scheduled transmissions.

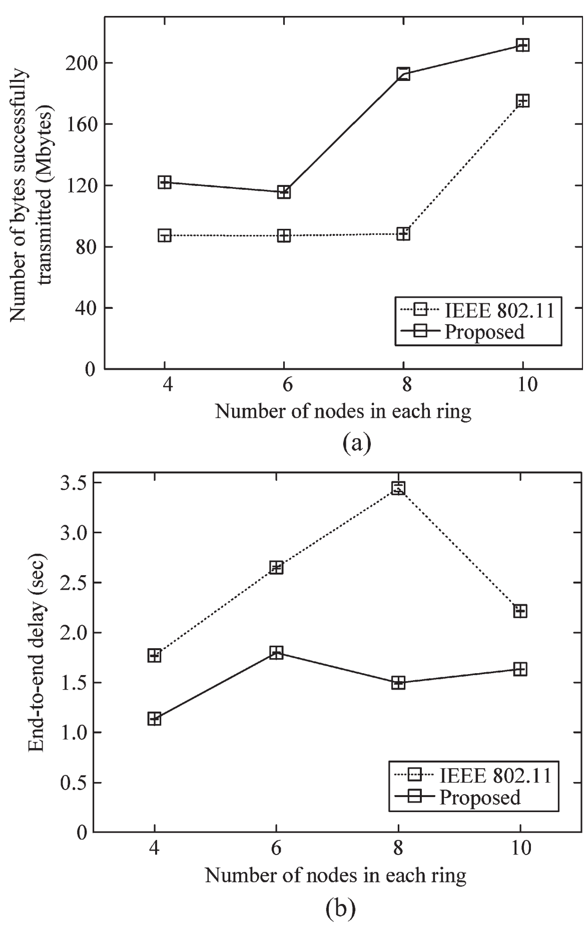


Fig. 9. Simulation results for double-ring networks. (a) Number of bytes successfully transmitted over an 890-s interval. (b) Average end-to-end delay.

in a 1000 $\times$ 1000 m area, respectively. Sixteen, 18, 20, and 22 nodes are selected as the source nodes for the 64-, 81-, 100-, and 121-node random networks, respectively. Half of source nodes transmit a CBR traffic flow with 1000-byte packets, whereas the other half of source nodes transmit a CBR flow with 700-byte packets. The data rates are set to 300 kb/s for all the cases. The ad hoc on-demand distance vector protocol is used for routing [20].

The simulation results for the random networks with fixed packet sizes and data rates are shown in Fig. 10. In Fig. 10(a), we find that the improvements in throughput are 18.30%, 20.02%, 27.10%, and 58.03%, respectively. We also find in Fig. 10(b) that the ratios of the average end-to-end delay with the proposed protocol to that with the IEEE 802.11 MAC are 73.51%, 88.03%, 82.90%, and 79.53% for the four random networks, respectively. The proposed scheme works well in both sparse and dense multihop wireless networks.

Fig. 10(c) shows the average numbers related to scheduled transmissions. The average numbers of scheduled transmissions that are canceled are 0.2, 2, 55.8, and 20.6, respectively (over five simulations for each scenario). Recall that an exposed node may cancel its transmission if any of the necessary conditions is not satisfied, as discussed in Section III. For the four random networks, the ratios of failed scheduled transmissions are 0.62%, 1.16%, 6.59%, and 3.65%, respectively.

We next adopt variable packet sizes in the simulation, where the packet size is uniformly distributed within range [100, 1100] bytes, and the data rate is uniformly distributed within range [100, 200] kb/s. Fig. 11 shows the simulation results for the four random networks. We find that the throughput improvements α are 14.50%, 14.77%, 25.01%, and 30.44%,

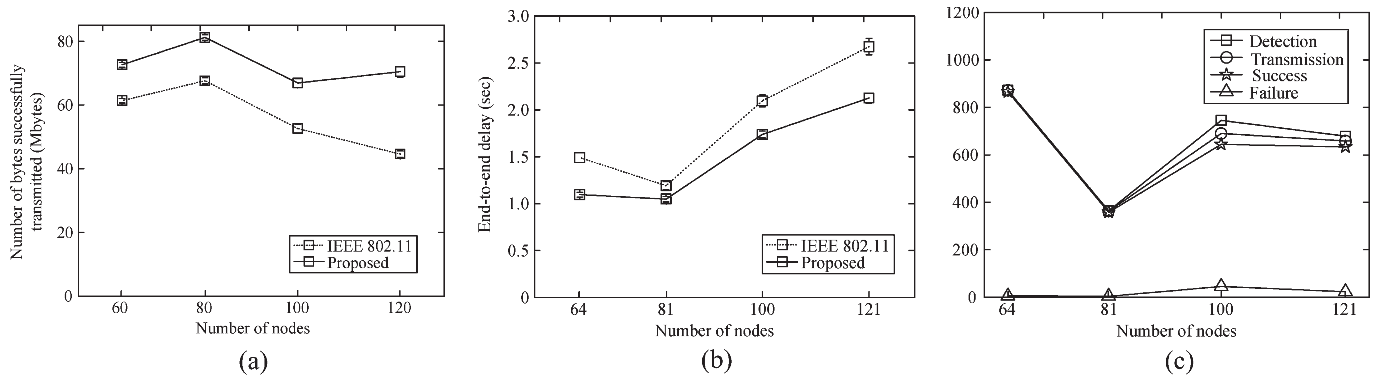


Fig. 10. Simulation results for random networks with fixed packet sizes and data rates. (a) Number of bytes successfully transmitted over an 890-s interval. (b) Average end-to-end delay. (c) Total numbers related to scheduled transmissions.

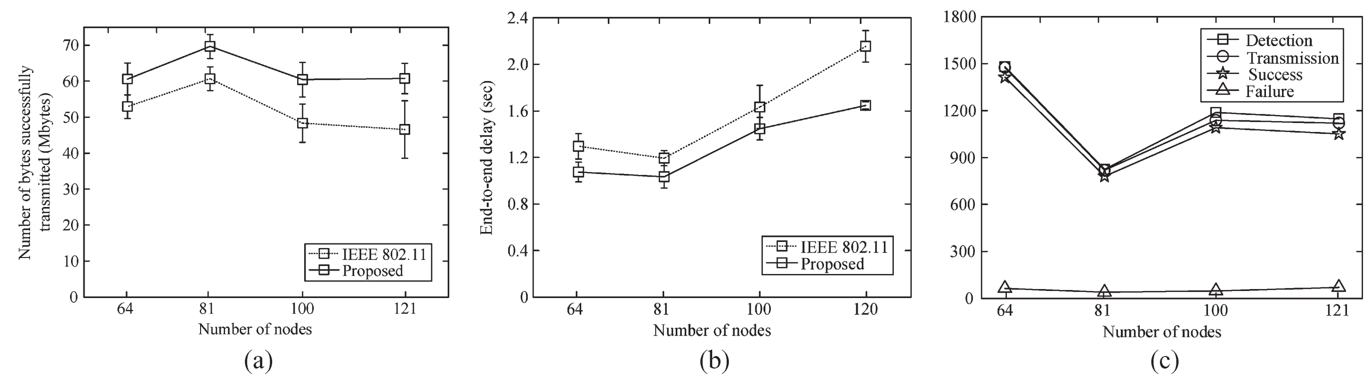


Fig. 11. Simulation results for random networks with randomly chosen packet sizes and data rates. (a) Number of bytes successfully transmitted over an 890-s interval. (b) Average end-to-end delay. (c) Total numbers related to scheduled transmissions.

respectively, whereas the delay ratios β are 82.95%, 86.57%, 88.52%, and 76.48%, respectively. These are consistent with those observed for the random networks with fixed packet sizes and data rates. Fig. 11(c) shows the numbers related to scheduled transmissions. Compared with the result for the previous case, it can be seen that the number of scheduled transmissions is slightly larger due to increased randomness.

V. Related Work

There have been considerable efforts on improving the throughput of wireless networks (see, e.g., [18], [19], and [21]–[23]). For example, multichannel MAC protocols are developed to exploit multiple orthogonal channels for concurrent transmissions [24]. MAC protocols exploiting busy tones [25], multiple-input multiple-output [26], and directional antennas [27], [28] are also shown to be helpful in alleviating the exposed-terminal problem. Note that this class of work requires either advanced PHY technologies or additional hardware.

There have been considerable efforts on finding the optimal carrier sensing range for IEEE 802.11 wireless networks [2]–[6]. In [6], Zhai and Fang presented an improved virtual carrier sensing mechanism, which is termed aggressive virtual carrier sensing, to improve spatial reuse. The basic idea is that if a node overhears only RTS or CTS, but not both, it would not consider the channel as busy and is allowed free transmission. The scheme presented in [4] tunes the physical carrier sensing threshold to enlarge the sensing range, such that the entire interference area is covered. As a result, all potentially interfering nodes will be eliminated. This technique does not use RTS/CTS and has been shown to improve the throughput in both chain and grid networks. However, this technique is developed under regular network topologies, where homogeneous nodes are evenly spaced. It is not clear how to adopt it for the more general topologies or heterogeneous networks.

Power control is also exploited for spatial reuse [7]–[11]. In [11], nodes within the carrier sensing range are regarded as potentially exposed terminals, whereas nodes within the interference range are regarded as potentially hidden terminals. Since these ranges change according to the transmit power, power control is used to balance the carrier sensing and interference ranges. Although providing some interesting insights, the authors found in their simulations that only modest throughput improvement was achieved in both the chain and random topologies.

Acharya *et al.* proposed a new MAC protocol, called MACA-P, in [12]. MACA-P introduces a control gap between the RTS–CTS exchange and the subsequent DATA–ACK exchange, which is used for exposed nodes to transmit RTS–CTS and for the alignment of the scheduled DATA frame transmission with the current DATA frame transmission. The authors show that MACA-P achieves higher throughput for the cases with many concurrent transmission opportunities. It is worth noting that the current version of MACA-P is not adaptive; the control gap, and hence the additional overhead, always exists. This further increases the overall control overhead of IEEE 802.11-like MACs. Such overhead was shown to be as high as 40% in a sensor platform [22], which is another limiting factor on throughput. When the network gets dense, there will be more frequent collisions among the RTSs sent by the exposed nodes. Such collisions will cause these nodes to back off, resulting in even lower throughput than IEEE 802.11. The authors suggest that some adaptive learning mechanism should be used to mitigate this shortcoming.

In [13], an offline training approach is proposed for detecting exposed links, and concurrent transmissions are scheduled through the use of RTSS and CTSS messages. The authors show that there are two main drawbacks to this scheme. First, the procedure for detecting exposed links may be considerably time consuming. As a result, it may not be efficient in supporting mobility. Second, this scheme requires modification of the PHY layer and may not be suitable for implementation on currently available hardware.

A relatively simple scheme is presented in [29], which enables nodes to identify themselves as exposed terminals and opportunistically schedule transmission of a small frame without RTS–CTS exchange. Note that this scheme does not verify the feasibility of scheduled transmissions, and the case of multiple scheduled transmissions is not considered, which may cause collisions among themselves and high cumulative interference at the current receiver. Simulation results in [29] showed little improvement in throughput when the number of nodes is large.

VI. Conclusion

The goal of this paper has been to improve the throughput and delay performance of IEEE 802.11-based multihop wireless networks. We proposed a location-assisted scheme that enhances the IEEE 802.11 MAC protocol by opportunistically scheduling concurrent transmissions to improve spatial reuse. Extensive ns−2 simulations showed that the proposed scheme can offer the desired performance improvement.

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References

[1] IEEE, *Wireless LAN Media Access Control (MAC) and Physical Layer (PHY) Specifications*, 1999.

[2] F. Ye, S. Yi, and B. Sikdar, "Improving spatial reuse of IEEE 802.11 based ad hoc networks," in *Proc. IEEE GLOBECOM*, San Francisco, CA, Dec. 2003, pp. 1013–1017.

[3] J. Deng, B. Liang, and P. K. Varshney, "Tuning the carrier sensing range of IEEE 802.11 MAC," in *Proc. IEEE GLOBECOM*, Dallas, TX, Nov./Dec. 2004, pp. 2987–2991.

[4] J. Zhu, X. Guo, L. L. Yang, and W. S. Conner, "Leveraging spatial reuse in 802.11 mesh networks with enhanced physical carrier sensing," in *Proc. IEEE ICC*, Jun. 2004, pp. 4004–4011.

[5] X. Yang and N. Vaidya, "On physical carrier sensing in wireless ad hoc networks," in *Proc. IEEE INFOCOM*, Miami, FL, Mar. 2005, pp. 2525–2535.

[6] H. Zhai and Y. Fang, "Physical carrier sensing and spatial reuse in multirate and multihop wireless ad hoc networks," in *Proc. IEEE INFOCOM*, Barcelona, Spain, Apr. 2006, pp. 1–12.

[7] J. P. Monks, V. Bharghavan, and W.-M. W. Hwu, "A power controlled multiple access protocol for wireless packet networks," in *Proc. IEEE INFOCOM*, Anchorage, AK, Apr. 2001, pp. 219–228.

[8] M. Cesana, D. Maniezzo, P. Bergamo, and M. Gerla, "Interference aware (IA) MAC: An enhancement to IEEE 802.11b DCF," in *Proc. IEEE Veh. Technol. Conf.—Fall*, Orlando, FL, Oct. 2003, pp. 2799–2803.

[9] C.-H. Yeh, "The heterogeneous hidden/exposed terminal problem for power-controlled ad hoc MAC protocols and its solutions," in *Proc. IEEE Veh. Technol. Conf.—Fall*, Los Angeles, CA, Sep. 2004, pp. 2548–2554.

[10] S. V. D. Heuvel-Romaszko and C. Blondia, "Enhancements of the IEEE 802.11, a MAC protocol for ad hoc network with history of power adjustment," in *Proc. IEEE Int. Conf. Wireless Netw., Commun., Mobile Comput.*, Maui, HI, Jun. 2005, pp. 48–54.

[11] Y. Zhou and S. M. Nettles, "Balancing the hidden and exposed node problems with power control in CSMA/CA-based wireless networks," in *Proc. IEEE Wireless Commun. Netw. Conf.*, New Orleans, LA, Mar. 2005, pp. 683–688.

[12] A. Acharya, A. Misra, and S. Bansal, "MACA-P: A MAC for concurrent transmissions in multi-hop wireless networks," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun.*, Dallas, TX, Mar. 2003, pp. 505–508.

[13] K. Mittal and E. Belding, "RTSS/CTSS: Mitigation of exposed terminals in static 802.11-based mesh networks," in *Proc. 2nd Workshop Wireless Mesh Netw.*, Reston, VA, Sep. 2006, pp. 3–12.

[14] H. Akcan, V. Kriakov, H. Brnnimann, and A. Delis, "GPS-free node localization in mobile wireless sensor networks," in *Proc. 5th Int. ACM Workshop Data Eng. Wireless Mobile Access*, Chicago, IL, Jun. 2006, pp. 35–42.

[15] A. Haeberlen, E. Flannery, A. Ladd, A. Rudys, D. Wallach, and L. Kavraki, "Practical robust localization over large-scale 802.11 wireless networks," in *Proc. ACM MobiCom*, Philadelphia, PA, Sep. 2004, pp. 70–84.

[16] D. Niculescu and B. Nath, "VOR base stations for indoor 802.11 positioning," in *Proc. ACM MobiCom*, Philadelphia, PA, Sep. 2004, pp. 58–69.

[17] T. Rappaport, *Wireless Communications: Principles and Practice*. Englewood Cliffs, NJ: Prentice–Hall, 1996.

[18] K. Xu, M. Gerla, and S. Bae, "Effectiveness of RTS/CTS handshake in IEEE 802.11 based ad hoc networks," *Ad Hoc Netw.*, vol. 1, no. 1, pp. 107–123, Jul. 2003.

[19] J. Li, C. Blake, D. S. J. D. Couto, H. I. Lee, and R. Morris, "Capacity of ad hoc wireless networks," in *Proc. ACM MobiCom*, Rome, Italy, Jul. 2001, pp. 61–69.

[20] C. Perkins, E. Belding-Royer, and S. Das, *Ad hoc On-Demand Distance Vector (AODV) Routing*, Jul. 2003. IETF RFC 3561.

[21] Y. Xiao and J. Rosdahl, "Throughput and delay limits of IEEE 802.11," *IEEE Commun. Lett.*, vol. 6, no. 8, pp. 355–357, Aug. 2002.

[22] A. Woo and D. Culler, "A transmission control scheme for media access in sensor networks," in *Proc. ACM MobiCom*, Rome, Italy, Jul. 2001, pp. 221–235.

[23] Y. Li, S. Mao, S. S. Panwar, and S. F. Midkiff, "On the performance of distributed polling service-based wireless MAC protocols," *IEEE Trans. Wireless Commun.,* in press.

[24] X. M. Gong, S. F. Midkiff, and S. Mao, "A cross-layer approach to channel assignment in wireless ad hoc networks," *ACM/Baltzer Mobile Netw. Appl. J.*, vol. 12, no. 1, pp. 43–56, Jan. 2007.

[25] Z. J. Haas and J. Deng, "Dual busy tone multiple access (DBTMA)—A multiple access control scheme for ad hoc networks," *IEEE Trans. Commun.*, vol. 50, no. 6, pp. 975–985, Jun. 2002.

[26] J.-S. Park, A. Nandan, M. Gerla, and H. Lee, "SPACE-MAC: Enabling spatial reuse using MIMO channel-aware MAC," in *Proc. IEEE ICC*, Seoul, Korea, May 2005, pp. 3642–3646.

[27] Y. Wang and J. J. Garcia-Luna-Aceves, "Spatial reuse and collision avoidance in ad hoc networks with directional antennas," in *Proc. IEEE GLOBECOM*, Taipei, Taiwan, Nov. 2002, pp. 112–116.

[28] M. Takata, M. Bandai, and T. Watanabe, "An extended directional MAC for location information staleness in ad hoc networks," in *Proc. 25th IEEE Int. Conf. Distrib. Comput. Syst.*, Columbus, OH, Jun. 2005, pp. 899–905.

[29] D. Shukla, L. Chandran-Wadia, and S. Iyer, "Mitigating the exposed node problem in IEEE 802.11 ad hoc networks," in *Proc. IEEE Int. Conf. Comput. Commun. Netw.*, Dallas, TX, Oct. 2003, pp. 157–162.

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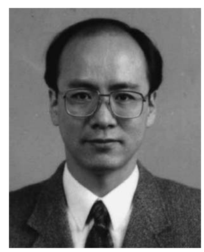

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