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A Location-Assisted MAC Protocol for Multi-hop Wireless Networks

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Abstract— **It has been shown in prior work that when used in multi-hop wireless networks, the 802.11 MAC suffers low throughput performance, especially when the number of hops is large. In this paper, we clarify the relation between exposed node and interference range, and propose a location-assisted MAC protocol that schedules concurrent transmissions in a multi-hop wireless network. In the proposed algorithm, after identifying a node as an exposed node, a simple procedure is executed to validate the concurrent transmission of the exposed node (called scheduled transmission). Based on location information, the scheduled transmission is allowed if the current and scheduled transmitters are out of the interference range of each other's target receiver. Simulation results show that the proposed algorithm can effectively improve the throughput of multi-hop wireless networks.**

I. INTRODUCTION

In this paper, we investigate the problem of improving the throughput of 802.11-based multi-hop wireless networks [1]. We propose to leverage spatial reuse in the multi-hop wireless environment by scheduling more concurrent transmissions. Throughout this paper, we call a transmission that first wins the channel *current transmission*, while a concurrent transmission that is opportunistically scheduled to coexist with the current transmission is termed *scheduled transmission*. The objective is to allow as many scheduled transmissions as possible to achieve an improved network throughput performance.

There is a general *trade-off* between the exposed-terminal and the hidden-terminal: when more exposed nodes are allowed to transmit (thus better spatial reuse), there will be increased chance of collisions in the network (i.e., a more severe hidden terminal problem). For example, when multiple nodes identify themselves as exposed terminals, they may attempt scheduled transmissions simultaneously and cause collisions among themselves. It is therefore important to achieve a balance between improving spatial reuse and increased chances of collisions.

There have been several proposals on improving the throughput of multihop wireless networks by scheduling concurrent transmissions. In [2], Acharya *et al.* proposed a new MAC protocol called MACA-P. A control gap is introduced between the RTS/CTS exchange and the subsequent DATA/ACK exchange, in order to accommodate RTS/CTS exchanges of scheduled transmissions. However, simulation results show that the performance of MACA-P is worse than that of 802.11 when the network is dense. In [9], a power control scheme was proposed to balance the carrier sensing range and the interference range. The authors argued that the situation is optimal when the carrier sensing disk exactly covers the the interference disk. Although providing some interesting insights, through simulations, the authors of [9] found that the improvement in network throughput was modest (see Section V-B and V-C in [9]). In [5], a simple solution is presented for scheduling concurrent transmissions. However, this scheme does not validate the feasibility of scheduled transmissions. If the scheduled receiver is near the current transmitter, the scheduled transmission will be corrupted by the current transmission. In addition, the case of multiple scheduled transmissions is not considered, which may cause collision among themselves. In [8], Ye *et al.* presented an improved virtual carrier sending mechanism, termed Aggressive Virtual Carrier Sensing (AVCS). The basic idea is that a node which overhears only RTS or CTS but not both will not consider the channel as busy. However, AVCS may cause additional collisions among scheduled transmissions or even with the current transmission. An interesting scheme with the same objective of leveraging spatial reuse is presented in [10]. Other than solving the exposed terminal problem, the proposed scheme tunes the physical carrier sensing threshold, such that the enlarged sensing range will cover the entire interference area. As a result, all potentially interfering nodes will be eliminated. This technique is developed under regular network topologies. It is not clear how to adopt this technique in more general topologies or for heterogeneous networks.

In this paper, we present a location-assisted MAC protocol to leverage concurrent transmissions in multi-hop wireless networks. We assume that every node knows its own location, and that nodes exchange location information with their neighbors. We believe that such an assumption is reasonable since GPS is becoming more and more accessible. There is also a rich literature on localization schemes in wireless networks in case GPS service is not available [3]. Specifically, we exploit location information to validate potential scheduled transmissions. A scheduled transmission should not interfere with the ongoing current transmission, and it should not be corrupted by the current transmission. We present a mathematical analysis of the feasible region for scheduled receivers and integrate a condition for the feasible scheduled transmission. Based on this analysis, we develop a protocol that validates and allows feasible scheduled transmissions. Through `ns-2` simulations, we show that the proposed scheme can effectively improve the throughput of multi-hop wireless networks, irrespective of the network topology and the number of nodes.

The remainder of this paper is organized as follows. In Section II, we mathematically derive the feasible region for scheduled receivers. We present a location-assisted MAC protocol for concurrent transmissions in Section III, and our simulations in Section IV. Section V concludes the paper.

II. A Case Study of the Feasible Region for Scheduled Receivers

In this section, we derive the region within which a scheduled transmission can be successfully completed. For simplicity, we assume that homogeneous radios are used, which means that all the transmissions are performed with identical power and all antennas have the identical property.

According to the Two-Ray Ground propagation model, for a transmission, the relation between the transmit power P_t and the received power P_r is as follows [6]:

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d_0^k}, \quad (1)$$

where G_t and G_r are the antenna gains of the transmitter and receiver, respectively; h_t and h_r are the heights of transmitter and receiver, respectively; k represents the path-loss exponent depending on the propagation environment; and d_0 is the distance between the transmitter and the receiver. Let P_i denote the power of an interfering transmission (with a distance R_i) measured at the intended receiver. For successful reception of the message, the receiver's signal-to-interference ratio (SIR) should be greater than a threshold T_{SNR}, i.e.,

$$SIR = \frac{P_r}{P_i} = \frac{P_t G_t G_r \frac{h_t^2 h_r^2}{d_0^k}}{P_t G_t G_r \frac{h_t^2 h_r^2}{R_i^k}} = \left(\frac{R_i}{d_0}\right)^k \geq T_{SNR}. \quad (2)$$

We can see that the transmission of a node located within a distance of $d_0 \sqrt[k]{T_{SNR}}$ from the target receiver, can interfere with the current transmission. Therefore, the interference range is defined as [7]

$$R_i = d_0 \sqrt[k]{T_{SNR}}. \quad (3)$$

Without loss of generality, let the coordinates of the current transmitter, the scheduled transmitter, and the scheduled receiver be $(d, 0)$, $(0, 0)$, and (x, y), respectively. Fig. 1 depicts the locations of these three nodes. Note that we do not show the location of the current receiver in the figure for simplicity. [1] Assume that the scheduled transmission will not interfere with the current transmission (otherwise, it is not be an exposed node). We focus on the location of the scheduled receiver in order to show *when* a scheduled transmission could be allowed.

Based on (3), for the scheduled transmission not being corrupted by the current transmission, the distance between the scheduled receiver and the current transmitter must be greater than a constant number times the distance between the scheduled transmitter and the scheduled receiver. Therefore, 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 $c = \sqrt[k]{T_{SNR}} > 1$. Rearranging the above equation, we obtain

$$\left(x + \frac{d}{c^2-1}\right)^2 + y^2 = \frac{c^2 d^2}{(c^2-1)^2}. \quad (4)$$

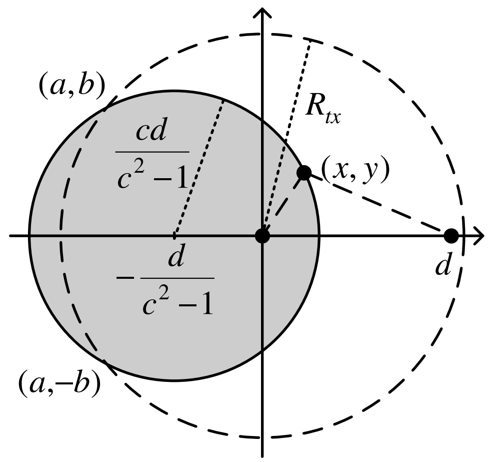


Fig. 1. The feasible region of scheduled receivers.

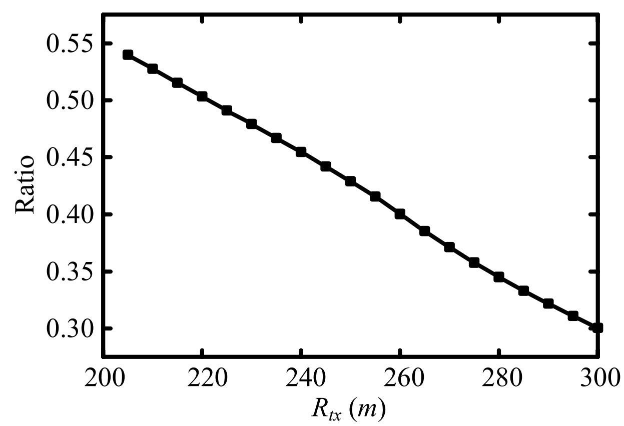


Fig. 2. Impact of network parameters on the feasible ratio ρ: ρ versus R_{tx}, when $d = 200$, $T_{SNR} = 10$, and $k = 4$.

As illustrated in Fig. 1, a scheduled receiver within the shaded disk will not be interfered by the current transmission, according to the SIR constraint (2). On the other hand, the scheduled receiver should also be located within the scheduled transmitter's transmission range in order to correctly receive the frame, i.e., $R_{tx}^2 \geq x^2+y^2$, represented by the dashed circle in Fig. 1. Note that nodes out of the dashed circle cannot decode the scheduled transmission successfully, even if the current transmission is absent. Therefore, the feasible region of the scheduled receiver, A, termed *feasible region*, is finally the overlapped portion of these two disks.

[1] This does not mean that the location of the current receiver is not important. Actually the location of the current receiver is considered in the proposed algorithm as shown in Fig. 5.

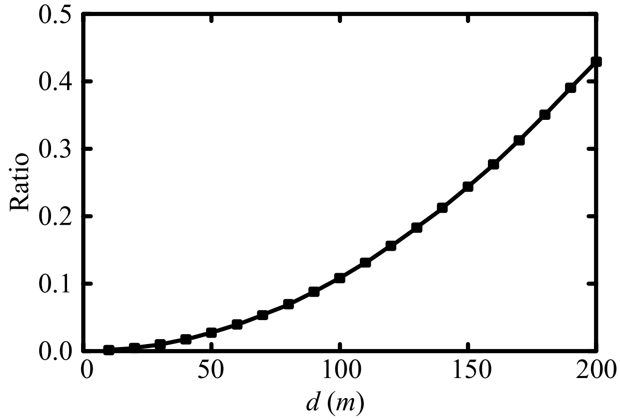


Fig. 3. Impact of network parameters on the feasible ratio ρ: ρ versus d, when $R_{tx} = 250$, $T_{SNR} = 10$, and $k = 4$.

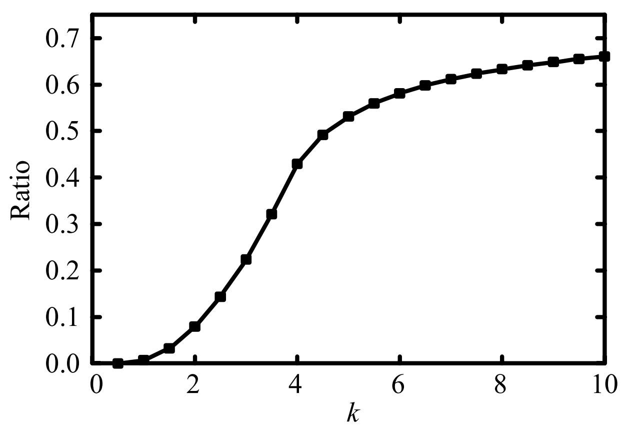


Fig. 4. Impact of network parameters on the feasible ratio ρ: ρ versus k, when $d = 200$, $T_{SNR} = 10$, and $R_{tx} = 250$.

When R_{tx} is larger than or equal to $d/(c-1)$, the transmission range covers the entire feasible region of scheduled receiver (the shaded disk in Fig. 1). Let ρ denote the ratio of the feasible region to the transmission region, termed *feasible ratio*. It follows that

$$\rho = \frac{\pi \frac{c^2 d^2}{(c^2-1)^2}}{\pi R_{tx}^2} = \frac{c^2 d^2}{R_{tx}^2 (c^2-1)^2}, \text{ for } R_{tx} \geq \frac{d}{c-1}. \quad (5)$$

On the other hand, when $d < R_{tx} < d/(c-1)$, the two disks partially overlap with each other. In this case, there exist two intersection points, and their coordinates are (a, b) and $(a, -b)$ (see Fig. 1), where

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

The area of the intersection depends on a. We can derive the expression of A, and thus the feasible ratio ρ as follows:

$$\rho = \begin{cases} \frac{\theta_1}{2\pi} - \frac{\sin\theta_1}{2\pi} + \frac{c^2 d^2}{R_{tx}^2 (c^2-1)^2}\left(1 - \frac{\varphi_1}{2\pi} + \frac{\sin\varphi_1}{2\pi}\right), \\ \qquad \text{for } \frac{\sqrt{c^2+1}}{c^2-1} d \leq R_{tx} < \frac{d}{c-1} \\ \frac{\theta_1}{2\pi} - \frac{\sin\theta_1}{2\pi} + \frac{c^2 d^2}{R_{tx}^2 (c^2-1)^2}\left(\frac{\varphi_2}{2\pi} - \frac{\sin\varphi_2}{2\pi}\right), \\ \qquad \text{for } \frac{d}{\sqrt{c^2-1}} \leq R_{tx} < \frac{\sqrt{c^2+1}}{c^2-1} d \\ 1 - \frac{\theta_2}{2\pi} + \frac{\sin\theta_2}{2\pi} + \frac{c^2 d^2}{R_{tx}^2 (c^2-1)^2}\left(\frac{\varphi_2}{2\pi} - \frac{\sin\varphi_2}{2\pi}\right), \\ \qquad \text{for } d < R_{tx} < \frac{d}{\sqrt{c^2-1}}, \end{cases} \quad (6)$$

where

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

Equations (5) and (6) allow us to evaluate the impact of the network parameters on the feasible region A and the feasible ratio ρ. Generally, the larger A or ρ, the higher the chance of feasible scheduled transmissions. Fig. 2 plots ρ for increased R_{tx}. It can be seen that ρ is a strictly decreasing function of R_{tx}, since larger R_{tx} will cause more severe interference at the scheduled receiver. In order to schedule more concurrent transmissions, it may be desirable to reduce the transmission range (if allowed by the network connectivity requirement). Fig. 3 plots ρ for increased d (i.e., the network gets more sparse). As d gets larger, the feasible region of the scheduled receiver also increases. This result is as expected since the current transmitter plays a role of an interfering node to the scheduled receiver. Therefore, increasing d means that the interfering node becomes further away and the interference becomes smaller. In Fig. 4, we plot ρ for different k. Note that k is a variable depending on the propagation environment. It has a value $k = 2$ in the free space environment, and a larger value in obstacle-rich environments [6]. Larger k means faster decay of signal power, and the interfering node will have a smaller impact on the receiver.

III. The Location-Assisted MAC Protocol

Having examined the relation between the network parameters and the feasible region of scheduled receivers, we proceed to present a location-assisted MAC protocol that schedules feasible scheduled transmissions.

A. Validating a Scheduled Transmission

Generally, when a node overhears an RTS followed by a data frame, it is identified as an exposed node. However, it is not *always* the case that such scheduled transmissions are feasible. For example, if the current transmitter is within the interference range of the scheduled receiver, the scheduled transmission will be corrupted, although it will not cause collision at the current receiver. In 802.11 MAC, exposed nodes are not allowed to initiate a transmission. With the help of location information, we can identify scheduled transmissions that will not cause collision with the current transmission.

Fig. 5 shows the procedure `validate_schdTx()` that evaluates the feasibility of a scheduled transmission. Recall

Procedure validate_schdTx()

calculate d_1 and d_2
estimate R_i^1 and R_i^2
if ($d_1 > R_i^1$ **AND** $d_2 > R_i^2$)
  return 1 *// the scheduled transmission is allowed*
else
  return 0 *// the scheduled transmission is canceled*
endif

Fig. 5. Procedure validating the scheduled transmission.

that the location information of the neighbors is available. In Fig. 5, d_1 is the distance between the scheduled transmitter and the current receiver, while d_2 is the distance between the current transmitter and the scheduled receiver. These can be easily computed from the coordinates of the nodes. R_i^1 and R_i^2 are the interference ranges of the current receiver and the scheduled receiver, respectively. These interference ranges can be estimated using (3). The conditional statement of the procedure in Fig. 5 represents the test to determine whether or not a transmitter is out of the interference range of the other transmitter's target receiver. If this test fails, the scheduled transmission will not be allowed even if a node is identified as an exposed node. Otherwise, a concurrent (scheduled) transmission may be scheduled to improve network throughput.

B. The Distributed Protocol

We now proceed to introduce the distributed location-assisted protocol. The basic operation of this MAC protocol resembles 802.11 MAC. However, by incorporating the validating procedure in Fig. 5, it can schedule concurrent transmissions and thus improve network throughput.

The state-transition diagram of the proposed protocol is given in Fig. 6, where the solid arrows indicate the state transition path of a feasible scheduled transmission. First, based on the frames overheard from the medium, a node may identify itself as an exposed node. Specifically, after receiving an RTS followed by a data frame, the node enters the exposed node state S_{exp}. The node in S_{exp} validates whether a scheduled transmission is feasible. The validation process consists of the following two steps: (i) determine whether or not the scheduled transmission will collide with the current transmission by running procedure `validate_schdTx()` as shown in Fig. 5; (ii) determine whether or not the scheduled data frame can be fitted into the transmission period of the current data frame. A scheduled transmission will be allowed if and only if both conditions are satisfied. If that is the case, the scheduled data frame will be transmitted, and the loop is closed when the scheduled receiver returns an ACK to the scheduled transmitter.

The starting time of a feasible scheduled transmission is computed as follows: First, as shown in Fig. 8, the value of

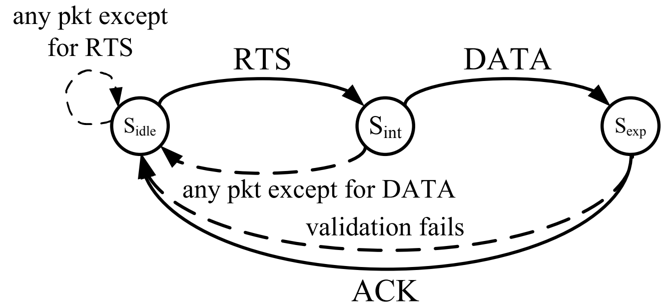


Fig. 6. State-transition diagram of the proposed protocol, where there are three states: (i) the initial state S_{idle}, (ii) the intermediate state S_{int}, and (iii) the exposed node state S_{exp}.

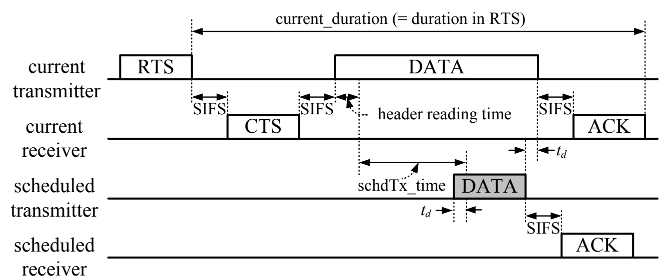
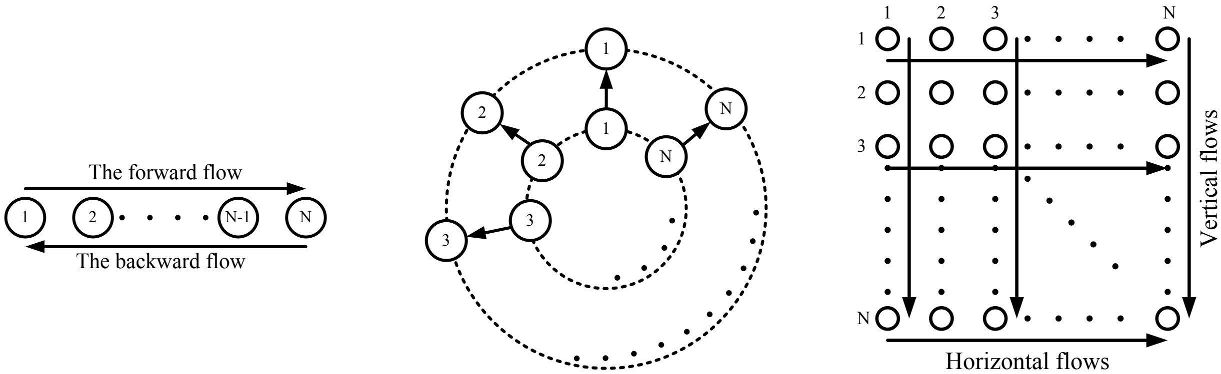


Fig. 8. A time-line illustration for the operation of the proposed protocol.

schdTx_time is computed as:

$$\begin{aligned}\text{schdTx\_time} = {} & \text{current\_duration} - \text{SIFS} - \text{CTS} - \text{SIFS} - \\ & \text{header reading time} - \text{scheduled data duration} - \\ & \text{SIFS} - \text{ACK} - \text{round-trip propagation delay}. \end{aligned} \tag{7}$$

Besides, a random value t_d is generated which is uniformly distributed within [0, SIFS/2]. If schdTx_time is smaller than t_d, the scheduled transmission cannot be fitted into the current data transmission period, and it will not be scheduled. Otherwise, the scheduled data frame is transmitted after reading the current data frame header, and after an additional delay of (schdTx_time - t_d). Note that the random delay (schdTx_time - t_d) is introduced to avoid the case of multiple scheduled transmissions. In a dense network, for the same current transmission, there could be multiple nodes identifying themselves as exposed nodes and each tries a scheduled transmission simultaneously. There may be collision among the scheduled transmissions. With the random delay, a scheduled transmitter will cancel its scheduled transmission (even if it is feasible) when it overhears another scheduled transmission in the neighborhood. Finally, 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 (i.e., it should be ready for receiving), since otherwise the scheduled transmitter should have overheard a CTS from the scheduled receiver (since it is only one-hop away) in response for an earlier RTS from some other transmitter.



(a) Chain topology (b) Double ring topology (c) Grid topology

Fig. 7. The network topologies used in the simulations.

IV. Simulation Studies

In order to validate the feasibility and quantify the performance gain achievable by the proposed scheme, we implemented the location-assisted MAC protocol using `ns-2.30`. In addition to the proposed algorithm, a simple mechanism was also implemented to distribute location information. In our implementation, each node maintains a table storing location information of its own and those sent by its one-hop neighbors. The RTS frame is modified to piggyback the locations of the sender itself (i.e., the current transmitter) and its target receiver. When a node overhears an RTS, it can extract the locations of the current transmitter and receiver for validating its scheduled transmission.

The first simulation study is performed with the chain network (shown in Fig. 7(a)), where the distance between any two adjacent nodes is set to 200 m. Throughout this section, the antenna parameters are set to the default values in `ns-2.30`, i.e., $R_{tx} = 250$ m and $R_{cs} = 550$ m. The channel rate is set to 1 Mb/s. In the simulations, the forward flow (from Node 1 to Node N) transmits a CBR traffic of 1000-byte packets, while the backward flow (from Node N to Node 1) transmits a CBR traffic of 700-byte packets. In each simulation run, the two flows start at $t = 10$ second and last for about 15 minutes. Each simulation is repeated five times. The throughput is obtained by averaging the results of five trials. We focus on the number of bytes successfully transmitted at the "agent" level (i.e., end-to-end throughput rather than one-hop throughput) during the simulations.

The simulation results for the chain networks are plotted in Fig. 9. Here the data rates of the flows for the 6-, 8-, 10-, and 12-node chain networks are set to 100Kb/s, 75Kb/s, 75Kb/s, and 75Kb/s, respectively. These parameters are chosen according to the simulation results presented in [4]. When the number of hops is equal to 8, the throughput of 802.11 MAC is 11,063,100 Bytes and the throughput of the proposed protocol is 16,631,880 Bytes. Then, the *normalized improvement*, defined as

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

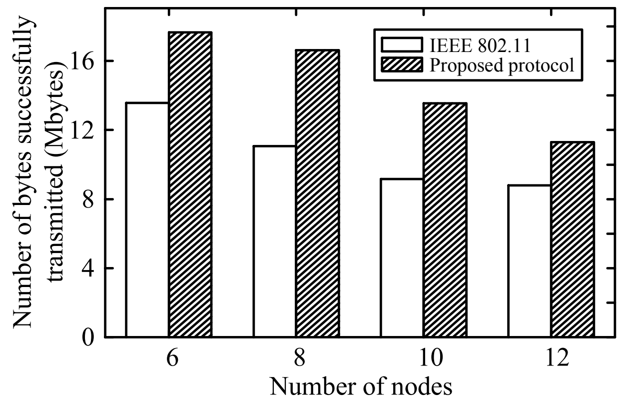


Fig. 9. Number of bytes successfully transmitted over the 15-minute interval: chain networks.

is 50.34%. For the 6-, 10-, and 12-node chain network, the normalized improvements achieved by the proposed scheme are found to be 29.99%, 48.18%, and 28.37%, respectively. It has been shown that when used for multi-hop wireless networks, our scheme achieves considerable throughput gains irrespective of the chain length.

Next, we present the simulation results for a specific double ring networks, where nodes are aligned along two circles with the same center (shown in Fig. 7(b)). The distance between two adjacent nodes in the inner ring is set to 200m. Then, the radius of the inner ring is equal to $200/\sqrt{2\left(1-\cos(\frac{2\pi}{N})\right)}$ m 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 200m. On the other hand, the radius of the outer ring is 100 m larger than that of the inner ring. 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, and all the outer-ring nodes are one-hop receivers. As in the simulations for the chain topology, all flows start at 10 second and each simulation lasts for 15 minutes. Fig. 10 shows the number of bytes successfully transmitted for both 802.11 and the proposed scheme. The proposed scheme achieves considerable throughput improvements in all cases, which are

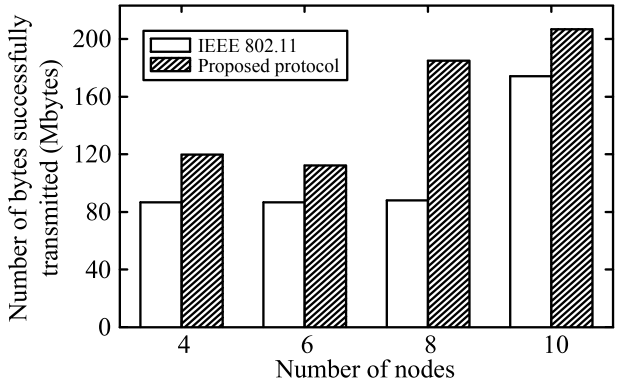


Fig. 10. Number of bytes successfully transmitted over the 15-minute interval: double ring networks.

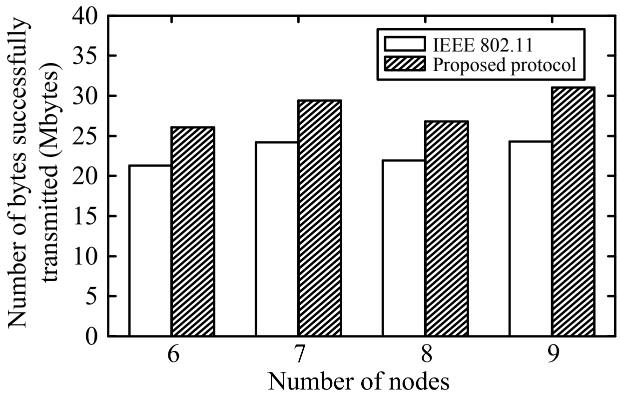


Fig. 11. Number of bytes successfully transmitted over the 15-minute interval: grid networks.

38.13%, 29.65%, 110.18%, and 18.66%, respectively.

Finally, we perform simulation studies using the more general grid network topology (shown in Fig. 7(c)). In a grid network, nodes are evenly placed in a square region while the distance between any two adjacent nodes is 200 m. There are two types of flows: (i) vertical flow from a top node to the corresponding bottom node, and (ii) horizontal flows from a leftmost node to the corresponding rightmost node. Odd indexed top nodes and odd indexed leftmost nodes are selected as sources. For example, in the 64-node grid network, the 1st, 3rd, 5th, and 7th nodes in the first row are the sources for vertical flows, while the 1st, 3rd, 5th, and 7th nodes in the first column are sources for horizontal flows. During the simulations, vertical flows transmit 700-byte packets, while horizontal flows transmit 1000-byte packets. The data rates are set depending on the size of the networks as follows [4]: 100Kb/s for the 36-node grid network, 50Kb/s for the 49- and 64-node grid network, and 30Kb/s for the 81-node grid network. As in the previous simulation studies, all flows start at 10 second and each simulation lasts for 15 minutes.

Fig. 11 shows the number of bytes successfully transmitted for both 802.11 and the proposed scheme. According to Fig. 11, the throughput improvements achieved by the proposed scheme are 22%, 22%, 22%, and 27% for the 36-, 49-, 84-, and 81-node grid networks, respectively. Clearly, our proposed scheme can effectively improve the performance of multihop wireless networks.

V. Conclusion

In this paper, we study the problem of improving the throughput of 802.11-based multi-hop wireless networks. We first clarified the relation between the exposed node and the interference range, which yields the feasible condition for scheduled receivers. Based on this analysis, we proposed a location-assisted MAC protocol, which enhances 802.11 MAC protocol by exploiting location information. Our `ns-2` simulation results showed that the proposed scheme can effectively improve the throughput performance of multi-hop wireless networks.

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