An Improved Contention Access Mechanism for FPRP to Increase Throughput

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Five-phase reservation protocol (FPRP) is a contention-based media access control protocol for wireless ad hoc networks. FPRP uses a five-phase reservation process to establish slot assignments based on time division multiple access. It allows a node to reserve only one slot in an information frame. Once a node has reserved a slot, it will cease contending for other slots. As a result, there may be less contending nodes in the remaining slots, so the time slots in an information frame are not fully used by FPRP. To improve time slot utilization, this paper proposes an improved pseudo-Bayesian algorithm, based on which an improved contention access mechanism for FPRP is proposed, in which nodes are allowed to contend for more than one slot in a reservation frame according to a certain probability/priority. Simulation results indicate that the proposed mechanism performs better than FPRP in time slot utilization and hence the network throughput under various scenarios.

Keywords: Ad hoc network, media access control (MAC) protocol, five-phase reservation protocol (FPRP), contention slot.

I. Introduction

A mobile ad hoc network (MANET) consists of a number of mobile terminals connected with wireless links and is independent from any fixed infrastructure [1]. MANETs can be established quickly and moved flexibly and therefore have wide applications in various types of communication, such as military and emergency. The media access control (MAC) protocol, which provides channel access control mechanisms to coordinate multiple nodes in a network, is an important part of ad hoc networks. To date, many time division multiple access (TDMA)-based MAC protocols have been proposed. There are reservation-based protocols, such as the five-phase reservation protocol (FPRP) [2], [3] and the hop reservation multiple access (HRMA) [4] protocol. In addition, there are contention-based protocols, such as the carrier sense multiple access with collision avoidance (CSMA/CA) [5] and the IEEE 802.11 distributed coordination function (DCF) [6]. Finally, there are hybrid protocols, such as TDMA/CSMA protocols [7], based on both contention and reservation.

The reservation-based TDMA protocols assign each node one or more TDMA slots to access the channel. Such protocols have many advantages, such as conflict-free, controllable maximum transmission delay, and high spatial reuse efficiency [1]. The reservation-based TDMA protocols can be classified into two categories: fixed allocation and dynamic allocation. Fixed allocation protocols make slot assignments at the scale of the whole network. They do not have the conflict problem but are not suitable for networks with dynamically changing topologies. In contrast, dynamic allocation protocols, such as FPRP [2], [3], HRMA [4], evolutionary-TDMA (E-TDMA) [8], and DRAND [9], use distributed algorithms to assign slots by coordinating nearby nodes. They can be used for networks

with dynamic topologies.

FPRP is a fully-distributed protocol with a low probability of conflict. Using dynamic slot assignments, FPRP has many advantages, such as being scalable with the network size, suitable for changing topology, and insensitive to node mobility. These merits make FPRP a very promising MAC layer protocol for MANETs [10].

FPRP was initially proposed in [2], [3]. Since then, several works have tried to improve FPRP in different ways. In [8], the authors proposed an E-TDMA scheduling protocol as an enhanced version of the FPRP. It uses two topology-dependent schedulers to enable conflict-free transmissions and support traffic prioritization. A slot assignment algorithm was proposed in [11] to swap reservation cycles (RCs) and reservation slots (RSs) in the FPRP frame. In this algorithm, nodes compete for different time slots in a reservation cycle, making the number of transmission nodes in each slot nearly equal. In [12], the authors modified the reservation mechanism to take into account different levels of urgency of the traffic. After the slot reservation cycle is completed, every node will maintain a table of slot assignments, which specifies which slots have been acquired by neighbor nodes. When the next reservation cycle starts, all nodes will contend for slots based on the prior information in the table, thereby improving the spatial channel utilization. An improved FPRP algorithm was proposed in [13], in which nodes use different initial probabilities for contention, according to different traffic loads. In this improved FPRP, the node that receives the collision report will check the report to decide whether it should continue to contend or stop immediately. Other improvements to FPRP were proposed in [10] to modify the frame structure, that is, an RS only contains one reservation and the five-phase reservation is changed to three phases. A new delay-sensitive, energy-efficient, fault-tolerant distributed time slot assignment algorithm was proposed in [14] for wireless sensor networks to assign slots using tiny request slots. This protocol uses a contention algorithm similar to FPRP and allows the assignment of the same slots to the nodes within a two-hop region. Several papers have considered cross-layer designs between routing protocols and FPRP [15], [16].

Although [8], [10]-[16] improved certain performance aspects of FPRP, time slot utilization was not improved. In FPRP, once a node has acquired a slot, it will stop contending for other slots. Therefore, there are fewer nodes contending for and utilizing the remaining slots, resulting in low slot utilization in FPRP.

This paper introduces a novel slot assignment method, which allows nodes to contend for more slots with a reasonable probability. The contributions of this paper are summarized as follows. First, an improved contention access mechanism for FPRP based on a pseudo-Bayesian broadcast algorithm is proposed. The slot utilization performance of the proposed protocol is validated via theoretical analysis and simulation results. Second, a novel simulation methodology is adopted to eliminate the artificial "boundary effect" of MANETs and obtain more accurate performance assessments. Third, the key strength of the proposed protocol is improved slot utilization. We go beyond this single metric and address other performance aspects, such as protocol parameter optimization, reservation cycles, and contention fairness, to give a full picture of the pros and cons of the proposed protocol. Our results show that the proposed contention access mechanism can achieve solid performance gains compared with the original FPRP.

The remainder of this paper is structured as follows. In section II, we briefly describe the FPRP protocol and illustrate its unsatisfactory performance in terms of slot utilization. An improved FPRP (I-FPRP) protocol applying the pseudo-Bayesian broadcast algorithm is subsequently proposed and theoretically analyzed in section III. In section IV, we investigate various performance metrics in detail and critically study the pros and cons of FPRP and I-FPRP via simulation results. Finally, conclusions are drawn in section V.

II. Slot Utilization Performance of FPRP

The frame structure of the FPRP protocol is shown in Fig. 1 [2], in which a reservation frame (RF) is followed by a sequence of information frames (IFs). There are N RSs and N information slots (ISs) in every RF and IF, respectively. An RS is composed of M RCs, each of which consists of a five-phase dialogue. If a node wants to reserve an IS, it contends in the RS. A slot is reserved in the RF and used in each IF until the next RF arrives to initiate the next round of reservation.

In FPRP, a node that wants to make a reservation will first send a reservation request (RR) packet with probability p to its neighbors. In the second phase, nodes that receive more than
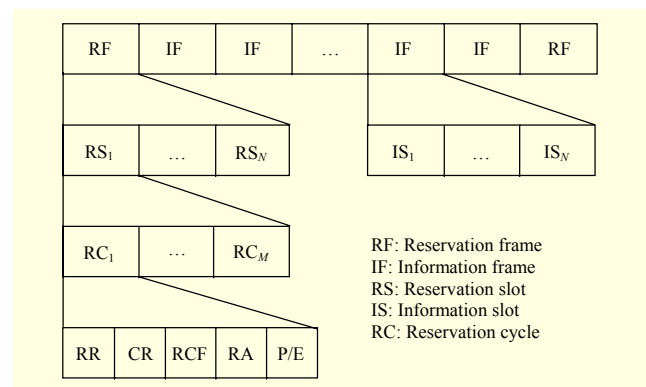

Fig. 1. Frame structure of FPRP [1].

one RR packet will respond with a collision report (CR) or otherwise be silent. This phase is designed to solve the well-known hidden terminal problem. If a node has sent an RR and receives nothing, it will broadcast a reservation confirmation (RCF) packet in phase three. In the next phase, all neighbors will send a reservation acknowledgment (RA) packet to confirm the reservation and inform nodes that are two hops away. Two types of packets are used in the fifth phase: the packing packet (PP) is sent by the nodes two hops away from the reservation node to inform nodes that are three hops away, and the elimination packet (EP) is sent with a probability of 0.5 to resolve a nonisolated deadlock (when there are two transmission nodes within one hop, and they cannot detect each other until one EP is received from one to the other). Further, nodes can always detect that they receive zero, one (success), or more (collision) packets, so they are aware of the success or failure events in each phase of FPRP.

A modified pseudo-Bayesian algorithm is chosen to compute the contention probability p in the RR phase. In a multihop pseudo-Bayesian algorithm, a node needs to keep two estimated values: one is the number of nodes n_c that contend within two hops; the other is the number of nodes n_b within two hops that need reservations but cannot contend in the current slot due to a nearby successful reservation. Some heuristic constants are used to capture the effect of a reservation success on the behavior of the nearby contenders. Specifically, for nodes that are one hop away from the success node, a portion (R_1) of its neighboring contenders ceases to contend in the current slot. Similarly, for nodes that are two and three hops away from the success node, this portion is R_2 and R_3, respectively. The multihop pseudo-Bayesian algorithm was derived in [2], [3].

The original FPRP protocol has the drawback of low slot utilization. This is because most nodes contend for slots at the beginning. However, once a node has reserved a slot, it will stop contending for slots, resulting in gradually decreasing slot utilization in the remaining slots.

Figure 2 shows the average number of transmission nodes in each slot for the FPRP protocol while the total number of nodes N varies from 100 to 400. The result is averaged over 200 random simulation runs, and the simulation settings are detailed in section IV. Figure 2 clearly shows a gradual reduction in the number of transmission nodes in the slots at the end of the frame.

The reason for such low slot utilization in FPRP is that FPRP assigns every node with only one slot even under saturated traffic conditions, which means that successive nodes are not able to utilize the remaining slots even when these slots are significantly underutilized. Intuitively, if nodes are allowed to contend for more than one slot, the underutilized slots can be
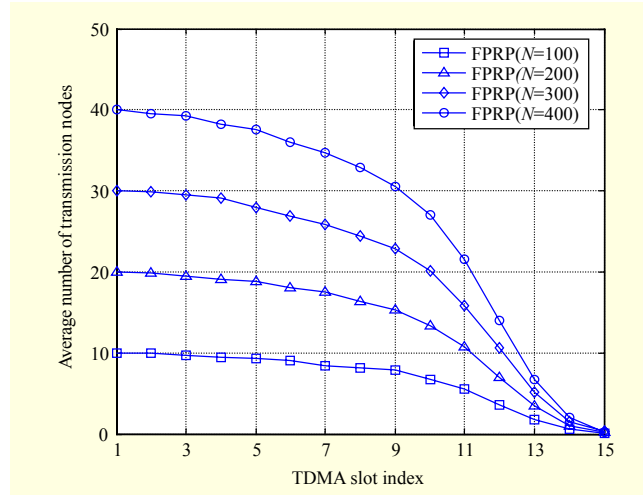

Fig. 2. Average number of transmission nodes in each slot (frame size=15 slots; RC number=15; transmission range of node R=1.5 units; number of nodes: N; traffic load: saturation).

better exploited and the overall slot utilization will be increased accordingly. Furthermore, a careful design of nodes' contention priorities for more slots can be used to support different traffic types and demands.

To improve time slot utilization, we propose an improved contention mechanism for FPRP to allow the nodes to acquire two slots. The new mechanism keeps estimation about the number of nodes (within two hops) that contend for the second slot. Since every node can hear any successful reservation within two hops, nodes can know the number of slots reserved by other nodes within two hops. Hence, they can calculate the new contention probability based on an improved contention mechanism, which will be proposed in the next section.

III. Improved Contention Access Mechanism

In the improved contention mechanism, because nodes are allowed to contend for two slots, a node that has reserved a slot will continue to contend at the next slot with a reasonable probability until it gets two slots. Therefore, it will still update the number of contending nodes by detecting if there is an "idle," "success," or "collision" event. Clearly, the estimated number of contention nodes in the next slot will be different from that in FPRP due to the influence of second-round contention nodes. In what follows, we will first present the new contention algorithm in I-FPRP and then describe its reasonableness.

In I-FPRP, nodes are allowed to contend for two slots with certain probabilities. We assume that the number of contending nodes for the second slot follows a Poisson distribution with mean λ. The reason underlying this assumption is to set the contention probability to be proportional to the density of
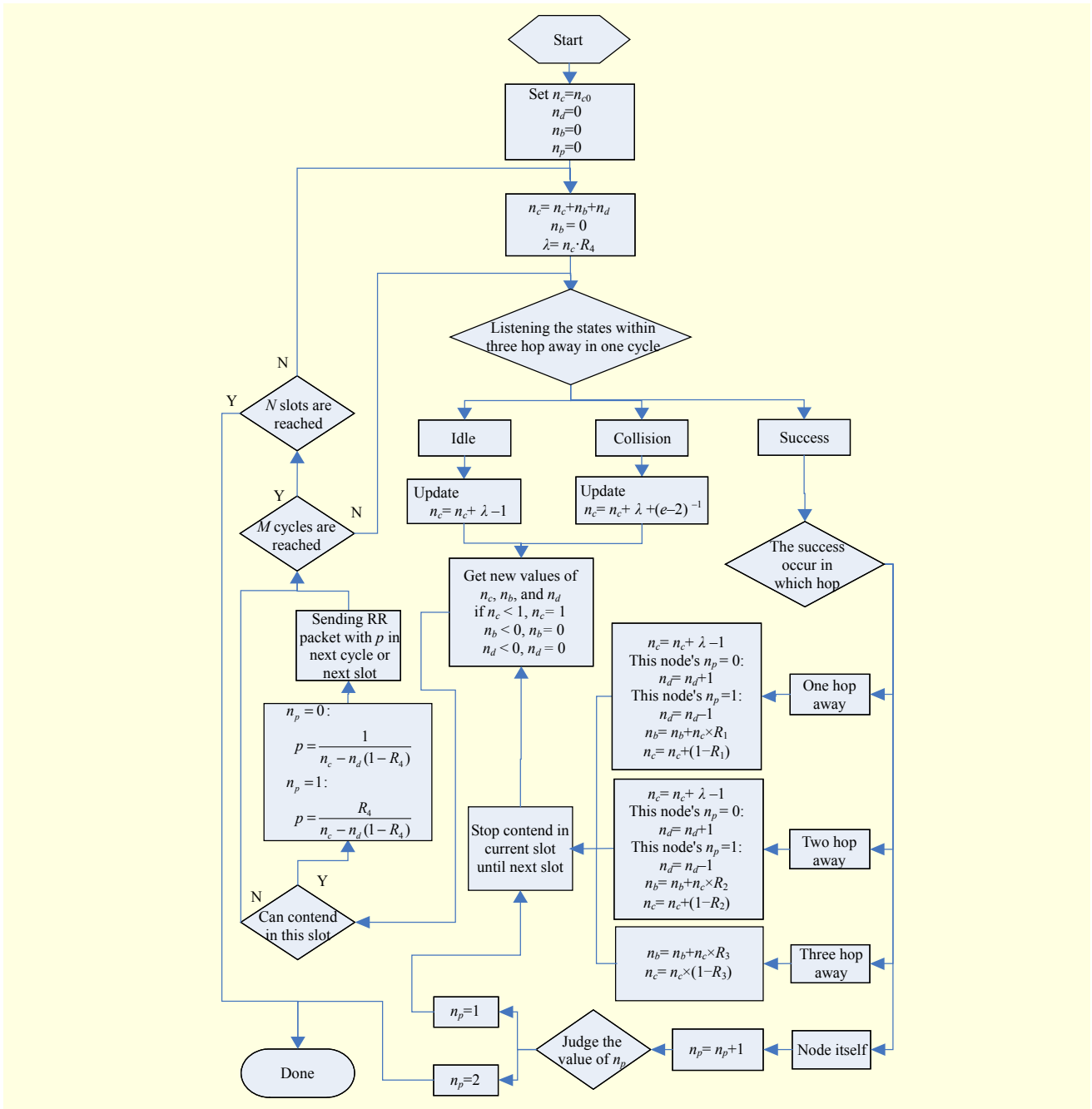
Fig. 3. New contention algorithm.

Poisson-type traffics. When nodes are allowed to contend for the second slot, it will affect n_c (the number of nodes that contend within two hops) and n_b (the number of nodes within two hops which need reservations). Considering fairness, the probability of nodes contending for the second slot should be less than nodes contending for the first slot. The new update of the estimation of the reservation probability should therefore be different to fulfill Bayesian's rule.

The procedure of the proposed I-FPRP algorithm is as follows (n_p denotes the number of slots that a node has

acquired):

In I-FPRP, a node should follow three estimations: n_c, n_b, and n_d, where n_c and n_b stand for the same values they do in FPRP. The third estimation n_d denotes the number of nodes that contend for the second slot within two hops. In addition, a protocol parameter R_4 as an additional weight on n_d is used to minimize the impact the nodes that contend for the second slot have on other contention nodes. As a result, each node can contend for slots with a reasonable probability/priority. In particular, $\hat{\lambda} = n_d \cdot R_4$ is the estimation of λ, and we can simply

regard that $\lambda = n_d \cdot R_4$.

As shown in Fig. 3, the update of the contention nodes number is added by λ after detecting an idle, success, or collision event. Nodes that contend for the second slot will then use a different probability. Obviously, the new mechanism allows nodes that had been assigned one slot to get another chance to apply for the second slot according to their traffic demands, leading to significantly increased slot utilization in the remaining slots.

We will subsequently explain the design principles underlying the above-proposed I-FPRP. In particular, we focus on explaining how λ, the parameter describing the contention probability for the second slot, is used for the updates of n_c. The key of our protocol design lies in a thorough understanding of the pseudo-Bayesian algorithm.

The multihop pseudo-Bayesian algorithm used in FPRP is modified from the (single-hop) pseudo-Bayesian broadcast algorithm [2], [3]. The original pseudo-Bayesian algorithm only performs well in single-hop ALOHA networks, whereas the multihop pseudo-Bayesian extends itself to multihop networks to obtain efficient estimation on the number of contention nodes within two hops. Following a similar procedure, we will first analyze the improved mechanism in single-hop networks and further extend it to multihop networks.

We define three states in the network: an idle state if there is no node transmitting, a success state if there is one node transmitting, and a collision state if there is more than one node transmitting. The pseudo-Bayesian algorithm assumes that the number of contention nodes during a slot can be approximated by a Poisson distribution with mean v. Moreover, each node keeps v as the best estimation for the number of contention nodes and broadcasts with probability $p=1/v$. Then, v is updated as follows [17]:

1) If a collision is detected in the current slot, then

$$v = v + (e - 2)^{-1}. \tag{1}$$

2) If an idle state or success state is detected, then
$$v = v - 1. \tag{2}$$

3) If other noncontention nodes in the current slot become contention nodes according to a Poisson distribution with parameter λ, then $v = v + \lambda$.

If we assume the second-round contention nodes to be new contention nodes appearing following a Poisson distribution with mean λ, then the new estimation on the number of contention nodes is given by the following theorem.

Theorem: Improved Pseudo-Bayesian Algorithm. In the network model explained above, when the number of nodes contending for the second slot is described by a Poisson distribution with parameter λ, the update of v after an idle, success, or collision state is as follows:

1) Collision:

$$v = v + \lambda + (e - 2)^{-1}. \tag{3}$$

2) Idle or success:

$$v = v + \lambda - 1. \tag{4}$$

This conclusion is proven in the Appendix. Although this conclusion is derived from single-hop networks, it can be directly extended to multihop networks following the design principles of FPRP [2], [3]. Based on pseudo-Bayesian and multihop pseudo-Bayesian theory in FPRP, the conclusion can be extended to the new contention mechanism in I-FPRP. Here, we use $\lambda = n_d \cdot R_4$ as the estimation of λ so that nodes can adopt different probabilities to contend for slots. The contention probabilities are given by

$$p = \begin{cases} \dfrac{1}{n_c - n_d(1 - R_4)} & n_p = 0, \\[3mm] \dfrac{R_4}{n_c - n_d(1 - R_4)} & n_p = 1. \end{cases} \tag{5}$$

Additionally,

$$(n_c - n_d) \cdot \frac{1}{n_c - n_d(1 - R_4)} + n_d \cdot \frac{R_4}{n_c - n_d(1 - R_4)} = 1. \tag{6}$$

Here, the total number of contention nodes is n_c and the number of nodes contending for the second slot is n_d. When $n_d=0$ and $R_4=0$, then $p=1/n_c$, which means that all nodes within two hops will contend for slots with the same p. Otherwise, the contention nodes will be separated into two portions: one is the first-round contention nodes with p_1; the other is the second-round contention nodes with $p_2 (p_2 < p_1)$. Formula (6) shows that the aggregated probabilities of all nodes are equal to one, theoretically validating the correctness of our derivation.

IV. Simulation Results

In this section, the respective performances of FPRP and the proposed I-FPRP are simulated and compared. A new simulation methodology is adopted to eliminate the artificial "boundary effect" that occurs in simulations of finite-sized networks. The performance of the protocols will be investigated from various aspects by changing the network parameters and protocol parameters.

1. Simulation Methodology

We consider $M \times M$ nodes randomly distributed in a square region consisting of $M \times M$ uniform grids. Each node is associated with one (small) grid and uniformly distributed within the grid. To eliminate the boundary effect, we only
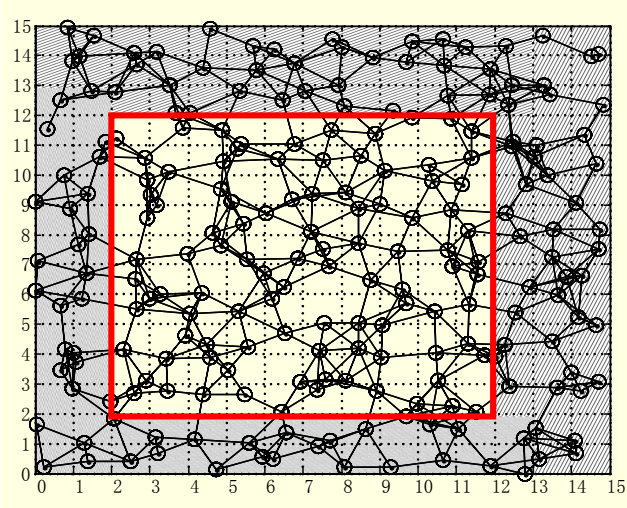
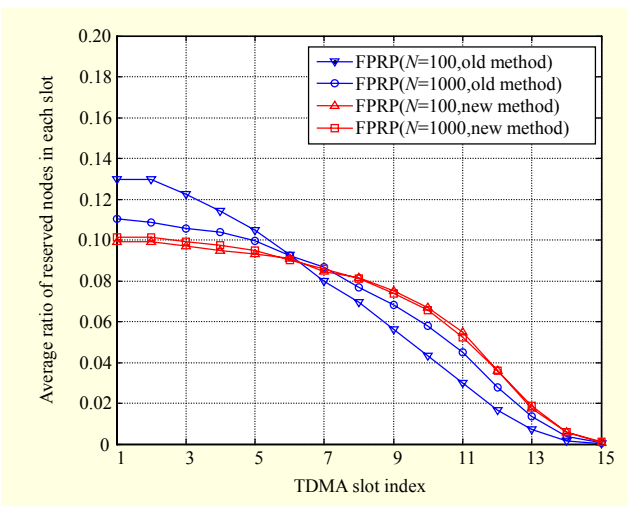Fig. 4. Illustration of new statistical method for simulation.

Fig. 5. FPRP slot utilization performance obtained by different simulation methodologies (frame size= 15 slots; transmission range of node R=1.5; R_4=0.1; packet arrival rate λ=5).

select a subset N ($N<M^2$) of nodes in the middle area as valid nodes to yield our simulation results.

As shown in Fig. 4, a 15×15 region area is used to run the simulation, while only the middle 10×10 nodes' network is used to produce the simulation results. Otherwise, nodes located near the edge have fewer nearby nodes to contend with, resulting in a statistical bias that could distort the real performance of the network. We note that such a boundary effect is more significant in smaller-sized networks.

In Fig. 5, boundary effects can lead to significantly different performance results in a small network with 100 nodes. When the network size increases to 1,000 nodes (with the same node density), the portion of nodes located at the edge will reduce, the boundary effect diminishing accordingly. Our simulation

Table 1. Key parameters in simulation.

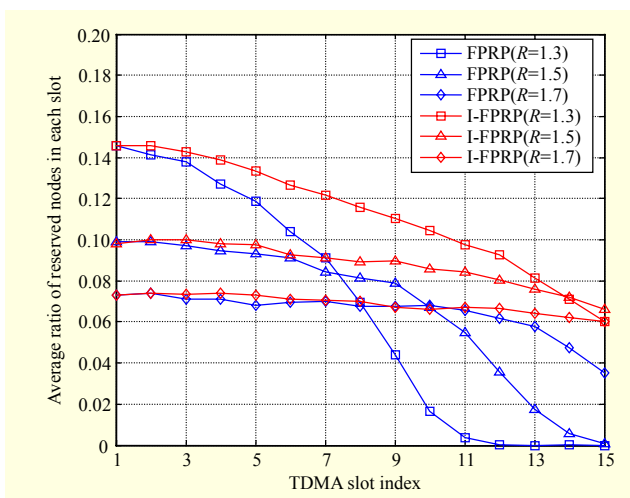| Parameters	Value
Location of nodes	Randomly distributed
Number of nodes	N=100
Scale of network	$M \times M$ (M=15)
Transmission range	R=1.5 units (about 1 km)
Constant parameters	R_1=0.8, R_2=0.6, R_3=0.33
Number of RC per RS	15
FPRP cycle time	200 μs
Simulation times	300 times

Fig. 6. Average ratio of reserved nodes in each slot (frame size= 15 slots; R_4=0.1; packet arrival rate λ=5).

methodology is able to eliminate the network-size-dependent boundary effects and accurately capture the performance of large-scale networks.

Without further specification, the key parameter values used in our simulation are given in Table 1.

2. Slot Utilization Performance

Compared with FPRP, the main benefit of the proposed I-FPRP is its ability to increase slot utilization and hence the network throughput.

Under the assumption of high traffic load (that is, high relative packet arrival rate), Fig. 6 compares the average ratio of reserved nodes in each slot for FPRP and I-FPRP when the transmission range varies from 1.3 to 1.7. It shows that in FPRP, the remaining slots are not fully utilized. In contrast, I-FPRP can better use the idle slots. A careful observation further reveals that the performance gain is more significant when the transmission range is smaller. We note that reducing the

transmission range will have the same effects on network topology as decreasing the spatial node density. We therefore conclude from Fig. 6 that I-FPRP is more desirable for sparse and power-constrained ad hoc networks.

For the case in which nodes are designed to contend for slots according to packet arrival rate, the average number of reserved slots for each node under a varying traffic load is presented in Fig. 7. Here, the packets of each node arrive according to a Poisson distribution with mean λ. It is assumed that a node will contend for two slots only when it has two or more packets. Figure 7 investigates the relationship between the traffic load and number of reserved slots in each node. The average number of reserved slots per node indicates the average throughput per node. When the traffic loads are relatively small, the throughput increases almost linearly with the traffic loads. At high traffic loads ($\lambda \geq 4$), the throughput saturates at certain values due to the increased levels of contention. The maximum achievable throughput under traffic saturation is related to the transmission range R and the protocol parameter R_4. Increasing R or equivalently increasing the spatial node density leads to increased contention probability and hence lower throughput. On the other hand, when the value of R_4 increases, the maximum achievable throughput increase initially and eventually decreases. This suggests the existence of an optimum value for R_4.

In Fig. 8, we further investigate the performance of I-FPRP with varying frame size. The frame size is the number of slots in one frame (that is, the total number of RSs). Because nodes in two hops cannot reuse the same slot, the frame size is typically chosen to accommodate a certain number of contention nodes within two hops with an acceptable outage probability. In Fig. 8, the case that $R_4=0$ is equivalent to the original FPRP, where each node contends for only one slot in a frame. Therefore, the reserved number of slots will not increase beyond one even when there are available slots. When R_4 increases, nodes have increasing chances to contend for a second slot; therefore, the average reserved slots per node increases. Clearly, the proposed I-FPRP shows a significant improvement on slot utilization when the frame size is relatively large.

Both Figs. 7 and 8 indicate that R_4, the second contention ratio, has significant impacts on the slot utilization performance. More importantly, the value of R_4 should be carefully chosen to optimize the overall performance. On one hand, the slot utilization performance suffers from too small values of R_4 because most nodes are prohibited to contend for the second slots. On the other hand, the performance also suffers from too large values of R_4 due to increased probabilities of contentions.

In Fig. 9, we show the slot utilization performance as a function of R_4 under varying network conditions such as the
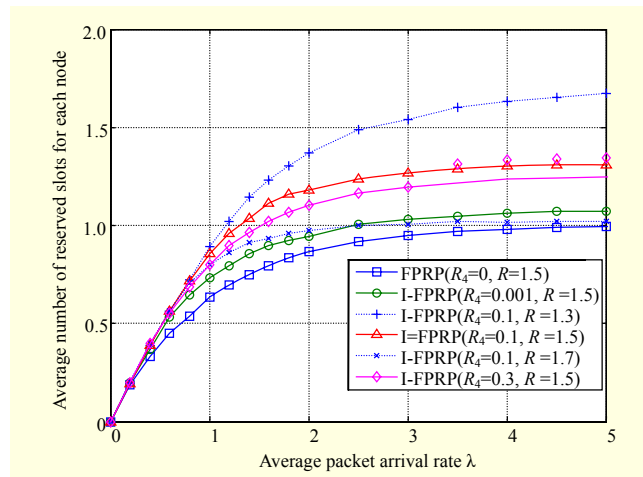

Fig. 7. Average number of reserved slots for each node with varying packet arrival rates (frame size: 15 slots).
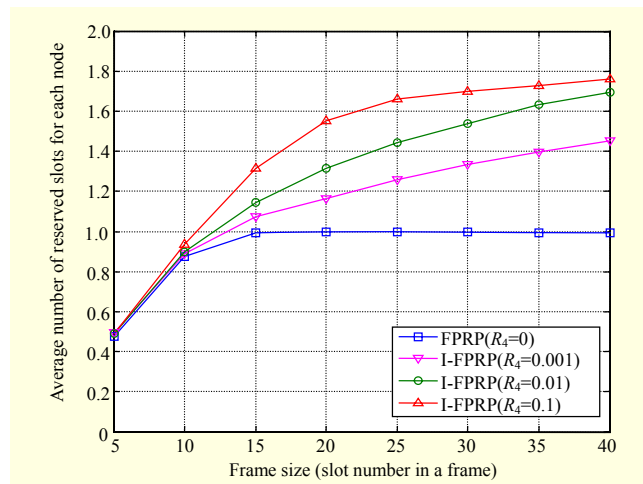

Fig. 8. Average number of reserved slots for each node with different frame size ($R=1.5$; $\lambda=5$).

traffic load λ and transmission range R. We note that increasing R can be understood as increasing the spatial node density. Interestingly, in all the simulations we performed, the optimum value of R_4 is found to be concentrated around 0.1. These initial results suggest that the optimum value of R_4 is insensitive to the network conditions (that is, traffic load, node density, and transmission range). An in-depth investigation on the optimum value of R_4 is expected to be our future work.

3. Overhead and Fairness

The advantages of I-FPRP over FPRP in terms of throughput or slot utilization have been clearly demonstrated through Figs. 6 to 9. However, I-FPTP also brings some potential drawbacks. The first concern is on the number of reservation cycles, that is, the signaling overhead used for time slot reservation. The
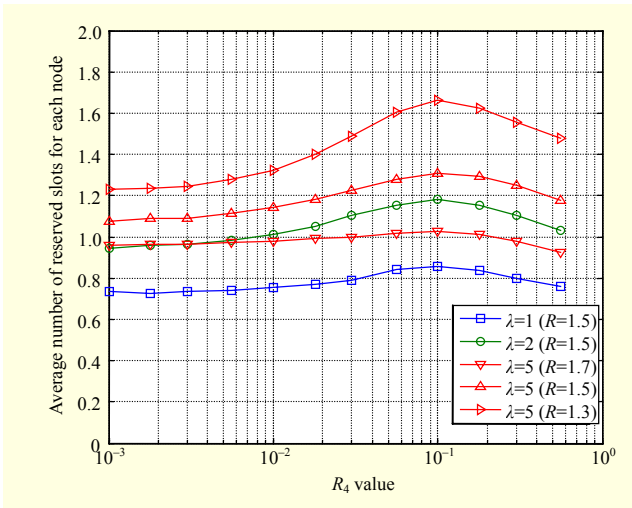
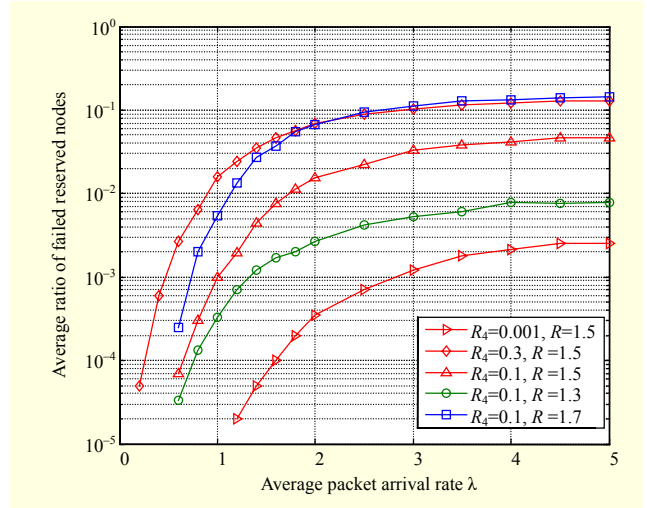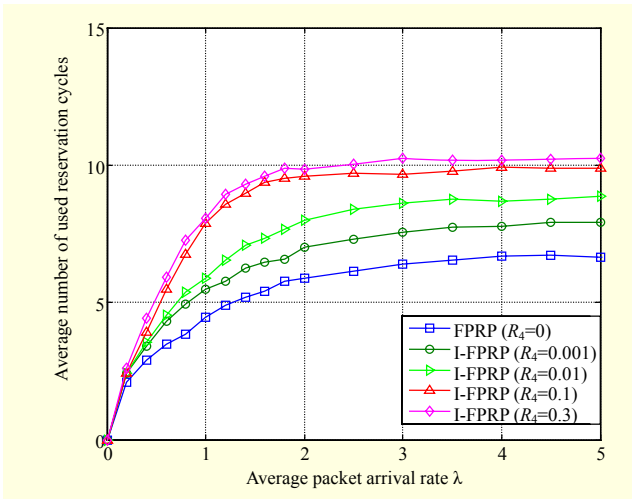Fig. 9. Average number of reserved slots for each node with varying R_4 values (frame size: 15 slots).

Fig. 10. Average ratio of used RC number for one succeed reservation with varying packet arrival rates (frame size: 15; R=1.5).

I-FPRP adds extra reserved cycles in the remaining slots. Because nodes can contend for the second slot, with the increase of R_4, the reservation cycles will increase as a logarithm function. Although extra reserved cycles do not lead to increased time delay because the RF frame includes a constant RC number in each slot, they do result in more power consumption.

Figure 10 shows that I-FPRP has slightly more reserved cycles than FPRP. Under saturated traffic conditions and when R_4 is chosen to be the optimum value, a less than twofold increase on the number of reservation cycles is observed. However, because the reservation cycles are typically very short compared with the data transmission cycles, the increased power consumption is expected to be insignificant. We also

Fig. 11. Average ratio of failed reservation nodes with varying packet arrival rates (frame size: 15 slots).

note that the I-FPRP is designed to improve the throughput. Under heavy traffic loads, the slightly extra power consumed in reservation cycles is fully justified by the extra throughput gains.

The second concern regarding I-FPRP is fairness among nodes. I-FPTP has a better performance than FPRP because I-FPRP allows nodes to contend for more than one slot in a reservation frame. However, this may result in some nodes failing to obtain a slot in an information frame. The failure ratio is defined as the ratio of nodes that fail to reserve a slot when needed, and it is related to traffic load R_4, transmission range R, and so on. Figure 11 indicates that the failure ratio increases when either the traffic load, second contention probability R_4, or transmission range R increases. However, even in the worst case, the failure ratio is kept less than 0.1. By carefully setting proper values for R_4 and R, it is possible to control the failure ratio to be less than one percent. The inherent performance tradeoff and optimization strategies will be left for our future work.

V. Conclusion

In this paper, we studied the contention-based reservation mechanism in FPRP and showed that slots are not fully utilized because nodes can only contend for one slot in an information frame. An improved contention access mechanism based on a pseudo-Bayesian broadcast algorithm was subsequently proposed to allow nodes to contend for more slots with certain probabilities related to their traffic demands. Theoretical and simulation results show that the proposed mechanism can significantly improve the overall slot utilization and hence the throughput of MANETs, especially for networks with low

spatial node densities. More importantly, such an improvement is achieved with an acceptable increase in the signaling overhead and a marginal and manageable deterioration to the overall user fairness. We conclude that the proposed I-FPRP makes a promising improvement to FPRP for high-throughput applications.

Appendix

Theorem: Improved Pseudo-Bayesian Algorithm. In the network above, when the number of nodes contending for the second slot is described by a Poisson distribution with parameter λ, the update of v after an idle, success, or collision state is as follows:

1) Collision: $v = v + \lambda + (e-2)^{-1}$.

2) Idle or success: $v = v + \lambda - 1$.

Proof: Let N_t denote the number of contention nodes at time t. When the network has an idle, success, or collision state for a given broadcast probability $b_t=1/v$ (and waiting probability $w_t=1-b_t$) and $N_t=n$, the probabilities of each state are

$$P(idle|N_t = n) = H_{b_t}(n) = w_t^n, \qquad (A1)$$

$$P(success|N_t = n) = S_{b_t}(n) = n \cdot b_t \cdot w_t^{n-1}, \qquad (A2)$$

$$P(collision|N_t = n) = C_{b_t}(n) = 1 - H_{b_t}(n) - S_{b_t}(n). \qquad (A3)$$

To estimate the influence of the three states on the number of contention nodes, we use $p_{n,t} = P(N_t = n)$ to denote the initial distribution of N_t when a network state is unknown and $p'_{n,t} = P\{N_t = n|E_t\}$ to denote the final distribution of N_t, where E_t denotes the state (idle, success, or collision) at slot t.

Using Bayes' rule, $p_{n,t}$ can be transformed to $p'_{n,t}$:

$$P(N_t = n|E_t) = \frac{P(E_t|N_t = n) \cdot P(N_t = n)}{P(E_t)}. \qquad (A4)$$

Using Poisson distribution with mean v to approximate the number of contention nodes N_t, v is considered to be the best estimation of N_t.

$$p_{n,t} = P_v(n) = \frac{e^{-v}v^n}{n!}. \qquad (A5)$$

Therefore, according to Bayes' rule in (A4) and the assumption in the pseudo-Bayesian algorithm, the distributions of N_t after detecting the three states can be calculated by:

1) Idle:

$$p'_{n,t} = P(N_t = n|idle) = \frac{p_{n,t} H_{b_t}(n)}{\sum_{k=0}^{\infty} p_{k,t} H_{b_t}(k)}$$

$$= \frac{e^{-vb_t} \cdot P_{vw_t}(n)}{\sum_{k=0}^{\infty} e^{-vb_t} \cdot P_{vw_t}(k)} = P_{vw_t}(n), \ (n \geq 0), \qquad (A6)$$

where $P_{vw_t}(n)$ denotes a Poisson distribution with mean $v \cdot w_t$;

2) Success:

$$p'_{n,t} = P(N_t = n|success) = \frac{p_{n,t} S_{b_t}(n)}{\sum_{k=0}^{\infty} p_{k,t} S_{b_t}(k)}$$

$$= \begin{cases} \dfrac{vb_t \cdot e^{-vb_t} \cdot P_{vw_t}(n-1)}{\sum_{k=1}^{\infty} vb_t \cdot e^{-vb_t} \cdot P_{vw_t}(k-1)}, & (n \geq 1), \\ 0, & (n = 0), \end{cases} \qquad (A7)$$

$$= \begin{cases} P_{vw_t}(n-1), & (n \geq 1), \\ 0, & (n = 0); \end{cases}$$

3) Collision:

$$p'_{n,t} = P(N_t = n|collision) = \frac{p_{n,t} C_{b_t}(n)}{\sum_{k=0}^{\infty} p_{k,t} C_{b_t}(k)}$$

$$= \frac{p_{n,t}\left(1 - H_{b_t}(n) - S_{b_t}(n)\right)}{\sum_{k=0}^{\infty} p_{k,t}\left(1 - H_{b_t}(k) - S_{b_t}(k)\right)}$$

$$= \begin{cases} \dfrac{\left(P_v(n) - e^{-vb_t}P_{vw_t}(n) - vb_t e^{-vb_t} P_{vw_t}(n-1)\right)}{1 - e^{-vb_t} - vb_t e^{-vb_t}}, & (n \geq 1), \\ 0 & (n = 0). \end{cases}$$
$$\qquad (A8)$$

When a successful reservation is made at slot t, the contention nodes number is decreased by one. So, at the end of slot t (or beginning of slot $t+1$), the initial distribution of N_t in slot $t+1$, denoted as $p''_{n,t}$ is different from $p'_{n,t}$; when there is an idle, success, or collision state in slot t, the distribution $p''_{n,t}$ is:

1) Idle: $p''_{n,t} = p'_{n,t} = P_{vw_t}(n);$ \qquad (A9)

2) Success: $p''_{n,t} = p'_{n+1,t} = P_{vw_t}(n);$ \qquad (A10)

3) Collision: $p''_{n,t} = p'_{n,t}.$ \qquad (A11)

Thus, in the next slot, the distribution of N_t after an idle or success state is also a Poisson distribution with mean vw_t. However, the distribution of N_t after a collision can be approximated as a Poisson distribution by setting the parameter v to be the mean of its resulting distribution.

Since the nodes that succeed at slot t will contend for a second slot in the next slot, the distribution of the number of contending nodes N_{t+1} is

$$p_{n,t+1} = \sum_{j=0}^{n} p''_{j,t} \cdot P_\lambda(n-j). \qquad (A12)$$

Here, $P_\lambda(n-j)$ denotes the probability of $n-j$ nodes contending the second slot [17].

We can derive a new probability $P(N_{t+1}=n|E_t)$ from (A9), (A10), and (A12).

1) Idle or success:

$$p_{n,t+1} = \sum_{j=0}^{n} p''_{j,t} \cdot P_\lambda(n-j) = \sum_{j=0}^{n} \frac{e^{-vw_t} \cdot (vw_t)^j}{j!} \cdot \frac{e^{-\lambda} \cdot \lambda^{n-j}}{(n-j)!}$$
$$= \frac{e^{-(\lambda+vw_t)} \cdot (\lambda+vw_t)^n}{n!} = P_{\lambda+vw_t}(n). \tag{A13}$$

2) Collision:

$$p_{n,t+1} = P(N_{t+1}=n|collision) = \sum_{j=0}^{n} p''_{j,t} \cdot P_\lambda(n-j)$$
$$= \begin{cases} 0 + \sum_{j=1}^{n} \dfrac{P_v(j) - e^{-vb_t} P_{vw_t}(j) - vb_t e^{-vb_t} P_{vw_t}(j-1)}{1 - e^{-vb_t} - vb_t e^{-vb_t}} \cdot P_\lambda(n-j), & (n \geq 1), \\ 0, & (n=0). \end{cases} \tag{A14}$$

Consider that

$$\sum_{j=1}^{n} \frac{P_v(j) - e^{-vb_t} P_{vw_t}(j) - vb_t e^{-vb_t} P_{vw_t}(j-1)}{1 - e^{-vb_t} - vb_t e^{-vb_t}} \cdot P_\lambda(n-j)$$
$$= \frac{P_{\lambda+v}(n) - e^{-vb_t} P_{\lambda+vw_t}(n) - vb_t e^{-vb_t} \cdot \sum_{j=1}^{n} \left(P_{vw_t}(j-1) \cdot e^{-\lambda} \cdot \lambda^{n-j} / (n-j)! \right)}{1 - e^{-vb_t} - vb_t e^{-vb_t}} \tag{A15}$$

and

$$\sum_{j=1}^{n} P_{vw_t}(j-1) \cdot \frac{e^{-\lambda} \cdot \lambda^{n-j}}{(n-j)!} = e^{-(vw_t+\lambda)} \cdot \lambda^{n-1} \cdot \frac{1}{n!} \cdot \frac{d\left(\left(1 + {vw_t}/{\lambda} \right)^n \right)}{d\left({vw_t}/{\lambda} \right)}$$
$$= e^{-(vw_t+\lambda)} \cdot \frac{(\lambda+vw_t)^{n-1}}{(n-1)!} = P_{\lambda+vw_t}(n-1). \tag{A16}$$

Formula (A14) can be rewritten as

$$p_{n,t+1} = P(N_{t+1}=n|collision)$$
$$= \begin{cases} \dfrac{P_{\lambda+v}(n) - e^{-vb_t} P_{\lambda+vw_t}(n) - vb_t e^{-vb_t} \cdot p_{\lambda+vw_t}(n-1)}{1 - e^{-vb_t} - vb_t e^{-vb_t}}, & (n \geq 1), \\ 0, & (n=0). \end{cases} \tag{A17}$$

Generally, $v \geq 1$ when $b_t = 1/v$. From (A13) and (A14), we obtain the estimation of N_{t+1}:

1) Idle or success:

$$E[N_{t+1}] = \sum_{k=0}^{\infty} k \cdot P_{\lambda+vw_t}(k) = \lambda + vw_t = \lambda + v(1-b_t)$$
$$= \lambda + v - 1; \tag{A18}$$

2) Collision:

$$E[N_{t+1}]$$
$$= \frac{\sum_{k=1}^{\infty} k \cdot P_{\lambda+v}(k) - e^{-vb_t} \cdot \sum_{k=1}^{\infty} k \cdot P_{\lambda+vw_t}(k) - vb_t e^{-vb_t} \cdot \sum_{k=1}^{\infty} k \cdot P_{\lambda+vw_t}(k-1)}{1 - e^{-vb_t} - vb_t e^{-vb_t}}$$
$$= \frac{\left[(\lambda+v) - e^{-vb_t} \cdot (\lambda+vw_t) - vb_t e^{-vb_t} \cdot (1+\lambda+vw_t) \right]}{1 - e^{-vb_t} - vb_t e^{-vb_t}}$$
$$= v + \lambda + \frac{1}{e-2}; \tag{A19}$$

Therein:

$$\sum_{k=1}^{\infty} k \cdot P_v(k-1) = e^{-v} \sum_{k=1}^{\infty} k \cdot \frac{v^{k-1}}{(k-1)!} = e^{-v} \cdot \frac{d}{dv}(ve^v) = 1+v. \tag{A20}$$

So, in a second contention network, we can estimate as follows:

1) Idle or success: $v = v + \lambda - 1$; \hfill (A21)

2) Collision: $v = v + \lambda + (e-2)^{-1}$. \hfill (A22)

□

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