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Power-Stepped Protocol: Enhancing Spatial Utilization in a Clustered Mobile Ad Hoc Network

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Abstract—While most previous studies on mobile ad hoc networks (MANETs) rely on the assumption that nodes are randomly distributed in the network coverage area, this assumption is unlikely to hold, as nodes tend to be cluttered around hot spots like the site of an accident or disaster. We refer to this as a clustered layout. Intuitively, a MANET with the clustered layout may suffer from serious performance degradation due to the excessive collisions in congested hot spots and space underutilization of sparse areas. In this paper, we propose a power-controlled network protocol, called the power-stepped protocol (PSP), that maximizes the spatial utilization of limited channel bandwidth. Using a number of discrete power levels available for the underlying wireless network hardware, PSP finds the appropriate power level for each node in a distributed and a coordinated manner without causing any serious problem at the medium access control and network routing layers. A unique feature of this approach is the use of the chosen radio power for both data and control packets, and thus, it requires neither any special mechanism (e.g., a separate control channel) nor frequent power adjustments. Our extensive ns-2-based simulation results have shown the proposed PSP provides excellent performance in terms of packet delivery ratio and delay, as well as the network capacity.

Index Terms—Clustered network, mobile ad hoc networks (MANETs), network capacity, node distribution, transmit power control.

I. INTRODUCTION

A KEY FEATURE in multihop packet radio networks, or mobile ad hoc networks (MANETs), is that the channel can be spatially reused to support multiple concurrent transmissions as long as they are sufficiently separated in space [1]. However, the benefit of spatial diversity is not scalable with respect to the physical size of network coverage area mainly due to the increased route length between two end nodes [2]. While dynamic properties such as node movement and the corresponding topology changes are important factors in assessing the average network performance, it is the static properties such as node density and node degree that determine the maximum achievable network capacity of a MANET.

This paper considers another important factor affecting the capacity scalability of a MANET, where both average node den-

sity and node degree are kept constant but nodes are not distributed randomly in space. While most of previous studies on MANET assume a *random layout* of nodes, nodes actually tend to be cluttered rather than scattered randomly. In other words, nodes are concentrated in some subareas (e.g., a disaster/accident site or a mobile sensor network). We refer to this type of node placement as the *clustered layout*. In contrast to the random layout, the clustered layout of nodes will have serious performance implications due to severe interference in concentrated subareas, and poor network connectivity and channel underutilization in sparsely populated subareas. A special care has to be taken if the network being designed is expected to form a clustered layout during its operation time.

One straightforward solution to the clustered layout is to apply transmit power control (TPC), which allows a node to adjust its radio transmit power according to node connectivity and/or traffic intensity. A major problem with this simple TPC scheme is that it creates *asymmetric links* where one end node can reach the other, but not the other way around. As we will see in Section III, they render the medium access control (MAC) protocol based on the IEEE 802.11 standard, as well as network layer protocols, such as Ad hoc On-demand Distance Vector (AODV) [3], inefficient because control packets implementing these protocols usually assume symmetric links. For this reason, most of TPC-based protocols are concerned primarily with variable radio power for data packets [4]–[11], and assume that control packets are transmitted at the highest radio power for maintaining symmetric links.

This paper proposes the power-stepped protocol (PSP) in which the same TPC mechanism is employed to maximize the spatial utilization of a MANET, but each node selects the transmit power in coordination with its neighbors so that the detrimental effect caused by asymmetric links can be avoided. In addition, PSP does not require each node to readjust its radio power whether it is a data or control packet unless node connectivity or traffic intensity in the node's vicinity changes significantly. This is practically important because the frequent power-level adjustments required in [5]–[7], [12], or a separate channel for control packets as suggested in [13] may not be feasible in some real implementations. The proposed PSP is implemented and evaluated using the ns-2 network simulator [14]. Our analysis and simulation will focus on static ad hoc networks because our primary interest is in network capacity rather than dynamic adaptability in a mobile environment.

The paper is organized as follows. Section II introduces the clustered layout and its characteristics. Section III presents the background information, focusing on the detrimental effect of asymmetric links on the MAC layer protocol, and overviews the

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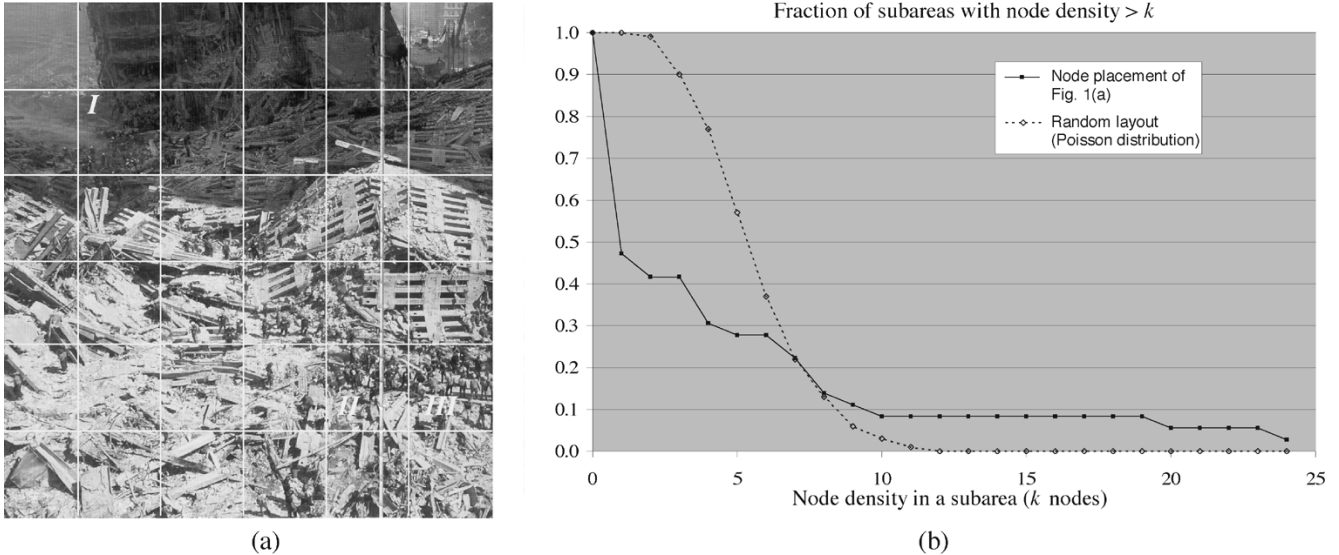


Fig. 1. Example of a clustered layout. (a) Rescue team at Ground Zero [17]. (b) Node density distribution.

power-controlled MAC algorithms in the literature. Section IV introduces the PSP algorithm and the corresponding power-stepping procedures executed by each node in coordination with its neighbors. In Section V, the effectiveness of PSP on the clustered layout is demonstrated via ns-2 simulation. Finally, Section VI makes concluding remarks and describes future work.

II. NETWORK MODEL: RANDOM AND CLUSTERED LAYOUT

This section introduces and characterizes the clustered layout in a MANET and also presents the topology generation method that induces node clustering. Although we consider only a single, static hot spot, this method can be easily extended to generate multiple hot spots, as well as hot spots that move and, thus, can be used to formulate clustered mobility models.

Random Layouts of Nodes: Since node mobility affects significantly the performance of a MANET, there has been active research in characterizing the general motion behavior and developing mobility models to be used for the simulation or analysis of MANETs. One important observation in most of the mobility models is that they all produce the *random layout* of nodes where nodes are well balanced and scattered across the entire MANET area.

Let us consider the spatial distribution of nodes in a MANET based on the random layout. Assume that the entire area is divided into a number of equal-sized subareas. Each node is positioned in a particular subarea with independent probability p , which is the reciprocal of the number of subareas s . The probability p_k that a subarea has exactly k nodes is given by the binomial distribution $p_k = \binom{n}{k} p^k (1-p)^{n-k}$, where n is the total number of nodes. As a limiting case, this becomes the well-known Poisson distribution $p_k = ((z^k e^{-z})/k!)$, where z is the mean number of nodes in a subarea, or n/s . Both binomial and Poisson distributions are strongly peaked around the mean z , and have a large- k tail that decays rapidly as a function of $1/k!$ [15]. In other words, with the random layout of nodes,

the majority of subareas have a similar number of nodes and significant deviations from the average case, e.g., a subarea with a large fraction of nodes, is extremely rare.

Clustered Layouts of Nodes: In a real network of mobile nodes, however, the node distribution can be very different from the Poisson distribution. For example, Fig. 1(a) shows an example of a disaster area where the infrastructureless ad hoc network is well suited for supporting communication. Many rescue team members gather at three hot spot subareas, denoted as *I*, *II*, and *III* in the figure, which may be a base camp or have many casualties. The three subareas out of 36 ($s = 36$) include about the half of the total rescue team members (66 out of 137). Fig. 1(b) shows the node density distribution of the disaster area in Fig. 1(a), as well as that of the random layout that follows the Poisson distribution. It is clear from Fig. 1(b) that the random layout does not model the node distribution of the real ad hoc network scenario. Even in the presence of node mobility, node clustering would persist because, for example, in Fig. 1(a), a mobile node (i.e., a rescue team member) leaving a hot spot subarea is most likely to move to another hot spot subarea. The significant impact of node clustering on network performance has not been addressed until recently [7], [16].

As evident in Fig. 1(b), the corresponding node distribution contains a heavy tail unlike the Poisson distribution and can be modeled by a *power-law distribution*. In general, a power-law distribution is one for which $Pr\{K > k\} \sim k^{-\alpha}$, where $0 < \alpha < 2$. A smaller value of α forms more concentrated clusters. If $\alpha < 2$, the distribution has an infinite variance, and if $\alpha < 1$, it has an infinite mean. This paper adopts the *Pareto distribution*, which is the simplest among the various power-law distributions available. If there are finite upper and lower bounds, denoted as a and b , respectively, the truncated distribution referred to as the *bounded Pareto distribution* can be used with the cumulative density function of $F(k) = ((1-(a/k)^\alpha)/(1-(a/b)^\alpha))$, where $a < k < b$, $0 < \alpha < 2$ [15].

In order to model the hot spots in a MANET, the network area is divided into a number of squared subareas. For each subarea, the topology generator picks a number of nodes to be assigned

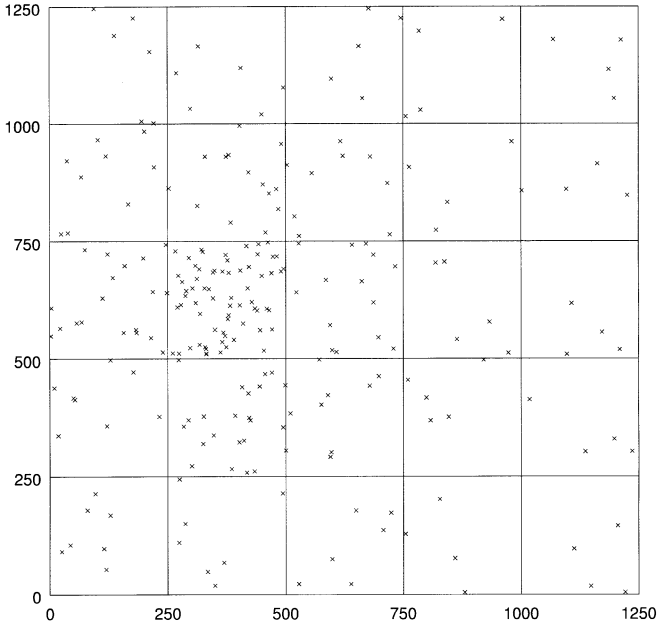


Fig. 2. Clustered layout of nodes (250 nodes in a $1250 \times 1250 \text{ m}^2$ area).

to that square according to a bounded Pareto distribution. A sub-area that happens to contain a large number of nodes (heavy tail) can be considered as a hot spot. Once the number of nodes in a particular sub-area is determined, they are randomly positioned within that sub-area. Fig. 2 shows the node distribution of the clustered layout generated with the above-mentioned method. The parameters used in this example are $n = 250$, $s = 25$, $\alpha = 1.1$, $a = 3$, and $b = 100$. These parameters are carefully chosen to exhibit a reasonable degree of clustering (with $\alpha = 1.1$) with an average number of nodes of ten in each sub-area ($250/25$ with $a = 3$ and $b = 100$).

III. DISCUSSION AND RELATED WORK

The clustered layout characterized in the previous section greatly degrades the network performance in terms of packet delivery ratio, delay, and network capacity. As discussed in the Introduction, the simple TPC scheme does not solve this problem, as it produces asymmetric links. This section discusses the negative effect of asymmetric links on the MAC layer protocol using the concept of *vulnerable regions*¹ where the hidden terminals can reside, and overviews the recently proposed power controlled MAC algorithms.

Effects of Asymmetric Links on Collision Avoidance: Distributed coordination function (DCF) is the basic medium access method in IEEE 802. 11, which is the most popular, widely deployed wireless local area network (LAN) standard. DCF supports best-effort delivery of packets at the link layer and is best described as the carrier sense multiple access with collision avoidance (CSMA/CA) protocol. Since collisions are not completely avoidable in DCF due to the

interference from hidden terminals in the vulnerable regions, it includes an optional four-way handshake mechanism based on request-to-send (RTS) and clear-to-send (CTS) control packets with Network Allocation Vector (NAV). Moreover, DCF uses extended interframe space (EIFS) to avoid collisions from distant nodes within *interference range* (I_R), which is usually twice the *transmission range* (T_R) based on the signal propagation model² [6]. When a node detects a transmission but cannot decode it, the node backs off for an additional EIFS duration after the current transmission completes. This is particularly important in protecting the acknowledgments (ACKs) at the end of the DATA transfer. However, this does not protect the reception of a DATA packet because its transmission time is usually longer than EIFS. In Fig. 3(a), the shaded area denotes the vulnerable region considering the effect of RTS/CTS and EIFS, when the transmit power of nodes S and R is 36.6 mW and T_R and I_R are 150 and 300 m, respectively. Nodes within the interference range of node R but outside of interference range of node S (shaded area) can potentially disrupt the reception of DATA at node R .

We now consider the effect of asymmetric links on the vulnerable region. As discussed in Section I, the simple TPC scheme allows each node to adjust its transmit power arbitrarily. However, this creates asymmetric links, which in turn, causes a large vulnerable region, and the collision problem is aggravated further. This is particularly true for low-power nodes because their RTS and CTS signals can reserve only a small fraction of spatial area for their communication. For example, when nodes S and R reduce their radio power to 4.8 mW, their T_R and I_R become 90 and 180 m, respectively, as indicated by the smaller circles in Fig. 3(b). However, if the transmit power of the neighboring nodes is 36.6 mW instead of 4.8 mW, the likelihood of collisions at node R increases because the vulnerable region becomes much larger as depicted in Fig. 3(b). Therefore, the simple TPC scheme is not a feasible solution due to asymmetric links.

Related Work: The TPC-based approach has been an active research area for various reasons such as energy conservation and topology and interference control. While most of previous approaches attempt to employ the TPC mechanism at the network layer [4], [8]–[11], some recent proposals integrate the TPC mechanism at the MAC layer [5]–[7], [12], [13]. Gomez *et al.* proposed the use of the maximum power level for RTS/CTS packets and lower power levels for data packets [5]. This does not increase or decrease the collision probability, but nodes can save a substantial amount of energy by using a low power level for transmitting data packets. In the power control MAC (PCM) protocol, not only control packets but also data packets are also transmitted at its maximum power level periodically in order for EIFS to work correctly as discussed above [6]. In the distributed power control (DPC) protocol, each node chooses different power levels for different neighbors to take into account

¹In carrier sensing medium access protocols, in order for a node to transmit a packet successfully without collision, any other interfering nodes should not attempt to transmit during the first node's transmission. This was referred to as "*vulnerable period*" [18], after which the term, *vulnerable region*, has been coined.

²There are two thresholds of power sensitivity to be used when receiving radio signals. When the power of the received signal is lower than *receive threshold* but higher than *carrier sense threshold*, the signal is not decoded intelligibly but is strong enough to disrupt any on-going communication. The corresponding distances to the two radio power sensitivity are referred to as *transmission range* and *interference range*, respectively [19].

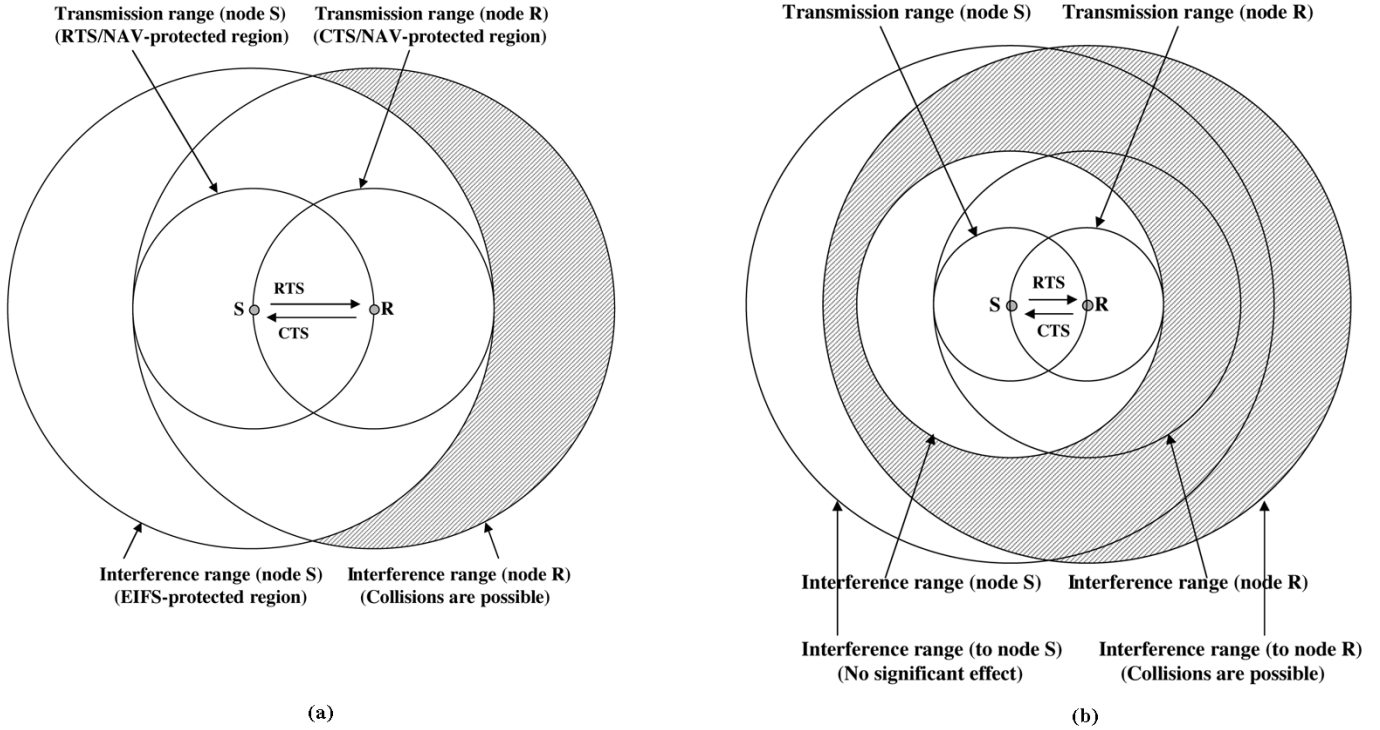


Fig. 3. Vulnerable regions (shaded area) with different transmit powers. (I_R is set to $2T_R$ for simplicity.) (a) A single transmit power ($T_R = 150$ m) is used. (b) Two transmit powers ($T_R = 90$ and 150 m) are used.

the differences in distances [12]. In the power controlled multiple access (PCMA) protocol [13], a source-destination pair uses request-power-to-send (RPTS) and acceptable-power-to-send (APTS) control packets to compute the optimal transmission power based on their received signal strength, which will be used when transmitting data packets. PCMA also uses the busy tone channel to advertise the noise level the receiver can tolerate. A potential transmitter first senses the busy tone to determine the upper bound on its transmission power.

The main difference between the aforementioned TPC schemes and the proposed PSP scheme is that the PSP uses the same radio power for both data and control packets to all neighboring nodes without assuming an additional frequency channel. In this sense, the method closest to ours is (COMPOW) [8], which uses the smallest common power at which the network is connected. This approach may work well in a MANET with the random layout, but it is not true with the clustered layout because the selected power level is appropriate only in sparse areas but not in hot spots.

IV. PROPOSED PSP ALGORITHM

Before detailing the PSP, we first present an illustrative example to show its advantages and formally define and characterize *power-stepped MANET*, which the PSP constructs and maintains. In a power-stepped MANET, each node can operate at a different radio power level but not more than one level higher or lower than that of any of its neighbors. This is to ensure the RTS/CTS-based collision avoidance mechanism will work reasonably well, while achieving the original goal of TPC (i.e., reduce interference).

A. Example of PSP

To illustrate the effectiveness of PSP, let us consider a MANET with the clustered layout of 250 nodes in a 1250×1250 m² network area. Similar to the assumptions used in [6], [8], and [20], five power levels of 4.8, 10.6, 36.6, 115.4, and 281.8 mW are available with the corresponding transmission ranges of 90, 110, 150, 200, and 250 m, respectively. When only one power level is available, the network topology can be illustrated as in Fig. 4(a) and (b), with T_R of 250 and 150 m, respectively. As can be seen in the figures, the congested hot spot area on the left side of the network in Fig. 4(a) would suffer from severe interference, while the sparse subareas on the right side of the network in Fig. 4(b) would suffer from poor connectivity. In order to ensure connectivity, a typical MANET with DCF would use a fixed T_R of 250 m as in Fig. 4(a). Even though the network is guaranteed to be connected, a node in hot spots experiences a large number of interfering signals and at the same time causes interference to its neighbors. In contrast, Fig. 4(c) shows the network connectivity based on the proposed PSP, and clearly, the congestion problem, as well as the connectivity problem are drastically reduced compared with the ones in Fig. 4(a) and (b).

Moreover, the main advantage of PSP over the simple TPC scheme is that each node adjusts its power level relative to its neighbors and, thus, the RTS/CTS mechanism can be effectively used to avoid collisions without increasing the vulnerable region. In order to illustrate how the PSP algorithm yields a smaller vulnerable region compared with the simple TPC, let us assume that two communicating nodes S and R use the radio power level of 4.8 mW ($T_R = 90$ m). Since neighbors of the two nodes have one of three power levels (one level higher,

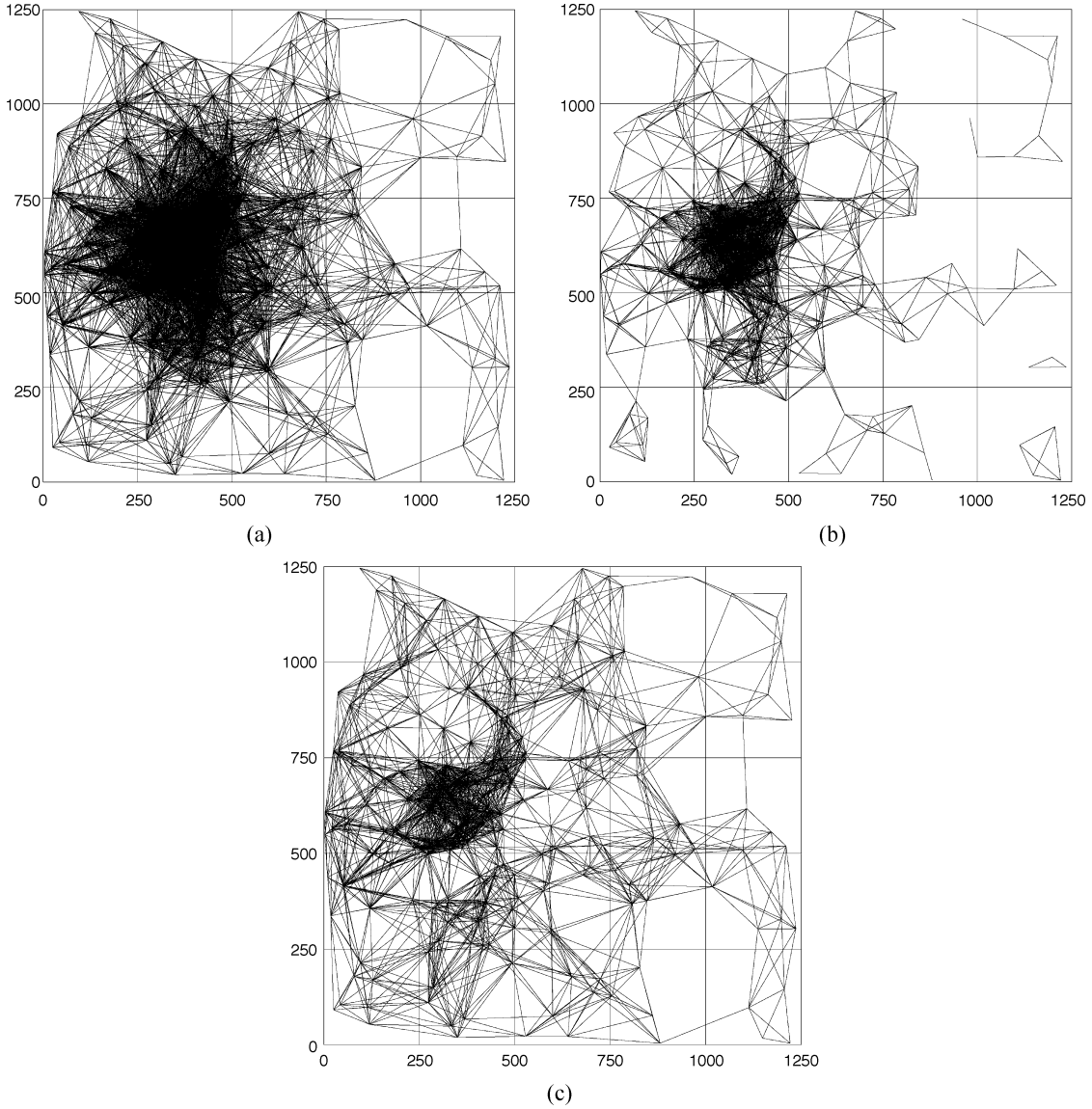


Fig. 4. Topology variation with different transmit powers. (a) With DCF ($T_R = 250$ m). (b) With DCF ($T_R = 150$ m). (c) With PSP ($T_R = 90 \sim 250$ m).

same level, and one level lower), they transmit at 2 mW ($T_R = 60$ m), 4.8 mW ($T_R = 90$ m), or 10.6 mW ($T_R = 110$ m). Fig. 5(a)–(c) shows the resulting vulnerable regions for these three cases. While the PSP algorithm does not completely eliminate collisions, these figures clearly show that the vulnerable region does not increase greatly as compared with DCF [see Fig. 3(a)], and is much smaller than the simple TPC scheme [see Fig. 3(b)].³ Therefore, the collision avoidance mechanism based on the four-way handshake will work well with the PSP.

In addition, the simple TPC scheme often suffers the following undesirable situation. Assume that node i reduces its radio power to reduce the number of neighbors and, thus, unwanted interference. Since node i 's transmission range is reduced, some neighboring nodes experience less interference and do not reduce their transmit power. Therefore, these nodes con-

tinuously use the same transmit power interfering with node i 's communication. Since node i does not detect any reduction in traffic intensity from its neighboring nodes, it further reduces its radio power, and so on, until it reaches the minimum power level, thus becoming isolated from the rest of the network. This anomaly does not occur with the PSP since it restricts each node's power level to be on par with that of its neighbors.

B. Power-Stepped MANET

This section formally states the definitions of neighbor set and power-stepped MANET, and introduces power-stepping procedures that change each node's transmit power, while preserving the power-stepped MANET.

Definitions of Node Sets and Power Levels: Let $\Gamma(i)$ be the set of neighbors of node i , which includes the node i itself, and P_i be the radio power level of node i chosen from a set of discrete power levels. Due to the presence of asymmetric links, two neighbor sets need to be differentiated as defined below.

³Simple calculation shows that, when T_R of nodes S and R is 90 m, the maximum vulnerable region is 64 530 m² with the PSP algorithm, while it is 683 610 m² with DCF (more than ten times larger). When T_R of nodes S and R is 110, 150, or 200 m, the ratio is 4.6, 2.1, and 1.0, respectively.

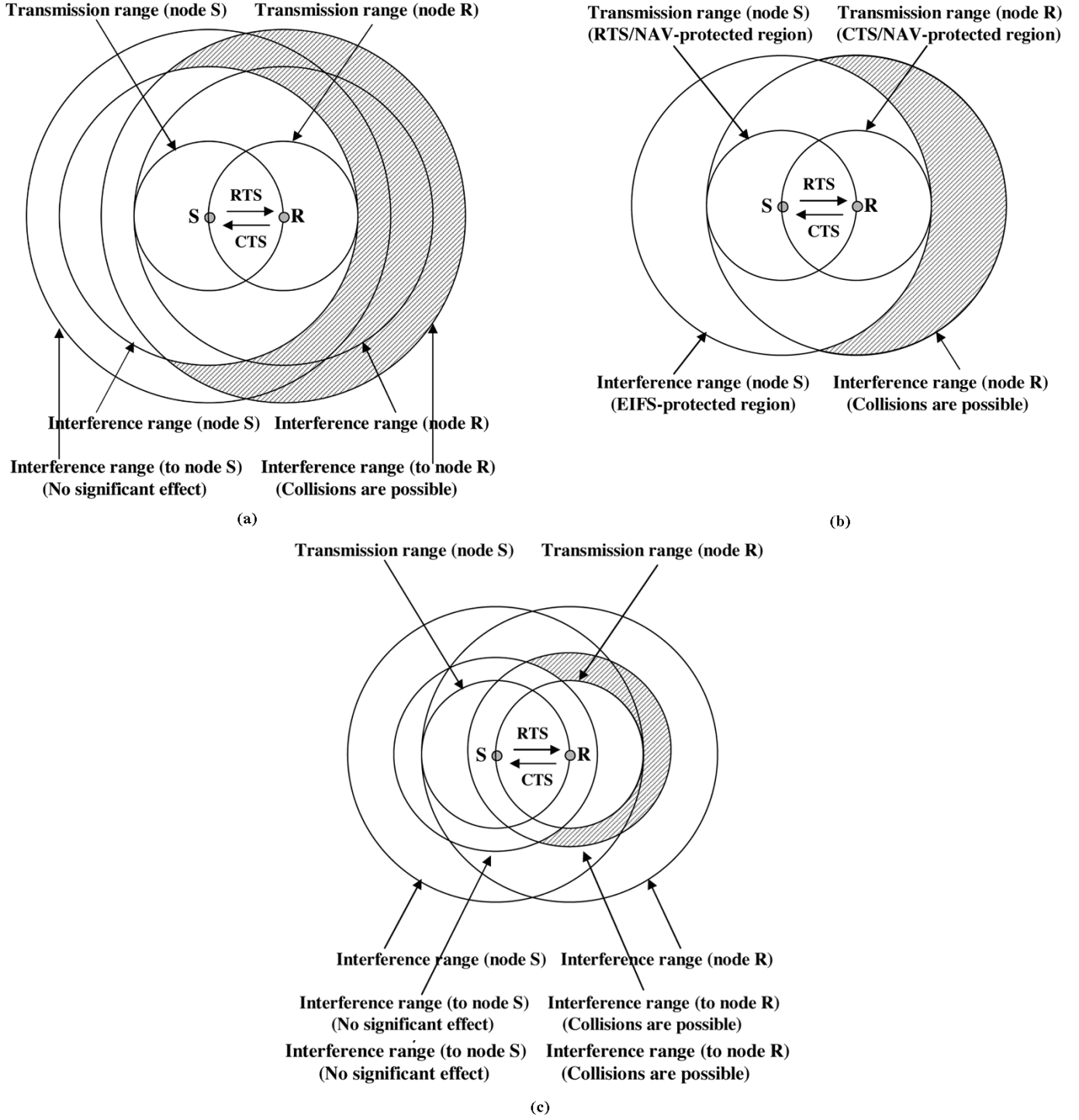


Fig. 5. Vulnerable regions (shaded area) caused by three different neighbors. (T_R 's of three types of neighbors are 150, 110, and 90 m, respectively.) (a) Higher level neighbors. (b) Same powered neighbors. (c) Lower level neighbors.

Definition 1: *In-bound neighbor set* of node i , $\Gamma(i)$, is the set of nodes that can reach node i , and *out-bound neighbor set* of node i , $\gamma(i)$ is the set of nodes that can be reached by node i . That is, $\Gamma(i) = \{j \mid \text{node } j \text{ can reach node } i\}$ and $\gamma(i) = \{j \mid \text{node } i \text{ can reach node } j\}$.

Definition 2: $P_M(i)$ and $P_m(i)$ are the maximum and minimum power levels among the nodes in $\Gamma(i)$, respectively, i.e., $P_M(i) = \max_{j \in \Gamma(i)} P_j$ and $P_m(i) = \min_{j \in \Gamma(i)} P_j$. Similarly, $Q_M(i)$ and $Q_m(i)$ are the maximum and minimum power levels among

the nodes in $\gamma(i)$, respectively, i.e., $Q_M(i) = \max_{j \in \gamma(i)} P_j$ and $Q_m(i) = \min_{j \in \gamma(i)} P_j$.

Definition 3: $\Gamma^2(i)$ and $\gamma^2(i)$ are the two-hop in-bound and out-bound neighbor sets, respectively, i.e., $\Gamma^2(i) = \Gamma(\Gamma(i))$ and $\gamma^2(i) = \gamma(\gamma(i))$. In addition, $P_M^2(i)$, $P_m^2(i)$, $Q_M^2(i)$ and $Q_m^2(i)$ are the maximum and minimum power levels among the nodes in $\Gamma^2(i)$ and $\gamma^2(i)$, respectively.

Note that the two-hop neighbor sets, by definition, include one-hop neighbor nodes. Note also that for node i , it is easier to

obtain $\Gamma(i)$ than $\gamma(i)$ because nodes in $\Gamma(i)$ can directly reach node i , but this is not necessarily true for nodes in $\gamma(i)$. Some nodes in $\gamma(i)$ with smaller power levels cannot reach node i and, thus, node i may not realize the existence of these nodes. For the same reason, $P_M(i)$ and $P_m(i)$ are easier to obtain than $Q_M(i)$ and $Q_m(i)$.

Definition 4: A *power-stepped MANET* is a MANET in which every node i satisfies the following two conditions (stepping rule): $P_j = (P_i - 1)$, P_i or $(P_i + 1)$ for all $j \in \Gamma(i)$ and $P_j = (P_i - 1)$, P_i or $(P_i + 1)$ for all $j \in \gamma(i)$.

Maintaining the Power-Stepped MANET: Maintaining a power-stepped MANET in the presence of node power level changes is a challenging task because it may necessitate the power level adjustments of their neighbors, which, in turn, propagate to neighbors' neighbors, and so on. In addition, it may cause oscillation between power-ups and power-downs throughout the network because the power-down of a node may satisfy the condition for one of its neighbors to power up. In order to prevent this oscillation, it is necessary to make both the power-up or power-down "safe" so that the power level adjustment is guaranteed not to propagate. In PSP, a safe power-down applies when a certain condition is satisfied: A node steps its radio power down only when the node uses the maximum radio power level among its neighbors. This power-down is safe in the sense that it does not cause its neighbors to adjust their power levels to maintain the stepped MANET. We now formally prove that this condition guarantees a safe power-down. Note that PSP does not apply a safe power-up as will be explained later in this section.

Theorem 1 (Safe Step-Down): A power-stepped MANET is preserved when node i with $P_i = P_M(i)$ decrements its power level by one.

Proof: It is necessary to prove that the two conditions in Definition 4 are preserved when nodes i changes its power level to $P_i' = P_i - 1$.

- 1) Since $P_i = P_M(i)$, $P_j = (P_i - 1)$ or P_i for all $j \in \Gamma(i)$. Since $P_i' = (P_i - 1)$ and $\Gamma'(i) = \Gamma(i)$, $P_j = P_i'$ or $(P_i' + 1)$ for all $j \in \Gamma'(i)$; therefore, the first condition is satisfied.
- 2) By definition, for all $j \in \gamma(i) - \Gamma(i)$, $P_j \leq P_i$. This fact together with $P_j = (P_i - 1)$ or P_i for all $j \in \Gamma(i)$ proves that $P_j = (P_i - 1)$ or P_i for all $j \in \gamma(i)$. Since $P_i' = (P_i - 1)$ and $\gamma'(i) \subseteq \gamma(i)$, $P_j = P_i'$ or $(P_i' + 1)$ for all $j \in \gamma'(i)$. Thus, the second condition is satisfied.

As in the case of safe step-down, safe step-up is also desirable. Thus, a node is allowed to step its radio power up only when it uses the minimum power among its neighbors. Compared with safe step-down, safe step-up is more difficult to achieve because a node does not have the complete knowledge of $\gamma'(i)$, i.e., the outbound neighbor set of node i , after it increments its power level from P_i to $P_i' = (P_i + 1)$. Even though P_i is the minimum among the nodes in $\Gamma(i)$, it is still possible that some nodes in $\gamma'(i)$ have a smaller power level than P_i and there will be a two-level difference in transmit power when node i steps up. One important observation is that these nodes cannot directly reach node i but can probably reach node i in two hops, assuming that there are some other nodes in their vicinity that connect these

nodes to node i . This assumption can be formulated as $\Gamma^2(i) \supseteq \gamma'(i)$ and the conservative (but not safe) step-up procedure can be described as follows: It is most probably safe for node i to step up when it has the minimum power level among its two-hop neighbors.

Theorem 2 (Conservative Step-Up): A power-stepped MANET is preserved when node i with $P_i = P_m^2(i)$ increments its power level by one provided $\Gamma^2(i) \supseteq \gamma'(i)$.

Proof: It is necessary to prove that the two conditions in Definition 4 are preserved when nodes i changes its power level to $P_i' = (P_i + 1)$. It is noted that since node i 's neighbors maintain the same power levels, the same set of nodes can reach node i , i.e., $\Gamma(i) = \Gamma'(i)$.

- 1) Since $P_i = P_m^2(i)$, $P_j = P_i$ or $(P_i + 1)$ for all $j \in \Gamma^2(i)$. Since $P_i' = (P_i + 1)$ and $\Gamma^2(i) \supseteq \Gamma(i) = \Gamma'(i)$, $P_j = (P_i' - 1)$ or P_i' for all $j \in \Gamma'(i)$. Thus, the first condition is satisfied.
- 2) Since $\Gamma^2(i) \supseteq \gamma'(i)$, $P_j = (P_i' - 1)$ or P_i' for all $j \in \gamma'(i)$. Thus, the second condition is satisfied.

Although the step-up procedure is conservative, it is not perfectly safe due to the additional assumption of $\Gamma^2(i) \supseteq \gamma'(i)$. That is, when there are some nodes in $\gamma'(i)$ but not in $\Gamma^2(i)$ with transmit power lower than P_i , these nodes will receive a signal from node i with the incremented power ($P_i' = (P_i + 1)$) and realize the two-level difference. The approach taken in the PSP algorithm is to perform the *corrective step-up* in order to maintain the power-stepped MANET. In other words, node i increments its power level up by one ($P_i' = (P_i + 1)$) when it identifies a neighbor in $\Gamma(i)$ that has more than one level higher transmit power ($P_M(i) > (P_i + 1)$ or $P_i < (P_M(i) - 1)$). This may cause the propagation of power level adjustments but not oscillation.

C. Description of the PSP Algorithm

While each node executes the step-up and step-down procedures stated above, the power-stepped MANET is preserved via periodic exchange of power level and neighbor set information among the neighbors. Based on the AODV routing protocol [3], the PSP algorithm utilizes the *Hello* messages to exchange these information and to identify the mutual neighbors as suggested in [21].

Triggering Mechanism of Step-Up and Step-Down: Traffic intensity or node connectivity is the decision factor in triggering the power-level adjustment. Therefore, each node steps up or down its power level when the traffic intensity is below or above a certain threshold. The traffic intensity can be measured in many different ways at different protocol layers. For example, *air utilization* may be a direct indication of traffic intensity and can be obtained by monitoring activities at the physical (PHY) layer [22]. At the MAC layer, number of collisions, number of packet drops, or contention window size can be used for a measure of traffic intensity. The number of neighboring nodes observable at the routing layer is also a good decision factor because it not only provides an indication of traffic intensity but also helps create a desired network topology with appropriate node connectivity. The PSP algorithm monitors the number of


```

// PSP (Power-Stepped Protocol) algorithm at node  $i$ 
// during a single Hello message period

Constant MIN_THRESH 6
Constant MAX_THRESH 8
Constant MINP 0 // the lowest power level (corresponds to 4.8 mW)
Constant MAXP 4 // the highest power level (corresponds to 281.8 mW)
Constant MAX_HELLO 3 // maximum number of Hello message periods to hear from a neighbor

Upon receiving a Hello message ( $\Gamma(j), P_j, P_m(j)$ ) from node  $j$  {
  // Update  $\Gamma(i), P_M(i), P_m(i)$ , and  $P_m^2(i)$ 
   $\Gamma(i) = \Gamma(i) \cup \{j\}$ ;
  if ( $P_j > P_M(i)$ ),  $P_M(i) = P_j$ ;
  if ( $P_j < P_m(i)$ ),  $P_m(i) = P_j$ ;
  if ( $P_m(j) < P_m^2(i)$ ),  $P_m^2(i) = P_m(j)$ ;

  // Determine whether link  $i-j$  is symmetric
  if ( $i \in \Gamma(j)$ ), link  $i-j$  is marked as symmetric; else, marked as asymmetric;
}

At the end of the current Hello message period {
  // Remove a neighbor if not heard for the last MAX_HELLO periods
  if (no Hello message from  $j \in \Gamma(i)$  for the last MAX_HELLO consecutive periods) {
     $\Gamma(i) = \Gamma(i) - \{j\}$ ;
    Update  $\Gamma(i), P_M(i), P_m(i)$ , and  $P_m^2(i)$ ;
  }

  // Safe step-down
  if ( $|\Gamma(i)| > MAX\_THRESH$ ) and ( $P_i = P_M(i)$ ) and ( $P_i > MINP$ ),  $P_i' = P_i - 1$ ;

  // Conservative step-up
  if ( $|\Gamma(i)| < MIN\_THRESH$ ) and ( $P_i = P_m^2(i)$ ) and ( $P_i < MAXP$ ),  $P_i' = P_i + 1$ ;

  // Corrective step-up
  else if ( $P_i < P_m(i) - 1$ ) and ( $P_i < MAXP$ ),  $P_i' = P_i + 1$ ;

  // Power adjustment
  if  $P_i' \neq P_i$ , adjust the radio power to power level  $P_i'$ 
}

Upon receiving a RREQ (route request) from node  $j$  {
  if link  $i-j$  is symmetric, broadcast forward the RREQ;
  else drop the RREQ;
}

```

Fig. 6. PSP algorithm with the power stepping procedures.

neighboring nodes at the routing layer to gauge the traffic intensity. However, since more nodes do not necessarily mean more traffic, it would be beneficial to use a combined metric such as the number of *active stations*, which have a packet ready for transmission [23]. Therefore, the performance results presented in Section V should be interpreted as the worst-case performance, especially when the traffic intensity is low but node connectivity is high.

In the PSP algorithm, a node increases its radio power when it finds less than “six” neighbors (*MIN_THRESH*), and decreases its radio power when it finds more than “eight” neighbors (*MAX_THRESH*). Choice of these numbers is based on the results in [24] and [25], where they considered the optimal number of nodes that maximizes the utilization without incurring excessive packet drops on retransmission-based CSMA protocols. The use of two different thresholds is to prevent possible oscillations during power-up and power-down.

Routing Over Asymmetric Links: Another design issue with the PSP is to provide a correct routing path in the presence of asymmetric links. In AODV, a route is discovered on demand by broadcasting a control packet called *RREQ* (route request) from

the source toward the destination. Upon receiving the RREQ, an intermediate node participates in the route discovery procedure by forwarding the RREQ. For an asymmetric link between nodes i and j , where $j \notin \Gamma(i)$ but $i \in \Gamma(j)$ (i. e. $P_i > P_j$), node j cannot determine whether or not to include the link as a part of a routing path because the reachability to node i is not known to node j . Thus, if node j receives an RREQ message from node i , it should not participate in forwarding the packet because the reverse path may not be available.

Our approach in the proposed PSP algorithm is to utilize the neighbor set information exchange via *Hello* messages to identify the set of symmetric links among all wireless links. Based on the AODV routing protocol, it is possible to include the neighbor set in *Hello* messages as was done in [21]. Upon receiving the neighbor set $\Gamma(i)$ from node i , node j can identify whether the wireless link between i and j is a symmetric link or not. If $j \in \Gamma(i)$, then it is symmetric; otherwise, it is an asymmetric link via which node i cannot be reached.

PSP Algorithm: Fig. 6 summarizes the PSP algorithm. Each node receives *Hello* messages from its neighbors, each of which includes the information regarding the sender (node

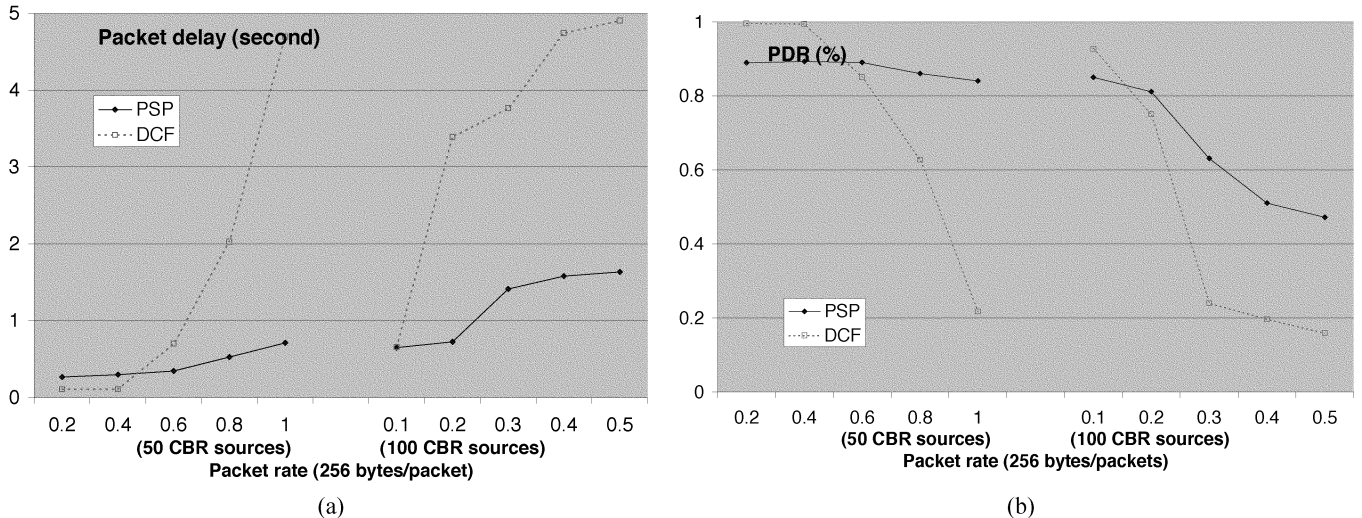


Fig. 7. Performance comparison. (a) Packet delay (seconds). (b) Packet delivery ratio (%).

j), as well as its neighbors, i.e., $\Gamma(j)$, P_j , and $P_m(j)$. No change is required if all the information is consistent with that received in the previous *Hello* message period. We assume that each mobile node can perform only one power-level change (either step-up or step-down) during a single *Hello* message period, and that the network is synchronous, i.e., messages are sent at the beginning of each *Hello* message period and are received by the neighboring nodes before the end of the period. Since PSP involves the MAC, as well as the routing layer activities, the implementation level of PSP is either in between MAC and routing layer or integrated with the underlying network protocol.

V. PERFORMANCE EVALUATION

In this section, the performance of the PSP algorithm with the clustered layout of nodes is evaluated using the *ns-2* network simulator [14], which simulates node mobility, a realistic physical layer, radio network interfaces, and the IEEE 802.11 MAC protocol. For comparison purposes, the standard DCF is also evaluated on the same clustered layout.

Simulation Environment: Similar to other previous studies on capacity analysis [2], [26], [27], our evaluation is based on the simulation of 250 “static” mobile nodes located over an area of $1250 \times 1250 \text{ m}^2$. The radio transmission range is assumed to be 250 m and a *two-ray ground propagation channel* is assumed with a data rate of 1 Mb/s. For the clustered layout, a bounded Pareto distribution with parameters $\alpha = 1.1$, $a = 3$, and $b = 100$ is used to determine the number of nodes in each of 25 subareas ($250 \times 250 \text{ m}^2$ each) as discussed in Section II.

The RTS-CTS-based MAC algorithm is used with the conventional backoff scheme. The AODV routing algorithm [3] is used to find and maintain the routes between two end nodes. Data traffic simulated is either constant bit rate (CBR) traffic or TCP traffic. In case of CBR traffic, 15–100 CBR sources generate 256-byte data packets every 0.1–1.0 s. Since CBR traffic is based on user datagram protocol (UDP) protocol, these CBR sources generate traffic regardless of network congestion. In case of TCP traffic, 15 to 75 FTP connections are simulated.

Source and destination nodes for the CBR/TCP traffic are randomly selected among the 250 mobile nodes. Note that the parameters are chosen to simulate a large-scale ad hoc network or a wireless sensor network, which involves a large number of mobile nodes and a large fraction of nodes communicate at a reduced data rate. Since the performance can vary significantly depending on the selection of pairs of communicating nodes, a number of simulation runs are repeated with the different sets of communicating nodes for the same number of CBR/TCP traffic sources.

Simulation Results and Discussion: Fig. 7(a) and (b) shows the network performance in terms of packet delay and *packet delivery ratio* (PDR) with 50 and 100 CBR sources, respectively. Each of 100 CBR sources transmits 0.1–0.5 packets/s. As shown in the figure, the network performance degrades faster with DCF compared with PSP. When the number of CBR sources is 100, the average delay differs by as much as 371% and the PDR differs by as much as 39%. The difference is more significant with a lower number (50) of CBR sources. The PSP exhibits negligible degradation with the packet rate up to 1.0, while the DCF suffers greatly. For the case of 50 CBR sources, higher packet rates (0.2–1.0 packets/s) are applied in order to provide the same traffic intensity as with the case of 100 CBR sources. Note that the PSP performs worse when traffic intensity is light (packet rate of 0.2–0.4 with 50 CBR sources and 0.1 with 100 CBR sources). As discussed in Section IV-C, this is because the PSP algorithm simulated uses the node connectivity rather than traffic intensity as the decision factor to step up or down. It would be an interesting future work to see if a combined metric (i.e., number of active nodes rather than all neighboring nodes) improves PSP even further so that it always outperforms DCF.

There is also a noticeable performance difference between CBR sources of 50 and 100, in spite of having the same traffic intensity. This is mainly because data transmissions are more “controlled” in the 50 CBR-source case. In other words, two subsequent packets from the same source do not collide or compete with each other. This can be clearly seen in Fig. 8(a), where the number of CBR sources varies from 15 to 75. The

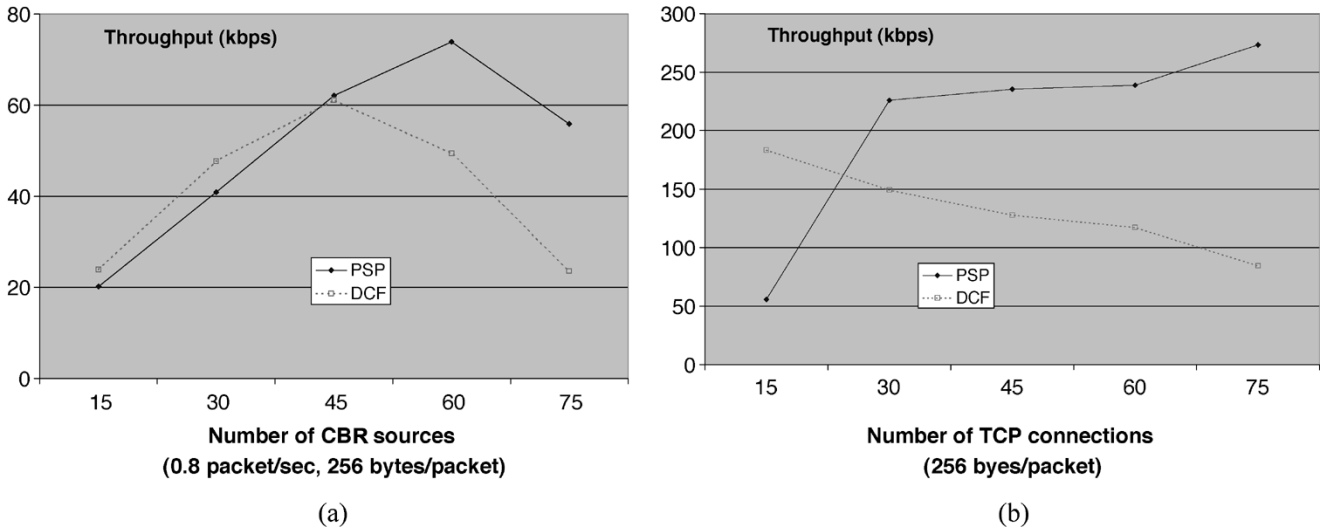


Fig. 8. Total end-to-end throughput (kilobits per second). (a) With CBR traffic. (b) With TCP traffic.

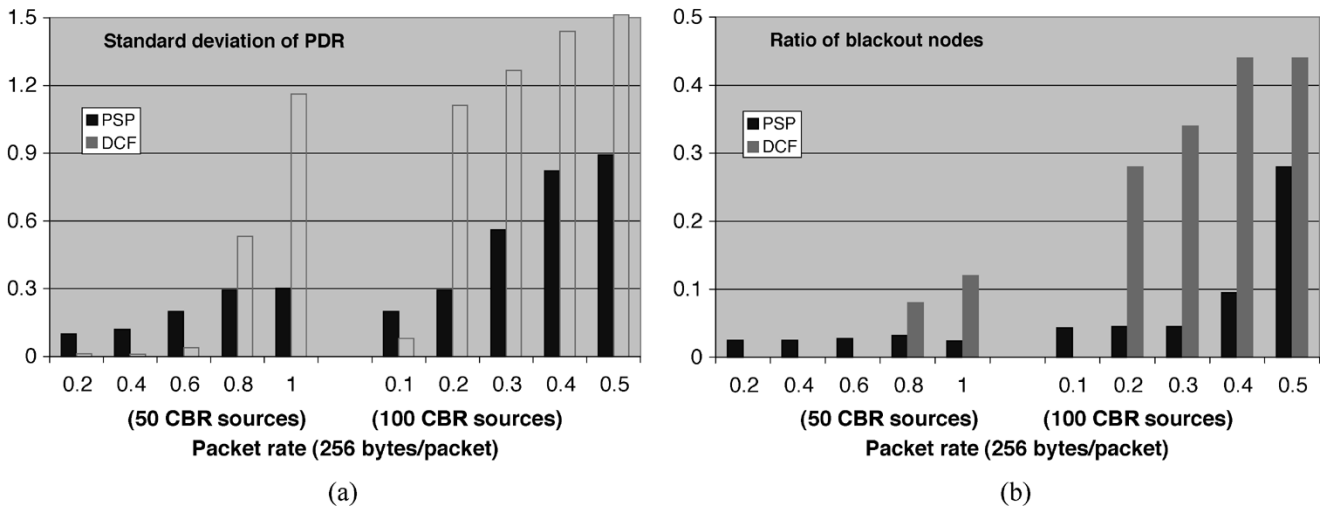


Fig. 9. QoS performance. (a) Standard deviation of PDR. (b) Ratio of “blackout” nodes.

performance degrades as the number of data streams increases, suggesting that interference among the streams is a critical limiting factor in determining network capacity. However, when the number of TCP sources increases, the throughput of PSP increases, while throughput of DCF decreases. This is because the degree of interference in PSP is significantly less than DCF.

Another important metric is quality-of-service (QoS), which can be measured by variations in packet delivery service. Low PDR may not be a problem to certain applications, but large variation in PDR limits the usability of the network, especially in those applications that require periodic services. Fig. 9(a) shows standard deviation of PDR for 50 and 100 CBR sources. As shown in the figure, DCF results in significant variations in PDR compared with PSP (again, when traffic intensity is low, the PSP shows a larger variation). This is expected because packets traversing a hot spot area would experience severe interference, while those traversing sparse areas would be routed with minimal contention/interference. More importantly, we observed “blackout” CBR sources that could not deliver any

packets during the simulation. Fig. 9(b) shows the percentage of these blackout sources among 50 and 100 designated sources. As many as 44% of the CBR sources are shut down with the DCF, while this effect is much lower with the PSP.

In order to investigate the performance improvement with the PSP, the MAC layer parameters were monitored during the simulation. Fig. 10 shows the success ratio of RTS-CTS handshake. The percentage of the CTS receptions relative to the RTS transmissions is illustrated in Fig. 10(a) and (b) for PSP and DCF, respectively. Nodes that transmit less than 10 RTS packets were not included in this graph. 100 CBR sources and 0.2 packet rate were used for this experiment. More than half of the nodes are successful in RTS-CTS handshaking for more than 60% of the time (marked as large dots) with PSP as shown in Fig. 10(a). In comparison, with DCF, most of nodes receive a CTS packet less than 30% of time in response to RTS packets (marked as triangles) as in Fig. 10 (b).

Fig. 11 shows the average contention window size of each node. This average was obtained by sampling the window size when each node decides to transmit a packet. When a

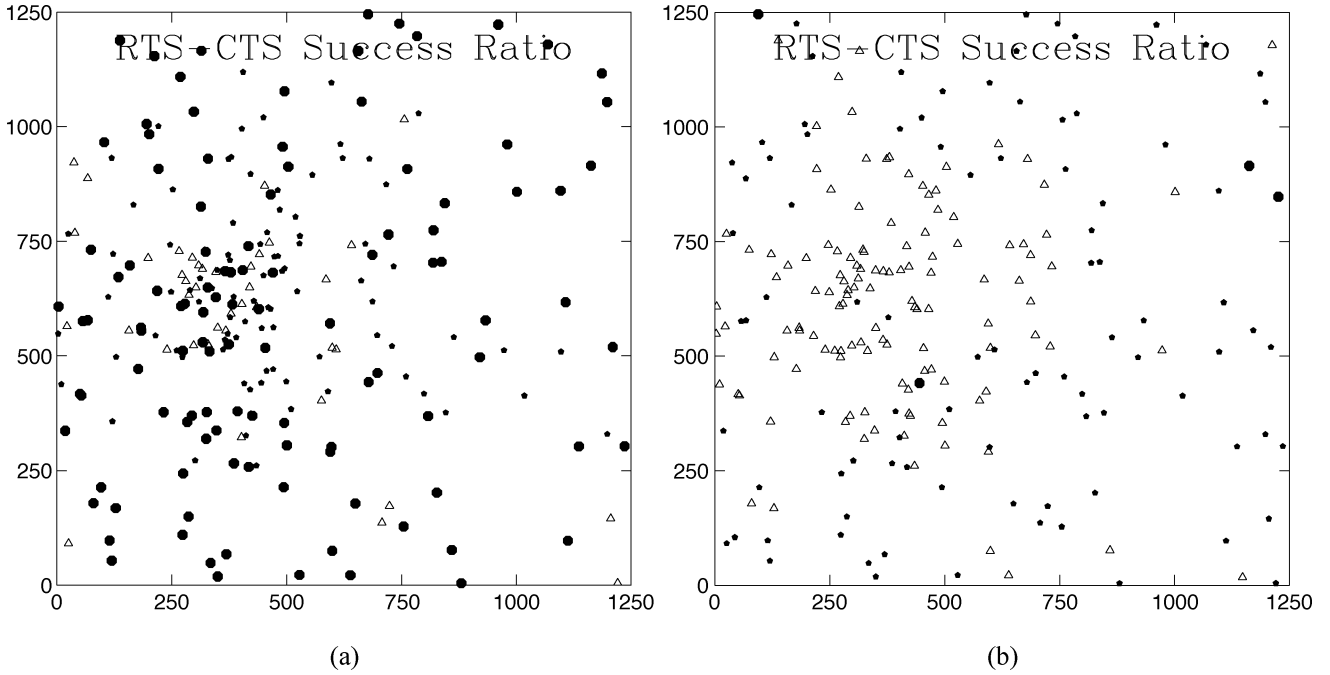


Fig. 10. Success ratio of RTS-CTS handshake (triangle: $<30\%$, small dot: $30\% - 60\%$, large dot: $>60\%$). (a) With PSP. (b) With DCF.

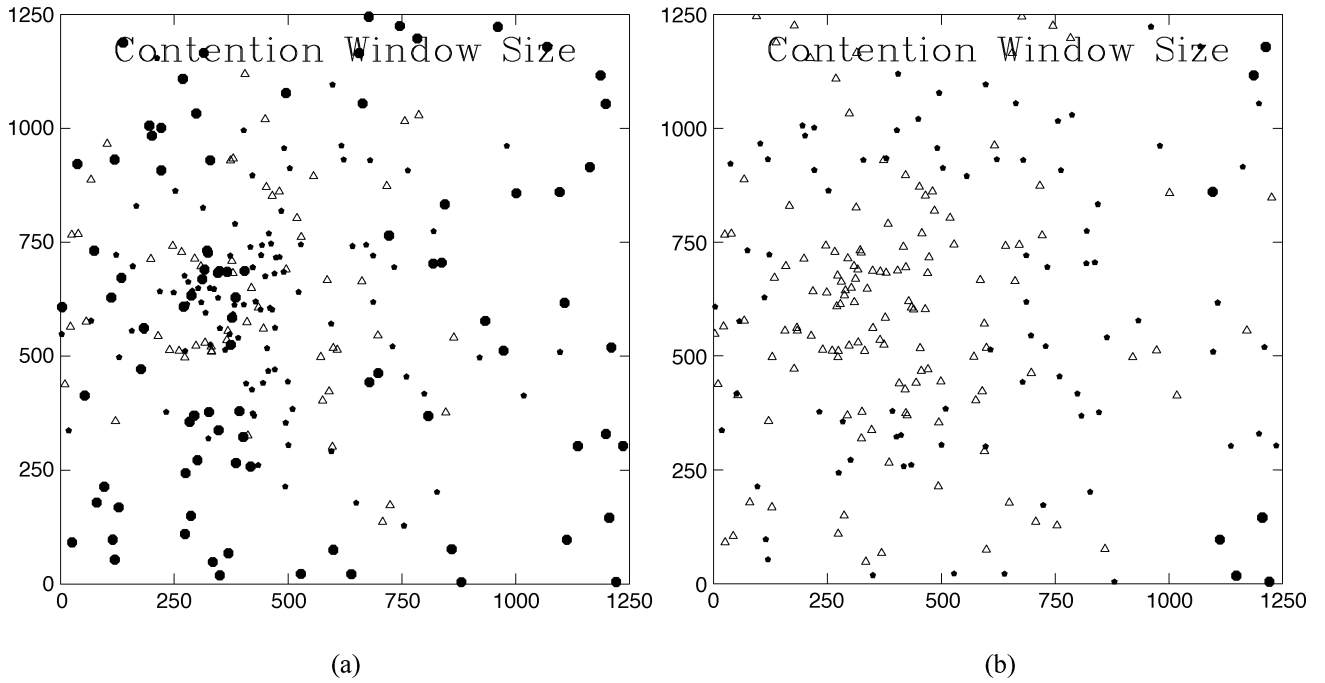


Fig. 11. Average contention windows size (triangle: >192 slots, small dot: $96 - 192$ slots, large dot: <96 slots). (a) With PSP. (b) With DCF.

packet collides, each node adjusts its contention window size to reduce the chance of further collisions. In our simulation study, the minimum window size is 32 and is doubled whenever a collision occurs until the maximum window size (1024) is reached. As shown in Fig. 11(a), the contention window size is smaller than 96 (marked as large dots) for more than half of the nodes with PSP, while it is mostly larger than 192 (marked as triangles) with DCF as in Fig. 11(b). Here, a larger window size with DCF means a longer backoff time and indicates that the node experiences more collisions. Summarizing the results

in Figs. 10 and 11, we can conclude that the performance advantage of PSP over DCF (Figs. 7–9) comes from the improved MAC layer behavior.

VI. CONCLUSION AND FUTURE WORK

This paper studied the capacity scalability of a multihop ad hoc network when node distribution is not random, and proposed the PSP algorithm. The clustered layout of nodes was characterized and modeled based on the topology generation

with a heavy-tail distribution used in modeling the Internet. Based on extensive simulation study using the ns-2 network simulator, the PSP algorithm is shown to provide much better performance than DCF in terms of average packet delay and packet delivery ratio. The PSP algorithm has a number of advantages over previously proposed power-control schemes as follows. First, no separate frequency channel is needed for control packets; second, frequent power adjustment is not required, thus avoiding nonnegligible overhead of power-level changes, and; finally, the performance of MAC and routing layer protocols does not deteriorate even in the presence of asymmetric links

While the PSP algorithm alleviates the problem associated with the clustered layout, even better performance can be achieved by considering the following issues. First, rather than using node degree (connectivity) to initiate the step-up or step-down procedure, traffic-based triggering is more promising as was discussed in Section IV. Second, step-up and step-down procedures in PSP are either perfectly safe or conservative. While this provision is necessary to preserve the power-stepped MANET, there could a more aggressive stepping procedure that will yield better performance. Third, since broadcast is much more error-prone than unicast due to the lack of link-level acknowledgment in wireless communication, it is not clear whether the PSP algorithm will continue to work when *Hello* messages are lost or corrupted. We are currently investigating these issues to offer a better and more realistic PSP-based solution that can be used in a MANET with the clustered layout of nodes.

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