Power-Stepped Protocol: A Novel Way of 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 a 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 (MAC) and network routing layers. A unique feature of this approach is to use the chosen radio power for both data and control packets in a single channel model, 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 to provide excellent performance in terms of packet delivery ratio and delay as well as the network capacity.

***Keywords**: Mobile ad hoc networks (MANETs), clustered network, node distribution, transmit power control, network capacity.*

1. 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 [6,16]. 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 [8, 27]. 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 density 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, actually nodes 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 the clustered layout for a non-negligible duration of 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 3, they render the *MAC (Medium Access Control)* layer protocol based on the IEEE 802.11 standards as well as network layer protocols, such as *AODV (Ad hoc On-demand Distance Vector)* [24], inoperable because control packets implementing these protocols usually work only on symmetric links. For this reason, most of TPC-based protocols are concerned primarily with low power transmission of data packets for energy conservation [5, 7, 12, 13, 20] or topology control [25, 26, 31], and assume that control packets are transmitted at the highest radio power.

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 may be avoided. In addition, PSP does not require each node to readjust its radio power 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 [7, 12, 13, 1] or a separate channel for control packets as suggested in

[19] may not be feasible in some real implementations. The proposed PSP is implemented and evaluated using the *ns-2* network simulator [21]. Our analysis and simulation will focus on static ad hoc networks because our primarily interest is in network capacity rather than dynamic adaptability in a mobile environment.

The paper is organized as follows. Section 2 introduces the clustered layout and its characteristics. Section 3 presents the background information, focusing on the detrimental effect of asymmetric links on the MAC layer protocol and overviews the power-controlled MAC algorithms in the literature. Section 4 introduces the PSP algorithm and the corresponding power- stepping procedures executed by each node in coordination with its neighbors. In Section 5, the effectiveness of PSP on the clustered layout is demonstrated via ns-2 simulation. Finally, Section 6 makes concluding remarks and describes future work.

2. 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 and Clustered Layouts of Nodes

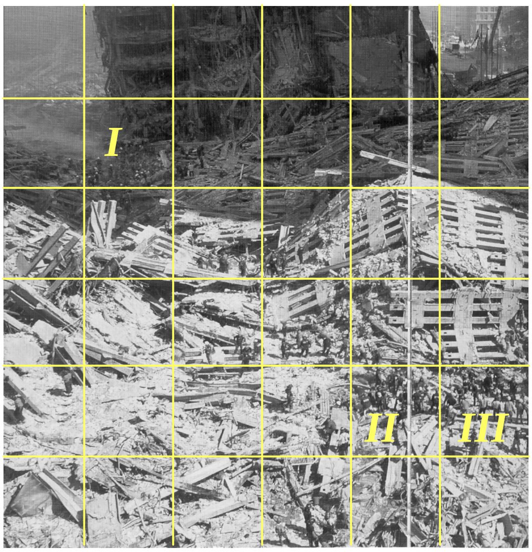
Since node mobility affects significantly the performance of a MANET, there has been active research in characterizing the general motion behavior and developing mobility models to be used for the simulation or analysis of MANETs. They include *Random Walk Model*, *Random Waypoint Model* [11], *Two-level Mobility Model*, *Reference Point Group Mobility Model* [9], and *Motion Vector Mobility Model* [10]. One important observation in most of these 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 $p_k = \frac{z^k e^{-z}}{k!}$, 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*! [32]. 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.

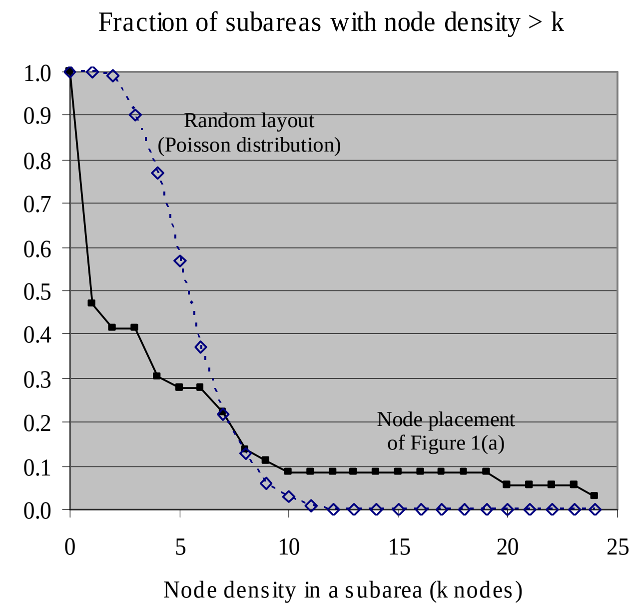
In a real network of mobile nodes, however, the node distribution can be very different from the Poisson distribution. For example, Fig. 1(a) shows an example of a disaster area where the infrastructure-less ad hoc network is well suited for supporting communication. Many rescue team members gather at 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 in a real ad hoc network situation. 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 [13, 30].

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 $F(k) = \frac{1-(a/k)^{\alpha}}{1-(a/b)^{\alpha}}$, where $a<k<b$, $0<\alpha<2$ [2].



(a) Rescue team at Ground Zero [28]

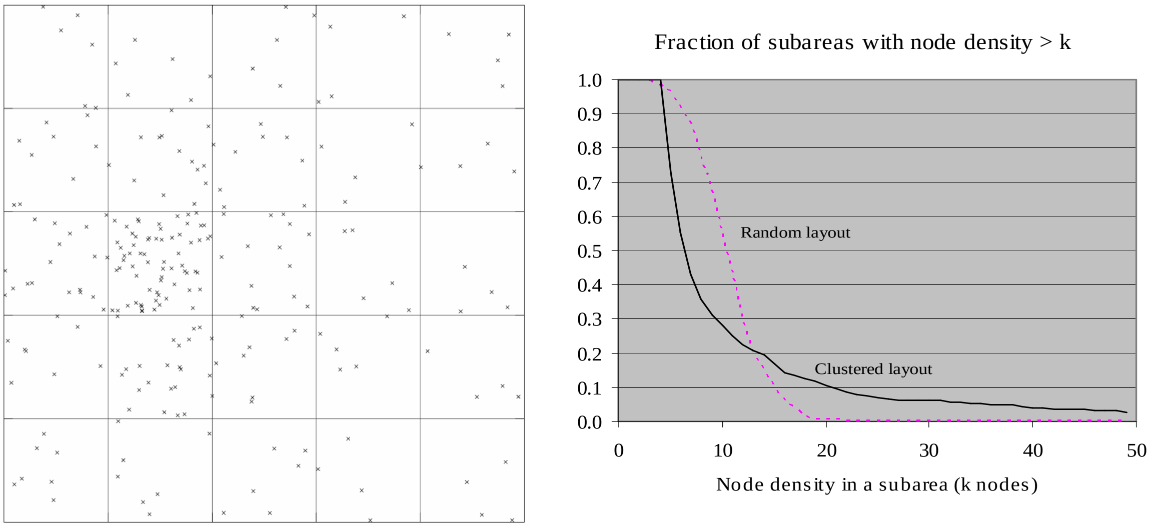


(b) Node density distribution

Fig. 1: Example of a clustered layout.

Topology Generation of Clustered Layout

While the aforementioned modeling technique is new to the area of MANETs, similar methods have been proposed to generate topology of Internet nodes. The *Waxman model* [18] is commonly used for topology generation. In this model, a predefined number of nodes are distributed randomly in a network area and a link is added between each pair of nodes with a certain probability that depends on the Euclidean distance between two end nodes of the link. In *BRITE* [18], the network area is divided into a number of squared subareas. For each square, the generator picks a number of nodes to be assigned to that square according



(a) Clustered layout (b) Node density distribution

Fig. 2. Clustered layout and its characteristics (250 nodes in a 1250×1250m^2 area).

to a bounded Pareto distribution.

We adopt the second approach to model the hot spots in a MANET. A subarea 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 subarea is determined, they are randomly positioned within that subarea. Fig. 2(a) shows the node distribution of the clustered layout generated with the above-mentioned method. The parameters used in the two examples are n=250, s=25, α=1.1, a=3, and b=100. These parameters are carefully chosen to exhibit a reasonable degree of clustering (with α=1.1) and to have the average number of nodes in each of 10 subareas (250/25 with a=3 and b=100). To visualize the distribution more clearly, Fig. 2(b) plots the node density distribution of the clustered layout in comparison to that of the random layout.

3. 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 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 interfering hidden terminals in the vulnerable regions, DCF includes an optional four-way handshake mechanism based on *Request-To-Send* (*RTS*) and *Clear-To-Send* (*CTS*) control packets and *Network Allocation Vector* (*NAV*). Moreover, DCF uses *EIFS* (*Extended Interframe Space*) to avoid collisions caused by the nodes within *interference range* (I_R), which is usually twice the *transmission range* (T_R) based on the signal propagation model[2] [12]. 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 especially effective in protecting the ACK reception 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 new vulnerable region due to interference, which is based on the transmit power of nodes *S* and *R* of 36.6 mW with T_R and I_R of 150 m and 300 m, respectively.

We now consider the effect of asymmetric links on the vulnerable region. As discussed in Section 1, the simple TPC scheme allows each node to adjust its transmit power without considering the power levels of its neighboring nodes. However, this creates asymmetric links, which, in turn, causes a large

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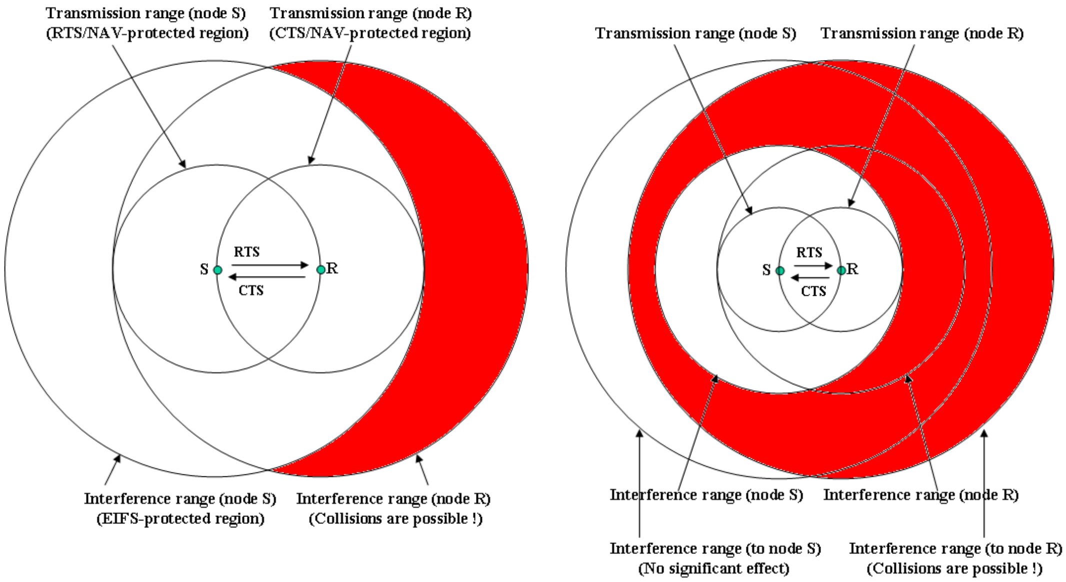
[1] The term, *vulnerable region*, is coined after the term, *vulnerable period*: In carrier sensing medium access protocols, in order for a node to transmit a packet successfully without collision, any other interfering nodes should not attempt to transmit during the first node's transmission. This was referred to as "*vulnerable period*" in [15].

[2] There 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 [23].



(a) One transmit power: T_R=150m (b) Two transmit powers: T_R=90m or 150m

Fig. 3: Vulnerable regions (shaded area) with different transmit powers.
(T_R denotes the transmission range and the corresponding interference range is assumed to be $2T_R$.)

vulnerable region, and the collision problem is further aggravated. 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 90m and 180m, respectively, as shown in Fig. 3(b). However, if there are higher-powered nodes around nodes *S* and *R*, e.g., a node with transmit power of 36.6 mW, these nodes may interfere with *R*'s reception. Thus, the vulnerable region becomes much larger as depicted in Fig. 3(b) resulting in a high collision probability. Therefore, the simple TPC scheme is not a feasible solution to the clustered layout problem.

Related Work

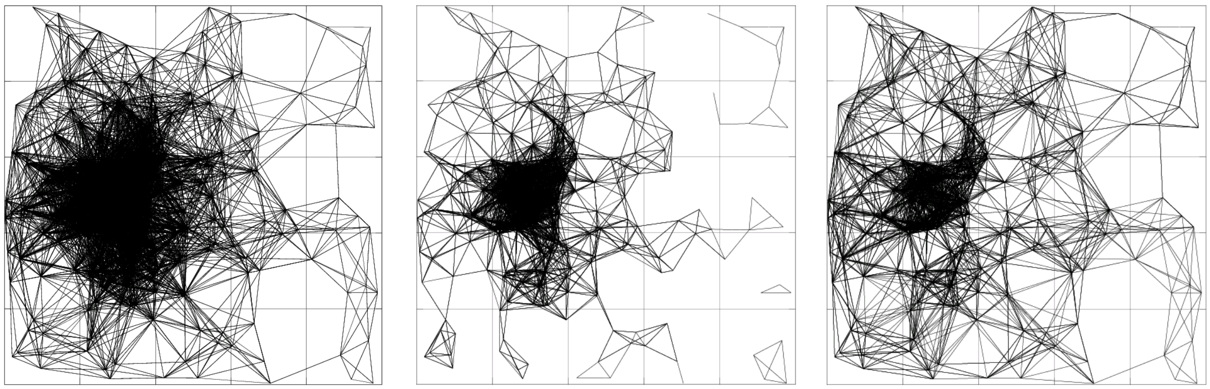
The TPC-based approach has been an active research area for various reasons such as energy conservation and topology and interference control. While most of the methods in the literature attempt to employ the TPC mechanism at the network layer [5, 20, 25, 26, 31], some recent proposals integrate the TPC mechanism at the MAC layer [7, 12, 13, 19, 1]. Gomez *et al.* proposed the use of the maximum power level for

RTS/CTS packets and lower power levels for data packets [7]. 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 data packets. In the *Power Control MAC* (*PCM*) protocol, data packets are also transmitted at its maximum power level (not always but periodically) because EIFS is only effective when data packets are transmitted at full power as discussed above [12]. In the *Distributed Power Control* (*DPC*) protocol, each node chooses different power levels for different neighbors to take into account the differences in distances [1]. In the *Power Controlled Multiple Access* (*PCMA*) protocol [19], 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* (*Smallest Common Powe*r) [20], which uses the smallest common power at which the network is connected. This approach works in a MANET with the random layout, but does not work well with the clustered layout because the selected power level is appropriate only in sparse areas but not in hot spots.

4. The 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).



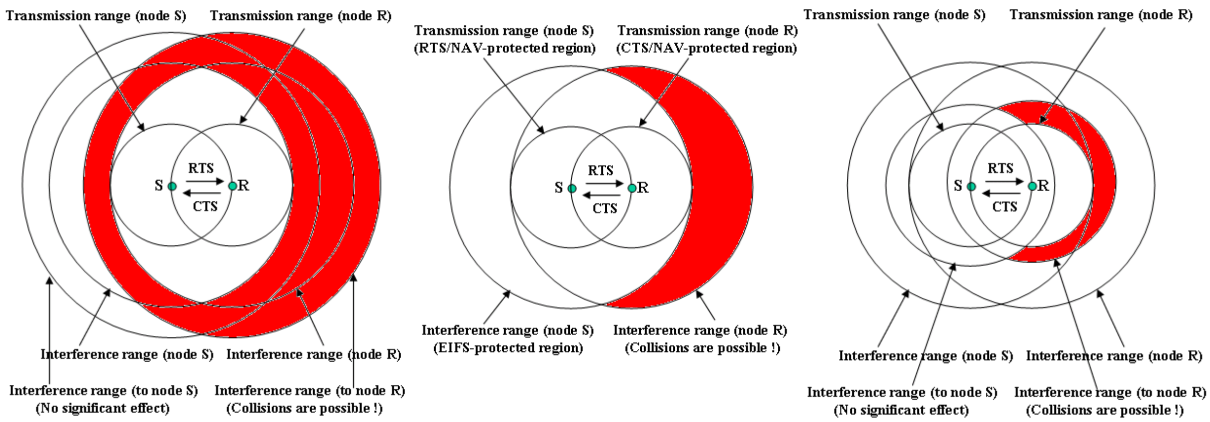
(a) With DCF: T_R=250m (b) With DCF: T_R=150m (c) With PSP: T_R=90~250m

Fig. 4: Topology variation with different transmit powers.

4.1 Example of PSP

To illustrate the effectiveness of PSP, let's consider a MANET with the clustered layout of 250 nodes in a 1250×1250 m^2 network area. Similar to the assumptions used in [4, 12, 20], five power levels of 4.8 mW, 10.6 mW, 36.6 mW, 115.4 mW and 281.8 mW are available with the corresponding transmission ranges of 90 m, 110 m, 150 m, 200 m and 250 m, respectively. When only one power level is available, the network topology can be illustrated as in Figs. 4(a) and 4(b), with T_R of 250 m 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 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 to the ones in Figs. 4(a) and 4(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 aggravating the vulnerable region. In order to illustrate how the PSP algorithm yields a smaller vulnerable region compared to the simple TPC, let's assume that two communicating nodes *S* and *R* use the radio power level of 4.8 mW (T_R=90 m). Since these two neighboring nodes have one of three



(a) Higher-level neighbors (b) Same-powered neighbors (c) Lower-level neighbors

Fig. 5: Vulnerable regions (shaded area) caused by three kinds of neighbors.
(T_R's of three types of neighbors are 150m, 110m, and 90m, respectively.)

power levels (one level higher, 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). Figs. 5(a), 5(b) and 5(c) show the resulting vulnerable regions for these three cases. As is the case of DCF, the PSP algorithm does not completely eliminate collisions. However, these figures clearly show that the vulnerable region does not increase greatly as compared to DCF, and is much smaller than the simple TPC scheme (see Fig. 3)[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 continuously 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.

[3] Simple calculation shows that, when T_R of nodes *S* and *R* is 90m, the maximum vulnerable region is 64530 m^2 with the PSP algorithm while it is 683610 m^2 with DCF (more than ten times larger). When T_R of nodes *S* and *R* is 110m, 150m or 200m, the ratio is 4.6, 2.1, and 1.0, respectively.

4.2 Power-Stepped MANET

This subsection 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

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.

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, $\Gamma(i) = \{j \mid \text{node } j \text{ that can reach node } i\}$ 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 rather easy to obtain $\Gamma(i)$ by receiving information from nodes in $\Gamma(i)$ but it is difficult to obtain $\gamma(i)$ because some nodes in $\gamma(i)$ with smaller power levels cannot reach node i while node i can reach 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 either the power-up or power-down "safe" so that the power level adjustment is guaranteed not to propagate. In PSP, a safe power-down is adopted, where a node steps its radio power-down only when the node uses the maximum radio power level among its neighbors.

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 $P_i' = P_i-1$. (i) 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. (ii) By definition, for all $j \in \gamma(i)-\Gamma(i)$, $P_j \le P_i$. 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. Q.E.D.

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 to 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.

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

<u>Proof</u>: It is necessary to prove that the two conditions in Definition 4 are preserved when nodes i changes its power level to $P_i' = P_i+1$. (i) 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. (ii) 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. Q.E.D.

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. This may cause the propagation of power level adjustments but not oscillation.

4.3 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* (*Ad hoc On-demand Distance Vector*) routing protocol [24], the PSP algorithm utilizes the *Hello* messages to exchange these information and to identify the mutual neighbors as suggested in [17].

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 PHY (physical) 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 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 are the ones that always have a packet ready for transmission [3]. Therefore, the performance results presented in Section 5 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 [14] and [29], where they considered the optimal number of nodes that maximizes the utilization without incurring excessive packet drops on retransmission-based *CSMA* (*Carrier Sense Multiple Access*) 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 case 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 is not 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 [17]. 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.

The 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 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.

```
// 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 (Γ(j), P_j, P_m(j)) from node j {
        // Update Γ(i), P_M(i), P_m(i), and P_m^2(i)
        Γ(i)= Γ(i)∪{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 ∈ Γ(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∈ Γ(i) for the last MAX_HELLO consecutive periods) {
                Γ(i)= Γ(i) - {j};
                Update Γ(i), P_M(i), P_m(i), and P_m^2(i);
        }

        // Safe step-down
        if (|Γ(i)| > MAX_THRESH) and (P_i = P_M(i)) and (P_i > MINP), P_i′= P_i-1;

        // Conservative step-up
        if (|Γ(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′≠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: The PSP algorithm with the power stepping procedures.

5. 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 [21], 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.

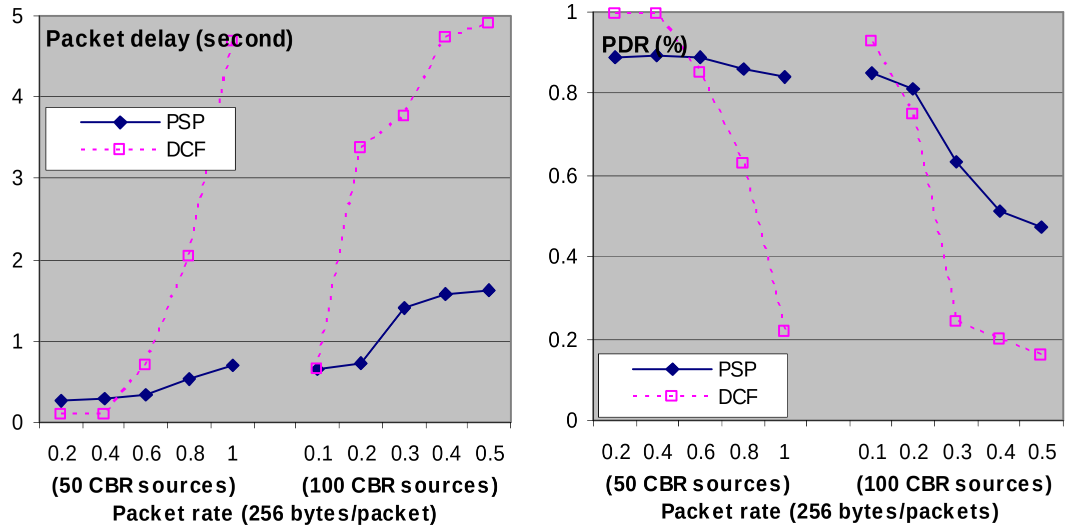
Simulation Environment

Similar to other previous studies on capacity analysis [8, 16, 27], our evaluation is based on the simulation of 250 "static" mobile nodes located over an area of 1250×1250 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 Mbps. For the clustered layout, a bounded Pareto distribution with parameters α=1.1, a=3, and b=100 is used to determine the number of nodes in each of 25 subareas (250×250 m^2 each) as discussed in Section 2.

The RTS-CTS-based MAC algorithm is used with the conventional backoff scheme. The AODV routing algorithm [24] is used to find and maintain the routes between two end-nodes. Data traffic simulated is constant bit rate (CBR) traffic: 15 to 100 CBR sources generate 256-byte data packet every 0.1~1.0 second. 15 to 75 TCP connections are also simulated to find the network capacity in the presence of interfering streams. 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 mobile 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

Figs. 7(a) and 7(b) show the network performance in terms of packet delay and *packet delivery ratio*

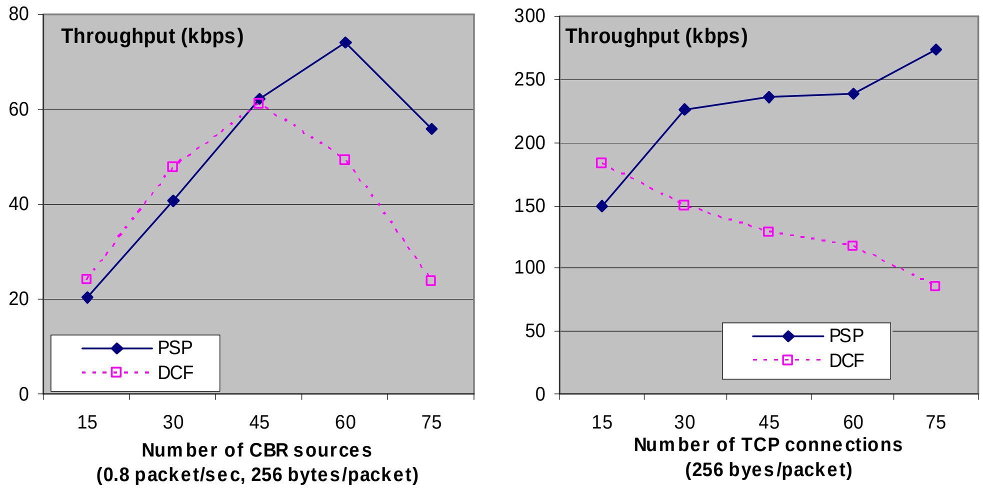


(a) Packet delay (second) (b) Packet delivery ratio (%)

Fig. 7. Performance comparison.

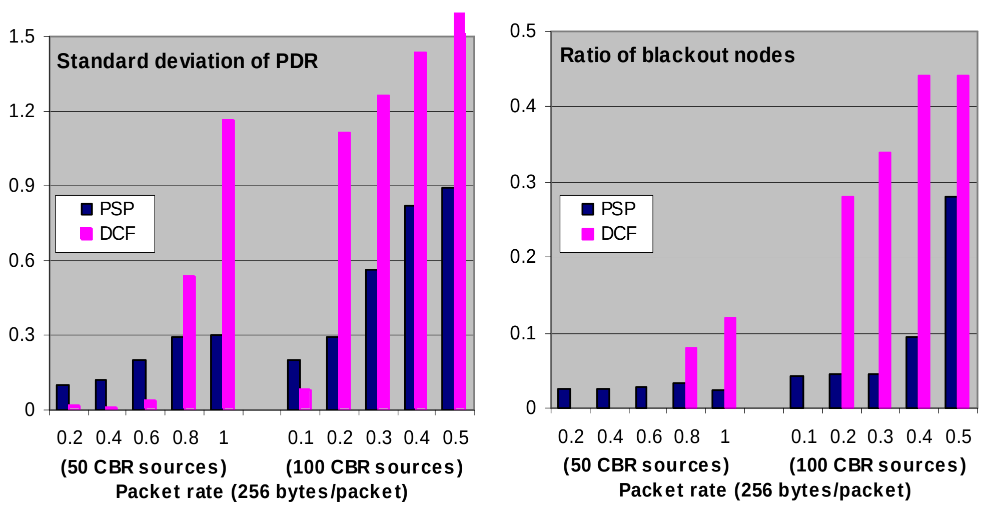
(*PDR*) with 50 and 100 CBR sources, respectively. Each of 100 CBR sources transmits 0.1~0.5 packets per second. As shown in the two figures, the network performance degrades faster with DCF compared to PSP. The PDR decreases as much as 39% and the average delay increases by as much as 371% when the number of CBR sources is 100. The difference is more significant with less 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 4.3, this is because the PSP algorithm simulated uses the node connectivity rather than traffic intensity as the decision factor to step up or down. If a combined metric (i.e., number of active nodes rather than all neighboring nodes) is used, the PSP is expected to always perform better than 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 performance degrades as the number of data streams increases, suggesting that inter-



(a) With CBR traffic (b) With TCP traffic

Fig. 8. Total end-to-end throughput (kbps)



(a) Standard deviation of PDR (b) Ratio of “blackout” nodes

Fig. 9. QoS performance.

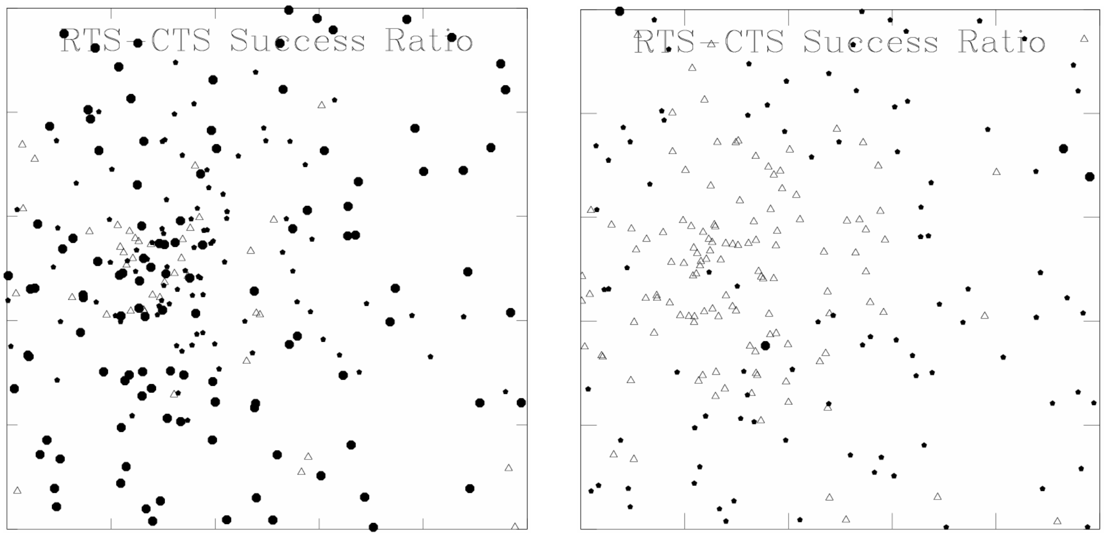
ference among the streams is a critical limiting factor in determining network capacity. However, when the number of TCP sources increases, the throughput of PSP increases while throughput of DCF decreases. This is because the degree of interference in PSP is significantly less than DCF.

A more serious problem is related to QoS (Quality of Service), 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 to 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.

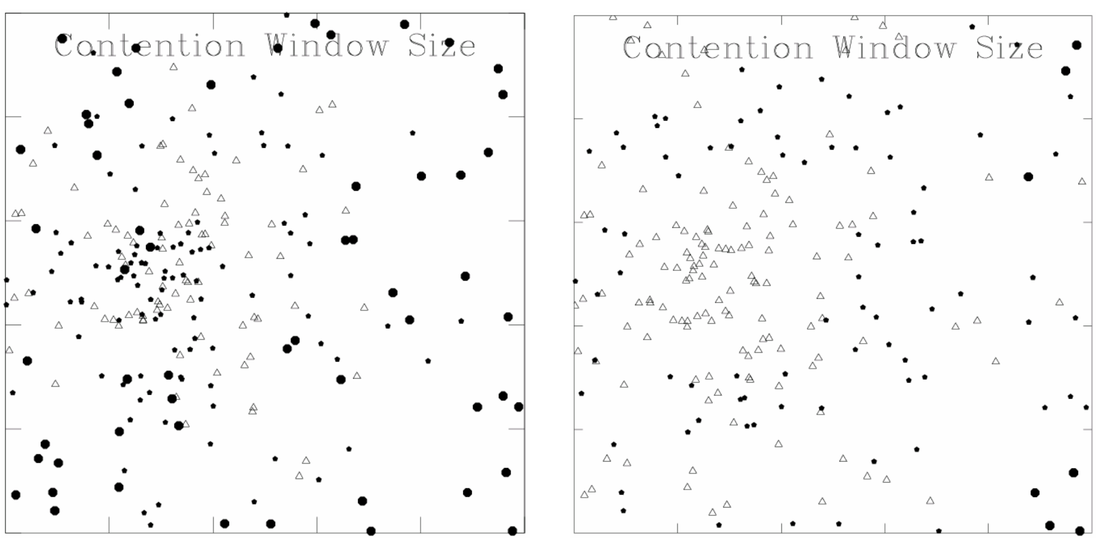
In order to investigate the performance improvement with the PSP, the MAC layer parameters were monitored during the simulation. Fig. 10 shows the success ratio of RTS-CTS handshake. The percentage of the CTS receptions relative to the RTS transmissions is illustrated in Figs. 10(a) and 10(b) for PSP 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 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).

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 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 Figs. 11(a) and 11(b), the contention window size is smaller than 96 for more than half of the nodes with PSP, while it is mostly larger than 192 with DCF. Summarizing the results in Figs. 10 and 11, we can conclude that the MAC layer protocol is one of the main causes of the performance degradation in DCF with the clustered layout.



(a) With PSP (b) With DCF

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).

6. Conclusions 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 non-negligible 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 4. 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 acknowledgement 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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