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The Broadcast Storm Problem in a Mobile Ad Hoc Network

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Abstract. Broadcasting is a common operation in a network to resolve many issues. In a mobile ad hoc network (MANET) in particular, due to host mobility, such operations are expected to be executed more frequently (such as finding a route to a particular host, paging a particular host, and sending an alarm signal). Because radio signals are likely to overlap with others in a geographical area, a straightforward broadcasting by flooding is usually very costly and will result in serious redundancy, contention, and collision, to which we call the *broadcast storm* problem. In this paper, we identify this problem by showing how serious it is through analyses and simulations. We propose several schemes to reduce redundant rebroadcasts and differentiate timing of rebroadcasts to alleviate this problem. Simulation results are presented, which show different levels of improvement over the basic flooding approach.

Keywords: broadcast, communication, mobile ad hoc network (MANET), mobile computing, wireless network

1. Introduction

The advancements in wireless communication and economical, portable computing devices have made mobile computing possible. One research issue that has attracted a lot of attention recently is the design of mobile ad hoc networks (MANET). A MANET is one consisting of a set of mobile hosts which may communicate with one another and roam around at their will. No base stations are supported in such an environment. Due to considerations such as radio power limitation, channel utilization, and power-saving concerns, a mobile host may not be able to communicate directly with other hosts in a *single-hop* fashion. In this case, a *multihop* scenario occurs, where the packets sent by the source host are relayed by several intermediate hosts before reaching the destination host.

Applications of MANETs occur in situations like battlefields or major disaster areas where networks need to be deployed immediately but base stations or fixed network infrastructures are not available. Unicast routing in MANET has been studied in several articles [7,8,15,16,23,25]. A working group called "manet" has been formed by the Internet Engineering Task Force (IETF) to study the related issues and stimulate research in MANET [22].

This paper studies the problem of sending a broadcast message in a MANET. Broadcasting is a common operation in many applications, e.g., graph-related problems and distributed computing problems. It is also widely used to resolve many network layer problems. In a MANET in particular, due to host mobility, broadcasting is expected to be performed more frequently (e.g., for paging a particular host, sending an alarm signal, and finding a route to a particular host [7,15,16,25]). Broadcasting may also be used in LAN emulation [3] or serve as a last resort to provide multicast services in networks whose topologies change rapidly.

In this paper, we assume that mobile hosts in the MANET share a single common channel with *carrier sense multiple access* (CSMA), but no collision detection (CD), capability. Synchronization in such a network with mobility is unlikely, and global network topology information is unavailable to facilitate the scheduling of a broadcast. So one straightforward and obvious solution is broadcasting by *flooding*. Unfortunately, in this paper we observe that serious redundancy, contention, and collision could exist if flooding is done blindly. First, because the radio propagation is omni-directional and a physical location may be covered by the transmission ranges of several hosts, many rebroadcasts will be redundant. Second, heavy contention could exist because rebroadcasting hosts are probably close to each other. Third, collisions are more likely to occur because the RTS/CTS dialogue is inapplicable and the timing of rebroadcasts is highly correlated.

Collectively, we refer to these problems associated with flooding as the *broadcast storm* problem. Through analyses and simulations, we demonstrate how serious the problem is. Two directions to alleviate this problem are to reduce the possibility of redundant rebroadcasts and to differentiate the timing of rebroadcasts. Following these directions, we develop several schemes, called *probabilistic*, *counter-based*, *distance-based*, *location-based*, and *cluster-based* schemes, to facilitate MANET broadcasting. Simulation results are presented to study the effectiveness of these schemes.

To the best of our knowledge, the broadcast storm problem has not been addressed in depth for MANET before. It is however worth summarizing some results for broadcasting that are for other environments. Works in [4,5,10–12,21] assume a packet-radio network environment. Most of these results rely on *time division multiple access* (TDMA, which requires timing synchronization) and certain levels of topology information. Their goal is to find a slot assignment. Obtaining an optimal assignment has been shown to be NP-hard [10]. The broadcast scheduling problem studied in [9,17,26,27], although carrying a similar name, is not intended to solve the problem addressed in this paper. Its goal is to assign a contention-free time slot to each radio station.

The rest of this paper is organized as follows. Section 2 defines and analyzes the broadcast storm problem. Mechanisms to alleviate the storm are proposed in section 3. Simulation results are presented in section 4 and conclusions are drawn in section 5.

2. Preliminaries

2.1. Broadcasting in a MANET

A MANET consists of a set of mobile hosts that may communicate with one another from time to time. No base stations are supported. Each host is equipped with a CSMA/CA (*carrier sense multiple access with collision avoidance*) [20] transceiver. In such environment, a host may communicate with another directly or indirectly. In the latter case, a *multihop* scenario occurs, where the packets originating from the source host are relayed by several intermediate hosts before reaching the destination.

The *broadcast problem* refers to the sending of a message to other hosts in the network. The problem considered here is assumed to have the following characteristics.

- *The broadcast is spontaneous.* Any mobile host can issue a broadcast message at any time. For reasons such as host mobility and lack of synchronization, preparing any kind of global topology knowledge is prohibitive (in fact this is at least as hard as the broadcast problem). Little or even no local connectivity information may be collected in advance.
- *The broadcast is unreliable.*[1] No acknowledgement mechanism will be used.[2] However, an attempt should be made to distribute a broadcast message to as many hosts as possible without paying too much effort. The motivations to make such an assumption are (i) a host may miss a broadcast message because it is off-line, it is temporarily isolated from the network, or it experiences repetitive collisions, (ii) acknowledgements may cause serious medium contention (and thus, another "storm") surrounding the sender, and (iii) in many applications (e.g., route discovery in [7,15,16,25]), a 100% reliable broadcast is unnecessary.

In addition, we assume that a host can detect duplicate broadcast messages. This is essential to prevent endless flooding of a message. One way to do so is to associate with each broadcast message a tuple (source ID, sequence number) as that in [7,25].

Finally, we comment that we do not confine ourselves to the broadcasting of the *same* message.[3] What we focus on in this paper is the message propagating behavior in a MANET – the phenomenon where the transmission of a packet will trigger other surrounding hosts to transmit the same (or modified) packet. We shall show that if flooding is used blindly, many redundant messages will be sent and serious contention/collision will be incurred. Our goal is to solve broadcast with efficiency in mind.

2.2. Broadcast storm caused by flooding

A straight-forward approach to perform broadcast is by *flooding*. A host, on receiving a broadcast message for the first time, has the obligation to rebroadcast the message. Clearly, this costs *n* transmissions in a network of *n* hosts. In a CSMA/CA network, drawbacks of flooding include:

- *Redundant rebroadcasts.* When a mobile host decides to rebroadcast a broadcast message to its neighbors, all its neighbors already have the message.
- *Contention.* After a mobile host broadcasts a message, if many of its neighbors decide to rebroadcast the message, these transmissions (which are all from nearby hosts) may severely contend with each other.
- *Collision.* Because of the deficiency of backoff mechanism, the lack of RTS/CTS dialogue, and the absence of CD, collisions are more likely to occur and cause more damage.

Collectively, we refer to the above phenomena as the *broadcast storm problem*. The following discussion shows how serious the problem is through analyses.

2.2.1. Analysis of redundant rebroadcasts

We first use two examples to demonstrate how much redundancy could be generated. In figure 1(a), it only takes two transmissions for the white node to broadcast a message, whereas four transmissions will be carried out if no attempt is made to reduce redundancy. Figure 1(b) shows an even

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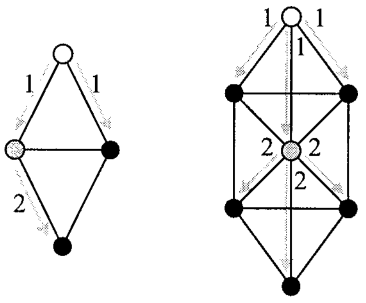
[1] A more strict one is *reliable broadcast* [1,24], whose goal is to ensure all hosts receive the message. High-level acknowledgements between hosts are exchanged. Such protocols are typically accomplished at the application layer and are out of the scope of this paper. However, the result in this paper may serve as an underlying facility to implement reliable broadcast.

[2] The MAC specification in IEEE 802.11 [20] does not require acknowledgement on receipt of broadcast packets.

[3] For instance, the routing protocols in [7,15,16,25] rely on broadcasting a UDP packet called *route_request* to search for a route from a source to a particular destination. When propagating such a request, a host generally appends its ID to the message so that appropriate routing information can be collected.



(a) (b)

Figure 1. Two optimal broadcasting schedules in MANETs. Connectivity between hosts is represented by links. White nodes are source hosts, and gray nodes are relay hosts.

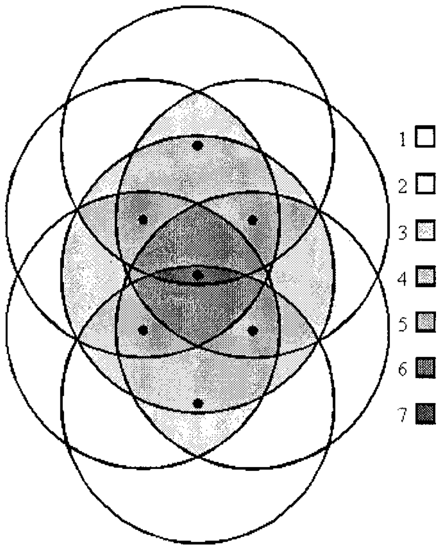


Figure 2. The signal overlapping problem corresponding to the scenario in figure 1(b).

more serious scenario: only two transmissions are sufficient to complete a broadcast as opposed to seven transmissions caused by flooding.

The main reason for such redundancy is that radio signals from different antennas are very likely to overlap with each other. Assuming that the area that can be covered by an antenna forms a circle, we show in figure 2 the signal overlapping problem corresponding to the scenario in figure 1(b). The gray levels in the figure indicate the levels of signal overlapping. As can be seen, many areas are covered by the same broadcast packet more than once. In the worst case, an area can be covered by the packet seven times.

In the following we will show through analyses that rebroadcasts are very costly and should be used with caution. First we consider the simple scenario in figure 3, where host **A** sends a broadcast message, and host **B** decides to rebroadcast the message. Let S_{A} and S_{B} denote the circle areas covered by **A**'s and **B**'s transmissions, respectively. The additional area that can benefit from **B**'s rebroadcast is the shaded region, denoted as $S_{\mathrm{B-A}}$. Let r be the radii of S_{A} and S_{B}, and d the distance between **A** and **B**. We can derive

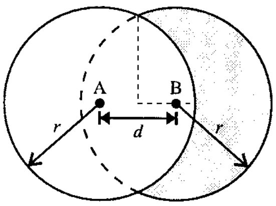


Figure 3. Analysis of the extra area that can benefit from a rebroadcast: **A** sends a broadcast packet and **B** decides to rebroadcasts the packet.

$|S_{\mathrm{B-A}}| = |S_{\mathrm{B}}| - |S_{\mathrm{A\cap B}}| = \pi r^2 - \mathrm{INTC}(d)$, where $\mathrm{INTC}(d)$ is the intersection area of the two circles centered at two points distanced by d,

$$\mathrm{INTC}(d) = 4\int_{d/2}^{r} \sqrt{r^2 - x^2}\,\mathrm{d}x.$$

When $d = r$, the coverage area $|S_{\mathrm{B-A}}|$ is the largest, which equals

$$\pi r^2 - \mathrm{INTC}(r) = r^2\left(\frac{\pi}{3} + \frac{\sqrt{3}}{2}\right) \approx 0.61\pi r^2.$$

This shows a surprising fact that a rebroadcast can provide only 0–61% additional coverage over that already covered by the previous transmission.

Also, we would like to know the average value of $\pi r^2 - \mathrm{INTC}(d)$. Suppose that **B** can randomly locate in any of **A**'s transmission range; the average value can be obtained by integrating the above value over the circle of radius x centered at **A** for x in $[0, r]$:

$$\int_0^r \frac{2\pi x \cdot [\pi r^2 - \mathrm{INTC}(x)]}{\pi r^2}\,\mathrm{d}x \approx 0.41\pi r^2.$$

Thus, after the previous broadcast, a rebroadcast can cover only additional 41% area on average.

Now consider the scenario of having received a broadcast message twice: if host **C** decides to rebroadcast after it heard **A**'s and **B**'s broadcasts. The area that can benefit from **C**'s rebroadcast is $S_{\mathrm{C-(A\cup B)}}$. Through simulations by randomly generating **A** and **B** on **C**'s transmission range, we found that on average $|S_{\mathrm{C-(A\cup B)}}| \approx 0.19\pi r^2$ (we remark that in the simulations the calculation of coverage was not derived by formal calculus, but by discrete estimation, where the area was partitioned into fine grids for approximation). This shows an even dimmer prospect of hoping that rebroadcasts propagate the message to new hosts.

In general, we would like to know the benefit of a host rebroadcasting a message after hearing the message k times. The result can be easily obtained from simulation by randomly generating k hosts in a host **X**'s transmission range and calculating the area covered by **X** excluding those areas already covered by the other k hosts. Denote this value by $\mathrm{EAC}(k)$ (EAC stands for *expected additional coverage*). Figure 4 shows our simulation result (again by grid estimation). As can be seen, when $k \geqslant 4$, the expected additional coverage is below 5%.

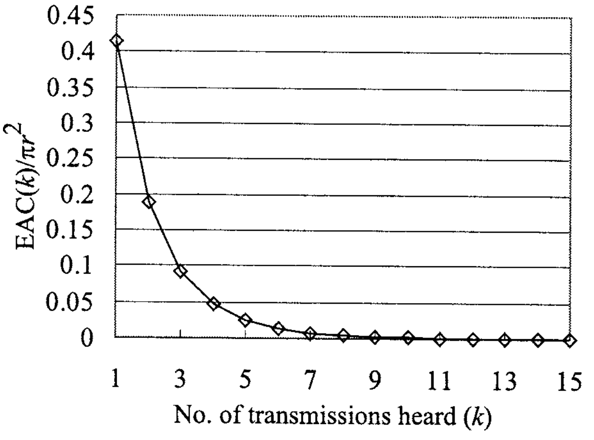


Figure 4. Analysis on redundancy: the expected additional coverage EAC(k) (divided by πr^2) after a host heard a broadcast message k times.

2.2.2. Analysis of contention

To address the contention problem, consider the situation where host **A** transmits a broadcast message and there are n hosts hearing this message. If all these hosts try to rebroadcast the message, contention may occur because two or more hosts around **A** are likely to be close and, thus, contend with each other on the wireless medium.

Let us analyze the simpler case of $n = 2$. Let hosts **B** and **C** be the two receiving hosts. Let **B** randomly locate within **A**'s transmission range. In order for **C** to contend with **B**, it must be located in the area $S_{\mathrm{A}\cap\mathrm{B}}$. So the probability of contention is $|S_{\mathrm{A}\cap\mathrm{B}}|/(\pi r^2)$. Let x be the distance between **A** and **B**. Integrating the above probability over the circle of radius x centered at **A** for x in $[0, r]$, the expected probability of contention is

$$\int_0^r \frac{2\pi x \cdot \mathrm{INTC}(x)/(\pi r^2)}{\pi r^2}\,\mathrm{d}x \approx 59\%.$$

Clearly, the contention is expected to be higher as n increases. We derived a simulation by randomly generating n hosts in **A**'s transmission range. We observe the probability $cf(n, k)$ that k hosts among these n hosts experience no contention in their rebroadcasting (*cf* stands for *contention-free*). The results are shown in figure 5. We can see that the probability of all n hosts experiencing contention (i.e., $cf(n, 0)$) increases quickly over 0.8 as $n \geqslant 6$. So the more crowded the area is, the more serious the contention is. On the other hand, the probability of having one contention-free host (i.e., $cf(n, 1)$) drops sharply as n increases. Further, it is very unlikely to have more contention-free hosts (i.e., $cf(n, k)$ with $k \geqslant 2$). Note that having $k = n - 1$ contention-free hosts implies having n such hosts, so $cf(n, n - 1) = 0$.

2.2.3. Analysis of collision

In a MANET, there is no base station or access point. Therefore, in this paper we exclude the use of the *point coordinate function* (PCF) described in the IEEE 802.11 MAC specification [20], and study mainly the behavior under the *distributed coordinate function* (DCF).

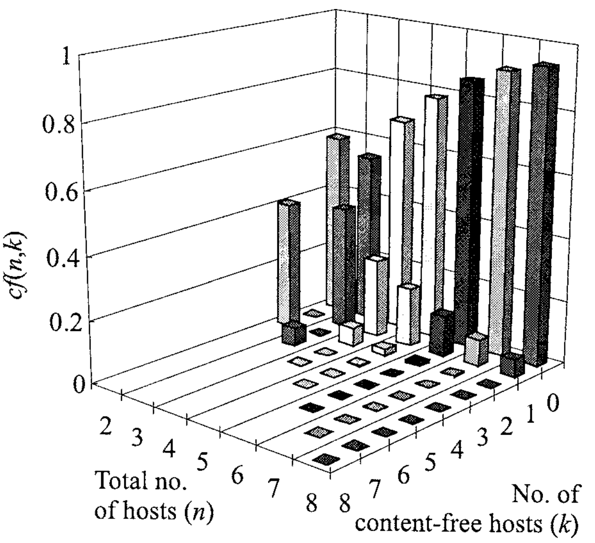


Figure 5. Analysis of contention: the probabilities of having k contention-free hosts among n receiving hosts.

The CSMA/CA mechanism requires a host to start a *backoff* procedure right after the host transmitted a message, or when a host wants to transmit but the medium is busy and the previous backoff has been done. To perform a backoff, a counter is first set to an integer randomly picked from its current backoff window. If the *channel clear assessment* (CCA) mechanism of the host detects no channel activity during the past *slot* (a fixed period), the counter is decreased by one. When the counter reaches zero, the backoff procedure is finished.

Now consider the scenario where several neighbor hosts hear a broadcast from host **X**. There are several reasons for collisions to occur. First, if the surrounding medium of **X** has been quiet for enough long, all of **X**'s neighbors may have passed their backoff procedures. Thus, after hearing the broadcast message (and having passed the DIFS period), they may all start rebroadcasting at around the same time. This is especially true if carriers can not be sensed immediately due to such as RF delays and transmission latency. Second, because the RTS/CTS forewarning dialogue is not used in a broadcast transmission, the damage of collision is more serious. Third, once collision occurs, without *collision detection* (CD), a host will keep transmitting the packet even if some of its foregoing bits have been garbled. And the longer the packet is, the more the waste.

The above problem is not addressed in the ordinary IEEE 802.11 MAC activities, possibly because the one-to-many communication behavior is not considered therein. For all the above reasons, we believe that the broadcast storm problem deserves serious study in a MANET environment.

3. Mechanisms to reduce redundancy, contention, and collision

One approach to alleviating the broadcast storm problem is to inhibit some hosts from rebroadcasting to reduce the redundancy, and thus, contention and collision. In the following, we present five schemes to do so. These schemes differ in how a mobile host estimates redundancy and how it accumulates knowledge to assist in making its decision. Except the last scheme, which relies on some local connectivity information, all schemes operate in a fully distributed manner.

3.1. Probabilistic scheme

An intuitive way to reduce rebroadcasts is to use probabilistic rebroadcasting. On receiving a broadcast message for the first time, a host will rebroadcast it with probability P. Clearly, when $P = 1$, this scheme is equivalent to flooding.

Note that to respond to the contention and collision problems addressed in sections 2.2.2 and 2.2.3, we should insert a small random delay (a number of slots) before rebroadcasting the message, so the timing of rebroadcasting can be differentiated.

3.2. Counter-based scheme

When a host tries to rebroadcast a message, the rebroadcast message may be blocked by a busy medium, the backoff procedure, and other queued messages. There is a chance for the host to hear the same message again and again from other rebroadcasting hosts before the host actually starts transmitting the message.

In section 2.2.1 we have shown that $\mathrm{EAC}(k)$, the expected additional coverage after hearing the message k times, is expected to decrease quickly as k increases. We can prevent a host from rebroadcasting when the expected additional coverage of the host's rebroadcast becomes too low. This is what the counter-based scheme is based on. Specifically, a counter c is used to keep track of the number of times the broadcast message is received. A counter threshold C is chosen. Whenever $c \geqslant C$, the rebroadcast is inhibited. The scheme is formally derived below.

S1. Initialize counter $c = 1$ when a broadcast message *msg* is heard for the first time. In S2, if *msg* is heard again, interrupt the waiting and perform S4.

S2. Wait for a random number of slots. Then submit *msg* for transmission and wait until the transmission actually starts.

S3. The message is on the air. The procedure exits.

S4. Increase c by one. If $c < C$, resume the interrupted waiting in S2. Otherwise $c = C$, proceed to S5.

S5. Cancel the transmission of *msg* if it was submitted in S2. The host is prohibited from rebroadcasting the same message in the future. Then the procedure exits.

Note that in S4, by "resume the interrupted waiting in S2", we mean that the host should go back to step S2 and wait for the remaining amount of time that it should have done after the point of interruption.

3.3. Distance-based scheme

In the previous scheme, a counter is used to decide whether to drop a rebroadcast or not. In this scheme, we will use the relative distance between hosts to make the decision.

For instance, suppose host **H** heard a broadcast message from **S** for the first time. If the distance, say d, between **H** and **S** is very small, there is little additional coverage **H**'s rebroadcast can provide. If d is larger, the additional coverage will be larger. In the extreme case, if $d = 0$, the additional coverage is 0 too. Earlier, we analyzed the relationship between the distance d and the additional coverage $\pi r^2 - \mathrm{INTC}(d)$. So this can be used as a metric by **H** to determine whether to rebroadcast or not.

Now, suppose that before a rebroadcast message is actually sent, host **H** has heard the same message several times. Let $d_{\min}$ be the distance to the nearest host from which the same message is heard. Then **H**'s rebroadcast will provide additional coverage no more than $\pi r^2 - \mathrm{INTC}(d_{\min})$. In our distance-based scheme, we will use $d_{\min}$ as the metric to evaluate whether to rebroadcast or not. If $d_{\min}$ is smaller than some distance threshold D, the rebroadcast transmission of **H** is cancelled. The scheme is formally derived below. In section 4, we will test several possible values of D.

S1. When a broadcast message *msg* is heard for the first time, initialize $d_{\min}$ to the distance to the broadcasting host. If $d_{\min} < D$, proceed to S5. In S2, if *msg* is heard again, interrupt the waiting and perform S4.

S2. Wait for a random number of slots. Then submit *msg* for transmission and wait until the transmission actually starts.

S3. The message is on the air. The procedure exits.

S4. Update $d_{\min}$ if the distance to the host from which *msg* is heard is smaller. If $d_{\min} < D$, proceed to S5. Otherwise, resume the interrupted waiting in S2.

S5. Cancel the transmission of *msg* if it was submitted in S2. The host is prohibited from rebroadcasting the same message in the future. Then the procedure exits.

Below, we comment on how to obtain the distance information. One possibility is to estimate from the signal strength of a received message. Specifically, let P_t and P_r be the power levels at which a message is sent and received, respectively. According to [28], $P_r = P_t(c_1/d)^n c_2$, where n, c_1, and c_2 are constants related to the physical environment, the carrier's wavelength, and antenna gains, respectively. Since P_r and P_t can be measured, the distance d can be estimated from this formula.

Having understood the relationship between the distance and the power, we can even directly replace the role of distances by signal strengths by establishing a signal-strength threshold. As a comment, we note that signal strength information was also used in [13] to facilitate routing in a MANET.

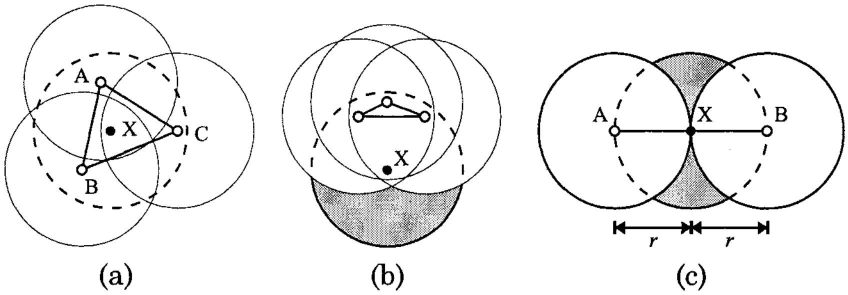


Figure 6. Scenarios of using convex polygons to determine whether to rebroadcast or not. (a) Host **X** is inside the triangle formed by three sending hosts. (b) **X** is outside of the polygon. (c) Analysis of maximum loss of additional coverage on using the polygon test.

3.4. Location-based scheme

Earlier we have used the number of times that a broadcast message has been heard or the distances to sending hosts as our rebroadcasting metrics. If we can acquire the locations of those broadcasting hosts, it is even possible to estimate the additional coverage more precisely. Such an approach may be supported by positioning devices such as GPS (Global Positioning System) receivers [18]. We note that location information was also used to facilitate route discovery in a MANET [6,19].

Without loss of generality, let a host's location be $(0, 0)$ (here we use xy-coordinates to facilitate our presentation; in fact, devices such as GPS receivers can provide 3-D locations in longitude, latitude, and altitude). Suppose a host has received the same broadcast message from k hosts located at (x_1, y_1), $(x_2, y_2), \dots, (x_k, y_k)$. We can calculate the additional area that can be covered provided that the host rebroadcasts the message. Let $AC((x_1, y_1), (x_2, y_2), \dots, (x_k, y_k))$ denote the additional coverage divided by πr^2. Then we can compare this value to a predefined coverage threshold A $(0 < A < 0.61)$ to determine whether the receiving host should rebroadcast or not. The scheme is formally derived below.

S1. When a broadcast message *msg* is heard for the first time, initialize AC to the additional coverage provided by the host's rebroadcast. If $AC < A$, proceed to S5. In S2, if *msg* is heard again, interrupt the waiting and perform S4.

S2. Wait for a random number of slots. Then submit *msg* for transmission and wait until the transmission actually starts.

S3. The message is on the air. The procedure exits.

S4. Update AC. If $AC < A$, proceed to S5. Otherwise, resume the interrupted waiting in S2.

S5. Cancel the transmission of *msg* if it was submitted in S2. The host is prohibited from rebroadcasting the same message in the future. Then the procedure exits.

One obstacle to using the above scheme is the cost of calculating AC, which is related to calculating many intersection areas among several circles. This problem is difficult already when there are four circles. One possibility is to use a grid-filling approximation to estimate its value.

An alternative is using a convex polygon to determine whether a rebroadcast should be carried out or not. For instance, suppose host **X** received a broadcast message three times from hosts **A**, **B**, and **C**. In figure 6(a), it shows that if **X** is inside the convex polygon formed by connecting the centers of **A**, **B**, and **C**, the additional coverage of **X**'s rebroadcast is small or even none. On the contrary, as shown in figure 6(b), if **X** is not in the polygon, it is likely that the rebroadcast will provide more additional coverage (the shaded area). These observations suggest that we can allow the host to rebroadcast only if it is not located within the convex polygon.

The following justifies the reason for the above convex approximation through geometry calculation. We show that if the polygon test prevents a host **X** from rebroadcasting (**X** is within the polygon), at most 22% of coverage will be lost in the extreme case. Observe that the additional coverage will be the largest when **X** is located on some boundary of the polygon. Let **A** and **B** be the two end points of that boundary. We see that the additional coverage will be the largest if **A** and **B** are each separated from **X** by the transmission range r as illustrated in figure 6(c). It is not hard to find that the size of the shaded area in figure 6(c) is

$$4\left[\int_0^{r/2}\sqrt{r^2-x^2}\,\mathrm{d}x-\int_{r/2}^{r}\sqrt{r^2-x^2}\,\mathrm{d}x\right]$$
$$=\left(\sqrt{3}-\frac{\pi}{3}\right)r^2\approx 0.22\pi r^2.$$

Now it is reasonable to say that if a host is in the convex polygon formed by the locations of previously sending hosts, the additional coverage that the host can provide is well below 22%.

3.5. Cluster-based scheme

The above schemes are based on *statistical* and *geometric* modeling to estimate the additional coverage of a rebroadcast. In the following, we show how to develop an approach based on *graph* modeling. Specifically, we will adopt the *clustering* concept of [2,16] to derive our scheme. Note that the clustering technique has been used to solve other problems

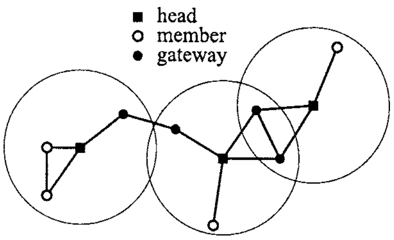


Figure 7. A MANET with three clusters.

in MANETs (e.g., traffic coordination [14], routing [14], and fault-tolerance [1]).

We first summarize the *cluster formation algorithm* proposed in [16]. It is assumed that a host periodically sends packets to advertise its presence. Thus any host can determine its connectivity with other hosts on its own. Each host has a unique ID. A cluster is a set of hosts formed as follows. A host with a local minimal ID will elect itself as a *cluster head*. This head host together with its neighbors will form a *cluster*. These neighbor hosts are called *members* of the cluster. Within a cluster, a member that can communicate with a host in another cluster is a *gateway*. To take mobility into account, when two heads meet, the one with a larger ID gives up its head role. Figure 7 shows an example of a clustered MANET.

Now back to our broadcast storm problem. We assume that clusters have been formed in the MANET and will be maintained regularly by the underlying cluster formation protocol. In a cluster, the head's rebroadcast can cover all other hosts in that cluster if its transmission experiences no collision. Apparently, to propagate the broadcast message to hosts in other clusters, gateway hosts should take the responsibility. But there is no need for a non-gateway member to rebroadcast the message. Based on these observations, our cluster-based scheme is formally developed as follows.

S1. When a broadcast message *msg* is heard for the first time, if the host is a non-gateway member, the rebroadcast is prohibited and the procedure exits. Otherwise, the host is either a head or a gateway. Proceed to S2.

S2. Use any of the probabilistic, counter-based, distance-based, and location-based schemes to determine whether to rebroadcast or not.

Note that the above scheme is derived by incorporating any of the schemes developed earlier into it. Step S1 is to prevent non-gateway members from rebroadcasting. As a cluster may still have many gateway members, step S2 then further utilizes other knowledge (such as additional coverage) to reduce the number of rebroadcasts.

4. Performance simulation

We have developed a simulator using C++. Central to the simulator is a discrete event-driven engine designed to simulate systems that can be modeled by processes communicating through signals. A simplified version of the MAC specification in IEEE 802.11 is referenced to simulate the CSMA/CA behavior among hosts.

The fixed parameters in our simulations are the transmission radius (500 m), the broadcast packet size (280 bytes), the transmission rate (1M bits per second), and the DSSS physical layer timing (PLCP overhead, slot time, inter-frame separations, backoff window sizing, as suggested in IEEE 801.11).

A geometric area called a *map* which contains 100 mobile hosts is simulated. A map can be of size 1×1, 3×3, 5×5, 7×7, 9×9, or 11×11 units, where a unit is of length 500 m (the transmission radius). Initially, hosts are randomly distributed over a map. To simulate host mobility, each host will roam around randomly in the map during the simulation. The roaming pattern of a host is simulated by generating a series of turns. In each turn, a direction, a velocity, and a time interval are generated. The direction is uniformly distributed from 0° to 360°, and the time interval uniformly distributed from 1 to 100 s. The velocity is randomly chosen from 0 to 10 km/h in a 1×1 map, and similarly from 0 to 30 km/h in a 3×3 map, from 0 to 50 km/h in a 5×5 map, from 0 to 90 km/h in a 9×9 map, and from 0 to 110 km/h in a 11×11 map, respectively. The arrival rate for the whole map is one broadcast request per second, and the broadcasting host is randomly picked for each request. Recall that we need to differentiate the timing of rebroadcasting. A small random delay ranging from 0 to 31 slots is inserted before each attempt at rebroadcasting (for instance, refer to step S2 of the counter-based scheme in section 3.2).

The performance metrics to be observed are:

- *REachability* (*RE*): the number of mobile hosts receiving the broadcast message divided by the total number of mobile hosts that are reachable,[4] directly or indirectly, from the source host.
- *Saved ReBroadcast* (*SRB*): $(r - t)/r$, where r is the number of hosts receiving the broadcast message, and t is the number of hosts that actually transmitted the message.
- *Average latency*: the interval from the time the broadcast was initiated to the time the last host finished its rebroadcasting.

4.1. Performance of the probabilistic, counter-based, distance-based, location-based, and cluster-based schemes

The simulation results of the probabilistic, counter-based, distance-based, location-based, and cluster-based schemes are shown in figures 8, 9, 10, 11, and 12, respectively. Each value in these figures is obtained through a simulation run of 10,000 broadcast requests.

Figure 8(a) shows the observed *RE* and *SRB* when applying the probabilistic scheme. In a small map (which implies a dense host distribution), a small probability P is sufficient to achieve high reachability. But a larger P is needed if the

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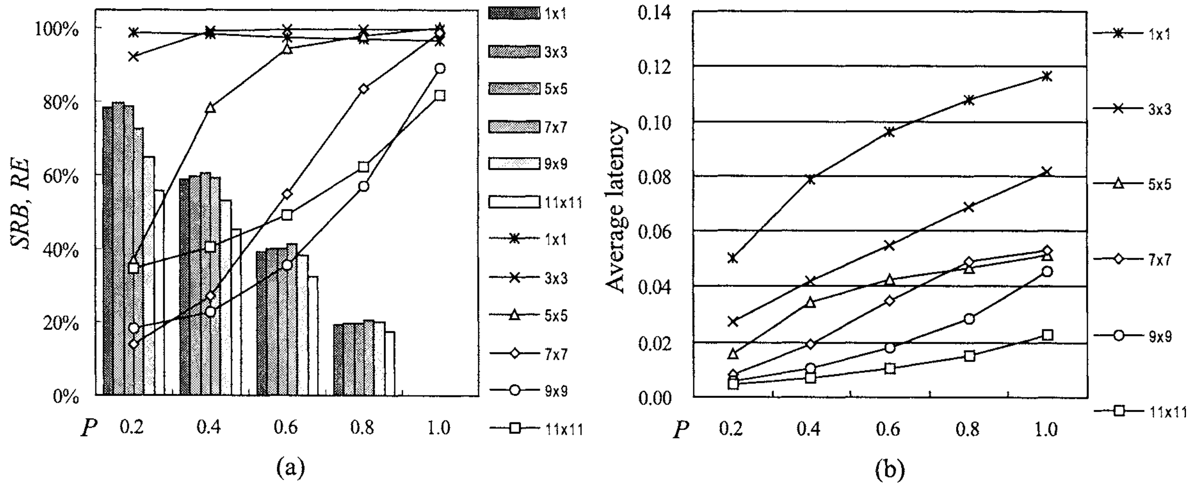
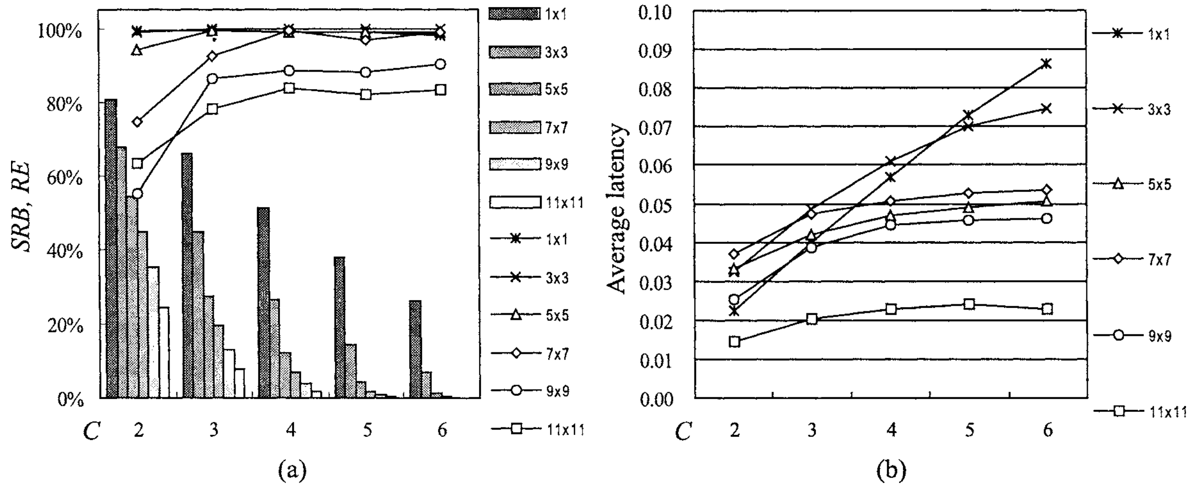
[4] This is to take the network partitioning problem into account.



(a) (b)

Figure 8. Performance of the probabilistic scheme. (a) Probability *P* versus reachability *RE* (shown in lines) and saved rebroadcast *SRB* (shown in bars). (b) Probability *P* versus average latency.



(a) (b)

Figure 9. Performance of the counter-based scheme. (a) Counter threshold *C* versus reachability *RE* (shown in lines) and saved rebroadcast *SRB* (shown in bars). (b) Counter threshold *C* versus average latency.

host distribution is sparse. The amount of saving (*SRB*) decreases, roughly proportionally to $(1 - P)$, as P increases. Also, note that the performance of broadcasting by flooding can be found at the position where the probability $P = 1$. Figure 8(b) shows the broadcast latency at various P values. Interestingly, a MANET with sparser hosts tends to complete broadcasting more quickly than one with denser hosts. The reason is probably due to the heavier contention on the channel in denser networks.

Figure 9 shows the performance of the counter-based scheme. From figure 9(a), we see that the reachability *RE* in fact reaches about the same level when the counter threshold $C \geqslant 3$. Note that when C is large enough (such as $C = 6$), the network's behavior is very close to one using flooding to broadcast. However, various levels of *SRB* can be obtained over the flooding scheme, depending on the density of hosts in a map. For instance, in denser maps (e.g., 1×1, 3×3, and 5×5) this scheme can offer 27–67% of *SRB* at $C = 3$, whereas in sparser maps (e.g., 7×7, 9×9, and 11×11) the scheme can offer 8–20% of *SRB*. When the map is very sparse (say 11×11) and C is very large (say 6), the amount of saving decreases sharply, because the number of neighbors of a host becomes very small (2.4 neighbors per host in an 11×11 map in average). Under such conditions, it is less likely that a host will receive the same broadcast message more than C times. We recommend that a threshold C of 3 or 4 is probably a reasonable choice.

The performance of the distance-based scheme is shown in figure 10. Note that the values of threshold D in the figure are chosen purposely to make a reasonable comparison between the distance-based scheme and the counter-based scheme. For instance, when $C = 2$, we know that $\mathrm{EAC}(2) \approx 0.187$ from figure 4. So we choose a D to match this value of addition coverage, i.e., $(\pi r^2 - \mathrm{INTC}(D))/(\pi r^2) \approx 0.187$. This gives a $D = 147$. The other D values along the x-axis in figure 10 are derived in a similar way. Note that when D is small enough (such as $D = 11$), the network's behavior is very close to one using flooding to broadcast.

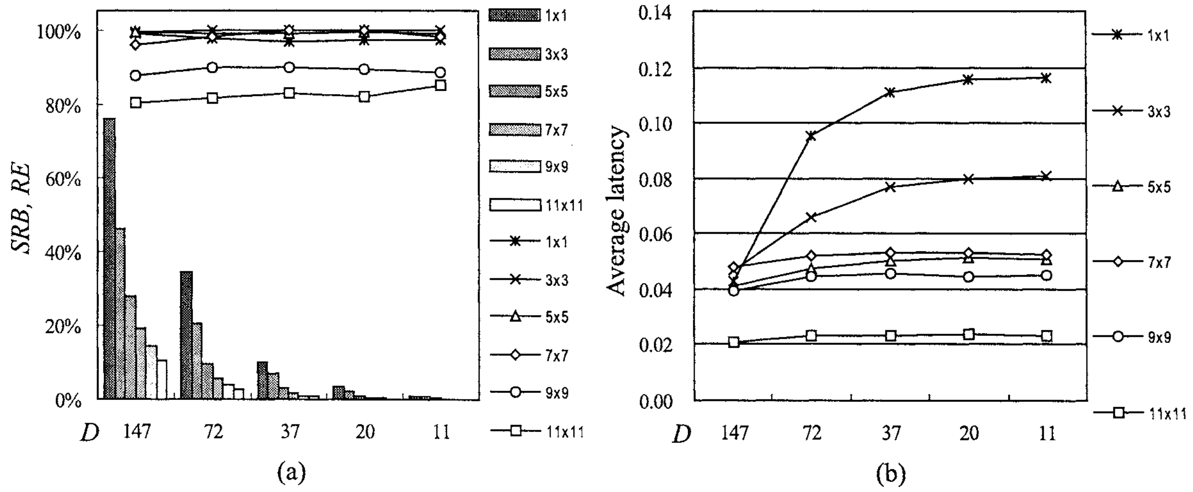


Figure 10. Performance of the distance-based scheme. (a) Distance threshold *D* versus reachability *RE* (shown in lines) and saved rebroadcast *SRB* (shown in bars). (b) Distance threshold *D* versus average latency.

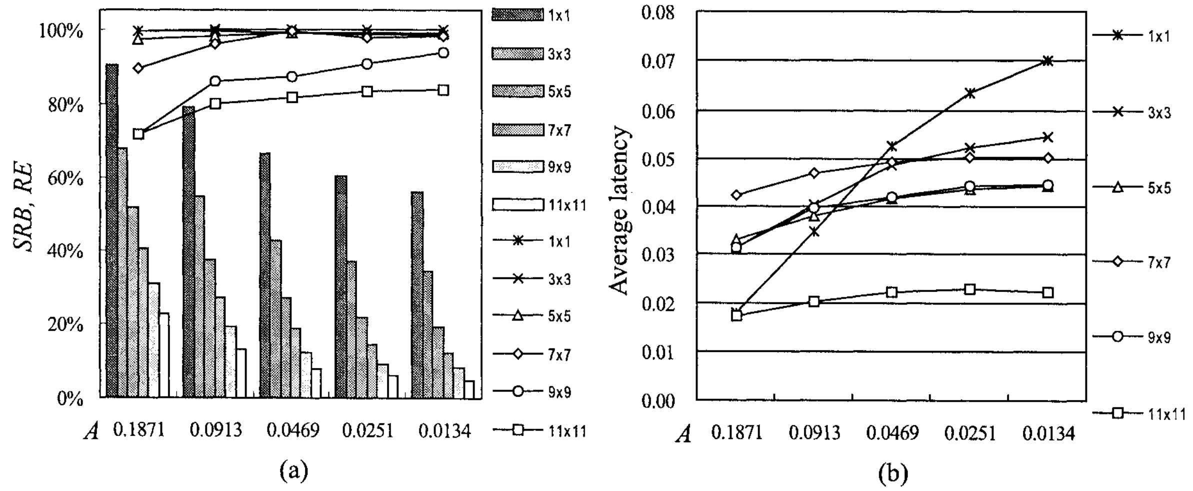


Figure 11. Performance of the location-based scheme. (a) Coverage threshold *A* versus reachability *RE* (shown in lines) and saved rebroadcast *SRB* (shown in bars). (b) Coverage threshold *A* versus average latency.

By comparing figures 9(a) and 10(a), we observe that the distance-based scheme can provide better reachability. But not many rebroadcasts are saved – its *SRB* values are worse than those of the counter-based scheme. Also, its broadcast latency is higher than that of the counter-based scheme, as shown in figures 9(b) and 10(b). The reason that the distance-based scheme saves less among of rebroadcasts than the counter-based scheme is as follows. In the distance-based scheme, a host may have heard a broadcast message many times but still decide to rebroadcast the message because none of the transmission distances are below the distance threshold D, whereas the rebroadcast may be canceled if the counter-based scheme is used.

Figure 11 illustrates the performance of the location-based scheme at various threshold values of A. Note that the values of A in the figure are chosen purposely to make a fair comparison with the distance-based and counter-based schemes (recall the earlier discussion about how to choose the values of D in figure 10). Clearly, as compared to the counter-based and distance-based schemes, the location-based scheme has the best reachability *RE* and the best saving *SRB*. Because of the saving, the broadcast latency is also the best among all schemes. The reason is that the location-based scheme uses the most accurate information (i.e., locations of the transmitting hosts) to determine the additional coverage of a rebroadcast.

Figure 12 shows the performance of the cluster-based scheme where the location-based scheme is incorporated in its step S2. Compared to the original location-based scheme, the cluster-based scheme apparently saves much more rebroadcasts and leads to shorter average broadcast latencies. Unfortunately, the reachability is unacceptable at sparser areas (such as 7×7, 9×9, and 11×11 maps). This is probably because when the number of hosts participating in rebroadcasting is reduced (mostly by its step S1), the collisions caused by the hidden terminal problem will significantly re-

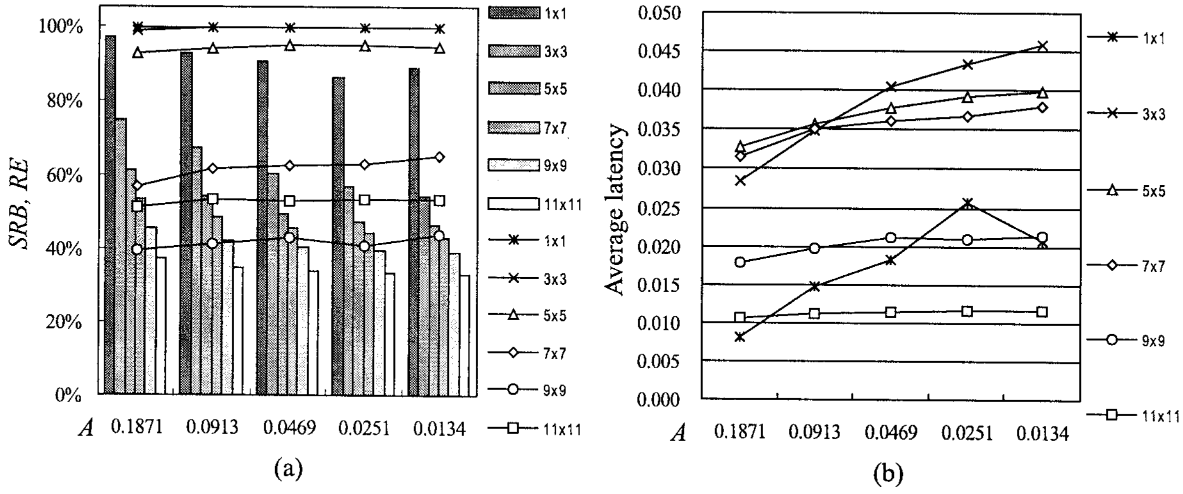


Figure 12. Performance of the cluster-based scheme by applying the location-based scheme in its step S2. (a) The coverage threshold A versus reachability RE (shown in lines) and saved rebroadcast SRB (shown in bars). (b) The coverage threshold A versus average latency.

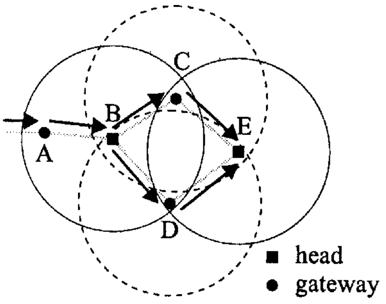


Figure 13. An example of the hidden terminal problem in the cluster-based scheme. Hosts **A**, **C**, and **D** are gateways, **B** and **E** are cluster heads.

duce the chance of successful transmissions. For example, figure 13 illustrates an interesting scenario where a broadcast packet was propagated through gateway **A** to head **B**. After **B** rebroadcasts the message, gateways **C** and **D** will try to rebroadcast the message. Unfortunately, because **C** and **D** can not hear each other, the two rebroadcasts from **C** and **D** are very likely to collide at **E**. Such problems of message corruption may significantly reduce the reachability, especially in sparser maps.

It is also worth mentioning that in figure 12(b) there is an anomaly that the broadcast latencies in a 1 × 1 map are particularly low. This is because in our simulations there were on average only 1.2 cluster heads. When there is only one head, the broadcast will be completed very quickly because there is no gateway.

4.2. The relationship between RE and SRB

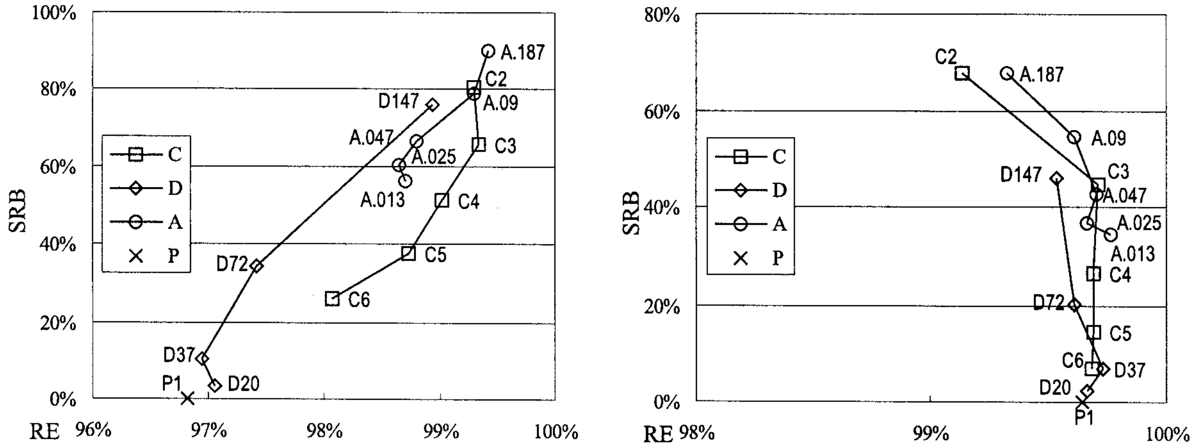
In the previous section, we have shown the reachability (*RE*) and the saved rebroadcasts (*SRB*) offered by different schemes at different threshold values. Apparently, it is desirable to have high *RE* as well as high *SRB*. In this section, we try to establish the relationship between these two metrics. In addition, we also provide a comparison among different schemes.

In figure 14, we show the *RE* and *SRB* offered by the counter-based, distance-based, and location-based schemes at different threshold values in various map sizes. These data are redrawn from figures 9(a), 10(a), and 11(a) through x–y scatter graphs. The x-axis indicates the *RE* and the y-axis indicates the *SRB*. So the parts closer to the upper-right corners of these graphs are more desirable.

Figure 14(a) shows that in a 1 × 1 map, both *RE* and *SRB* approach toward the upper-right corner of the graph as a "less strict" threshold value is used in each of these three schemes ("less strict" in the sense that it is easier to satisfy the condition to prohibit a broadcast packet from being rebroadcast). For instance, $C = 2$ is less strict than $C = 3$, $D = 147$ is less strict than $D = 72$, and $A = 0.187$ is less strict than $A = 0.09$. Since a 1 × 1 map indicates a more crowded scenario, this actually justifies the severity of the broadcast storm problem when mobile hosts are close to each other, and thus, reducing the possibility of rebroadcasting is very important. Overall, the location-based scheme with $A = 0.187$ is the best choice.

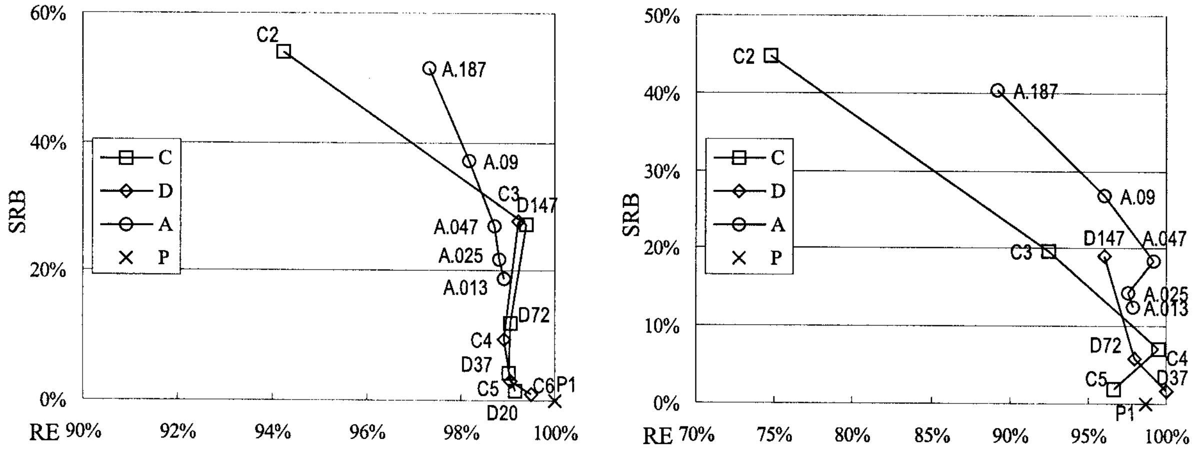
Figure 14(b) shows the same simulation results in a 3 × 3 map. The least strict threshold values ($C = 2$, $D = 147$, and $A = 0.187$) no longer offer the highest *RE* now. However, the *RE*'s offered by all schemes at all threshold values are all pretty satisfactory (all above 99%). So one could choose a scheme that offers the best *SRB*. Overall, the counter-based scheme with $C = 2$ and the location-based scheme with $A = 0.187$ are better choices.

Figures 14(c)–(f) show the results in larger maps. Generally speaking, in all three schemes, the relationship between *RE* and *SRB* shows a tradeoff: a higher *RE* will lead to a lower *SRB*, and vice versa. Thus, it really depends on whether one would emphasize *RE* or *SRB* when choosing an appropriate threshold value. As to the performance of these three schemes, the location-based scheme is still the best choice as its curve is closest to the upper-right corners of these graphs.



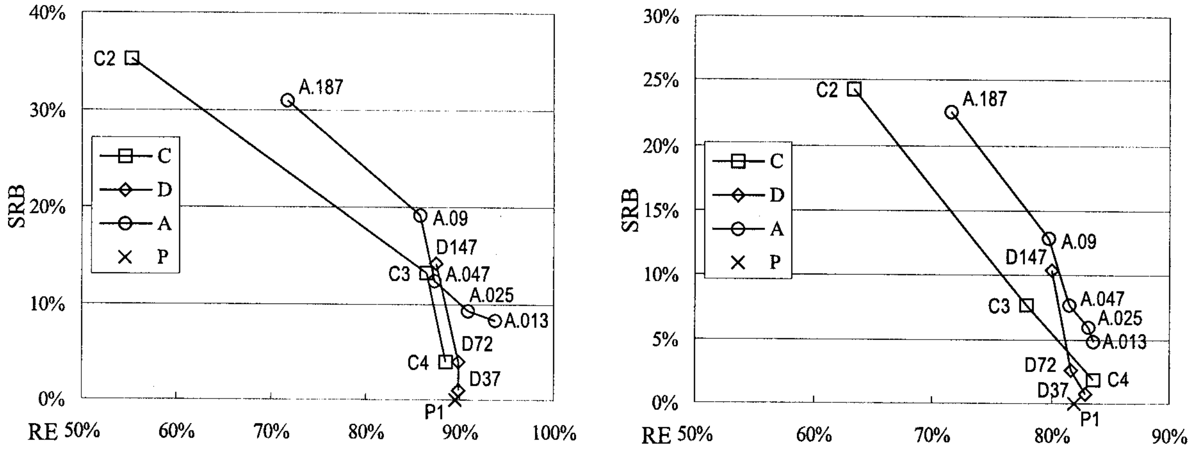
(a) 1x1 map

(b) 3x3 map



(c) 5x5 map

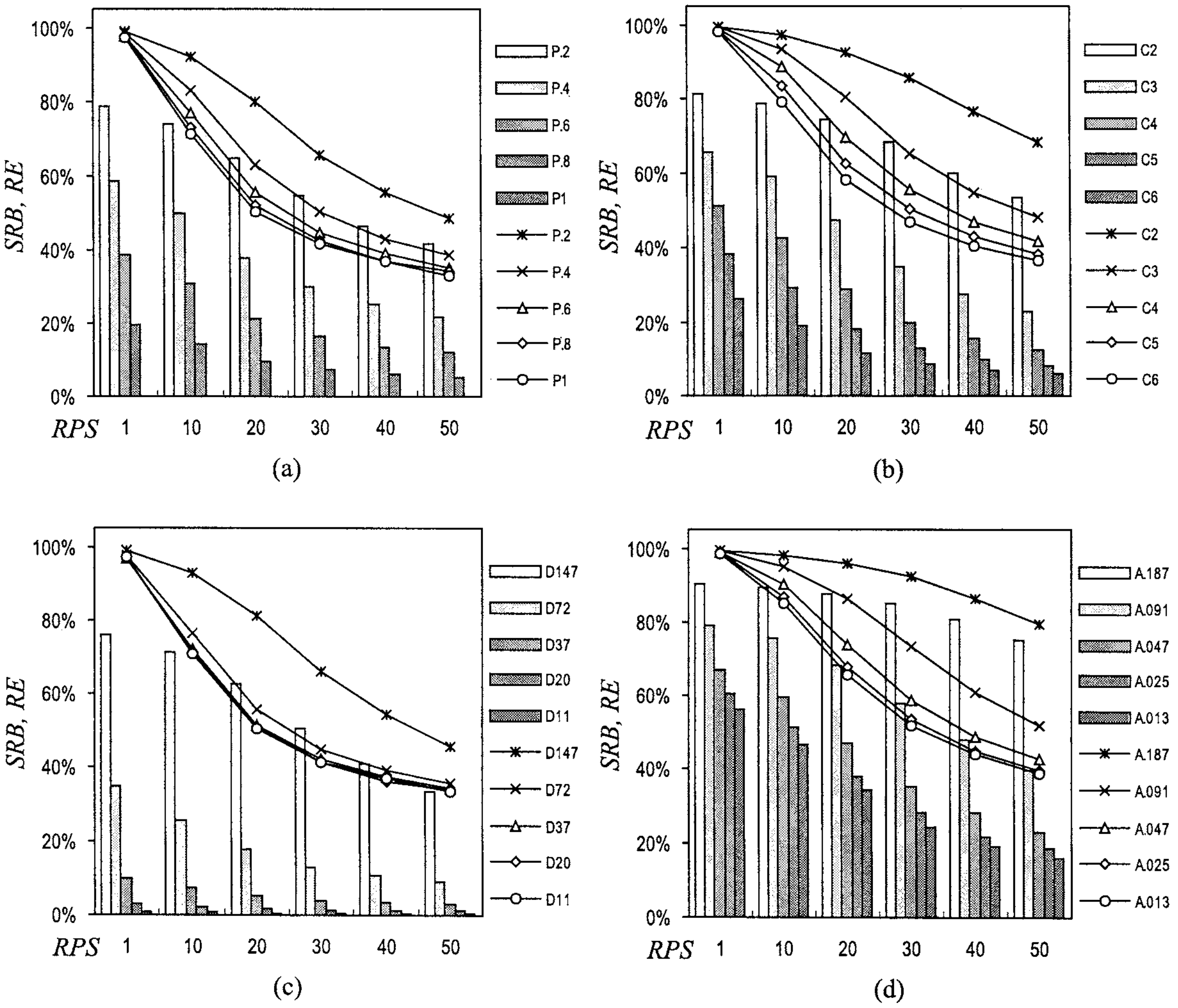
(d) 7x7 map



(e) 9x9 map

(f) 11x11 map

Figure 14. The reachability (*RE*) and save rebroadcast (*SRB*) offered by the probabilistic, counter-based, distance-based, and location-based schemes at different threshold values in various map sizes. These schemes are denoted by P, C, D, and A, respectively. The values appended to P, C, D, and A are the corresponding threshold values.



(a) (b) (c) (d)

Figure 15. The effect of load on *RE* and *SRB* in a 1 × 1: (a) probabilistic scheme, (b) counter-based scheme, (c) distance-based scheme, and (d) location-based scheme.

To conclude this section, observe that in each graph in figure 14, there is a point "P1", which indicates the *RE* and *SRB* offered by the probabilistic scheme with $P = 1$ (i.e., the flooding scheme, so its $SRB = 0$). As can be seen, except in a 5 × 5 map, it is always beneficial to adopt our proposed schemes as one can always find a scheme which offers a higher *RE* with a non-zero *SRB*.

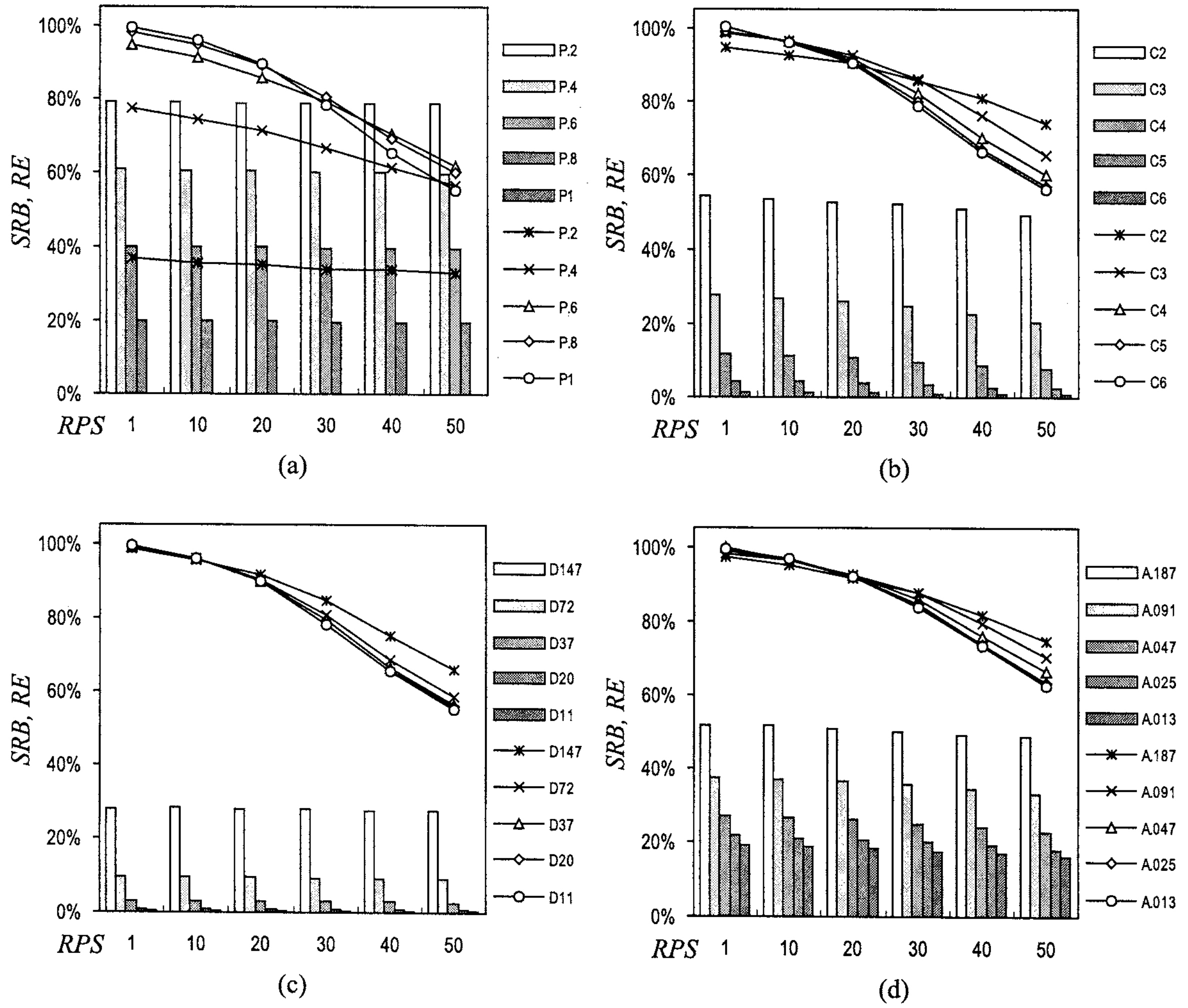
4.3. The effect of load

In all previous simulations, we have used an arrival rate of one broadcast request per second. We have also increased the arrival rates to 10, 20, 30, 40, and 50 broadcast requests per second to observe the effect. Four schemes, the probabilistic, counter-based, distance-based, and location-based schemes, were tested. The simulation results are shown in figures 15, 16, and 17 for maps of sizes 1×1, 5×5, and 9×9, respectively. Note that the value appended at each scheme indicates the threshold value used.

From these figures, we make three observations. First, we see an interesting fact that a heavier load will result in a lower reachability. This is true for all schemes, because a heavier load actually means more contention and collision among broadcast packets. The effect is more serious in denser maps than in sparser maps. We believe that this can justify the severity of the broadcast storm identified in this paper.

Second, to increase the reachability *RE*, a less strict threshold value should be used in smaller maps, whereas a stricter threshold value should be used in larger maps. Taking the counter-based scheme as an example, in figure 15(b), a threshold $C = 2$ will offer the highest *RE* in a 1 × 1 map. When a larger 5 × 5 map is considered, figure 16(b) shows that the counter-based scheme with $C = 2$ is no longer the best when the load is below 20 broadcast requests per second. However, it still has its advantage when the load is above 20. Moving to a much larger 9 × 9 map, figure 17(b) shows that $C = 2$ will offer the lowest *RE*. The same scenario can be observed in other schemes too. This observation also implies that a larger map can distribute the broadcast requests to larger physical areas, and thus lower the severity of contention and collision caused by rebroadcasting.

Third, we observe that for all schemes, the *SRB* will decrease as the load increases in a 1 × 1 map. This trend is



(a) (b) (c) (d)

Figure 16. The effect of load on *RE* and *SRB* in a 5 × 5: (a) probabilistic scheme, (b) counter-based scheme, (c) distance-based scheme, and (d) location-based scheme.

very unfavorable because this means that there are more hosts trying to help rebroadcast the broadcast packets, but the level of *RE* keeps on going down as load increases. Fortunately, in larger maps, such as 5 × 5 and 9 × 9, the *SRB* remains almost unchanged as load increases. This again justifies that the more crowded the area is, the more serious the broadcast storm is.

5. Conclusions

This paper has identified an important issue in a MANET, the broadcast storm problem. We have demonstrated, through analyses and simulations, how serious this problem could be. Several schemes, namely probabilistic, counter-based, distance-based, location-based, and cluster-based schemes, have been proposed to alleviate this problem. Simulation results based on different threshold values are presented to verify and compare the effectiveness of these schemes. As compared to the basic flooding approach, a simple counter-based scheme can eliminate many redundant rebroadcasts when the host distribution is dense. The distance-based scheme has higher reachability than the counter-based scheme, but the amount of saving (in terms of the number of saved rebroadcasts) is not satisfactory. Among all, the location-based scheme is the best choice because it can eliminate most redundant rebroadcasts under all kinds of host distributions without compromising reachability.

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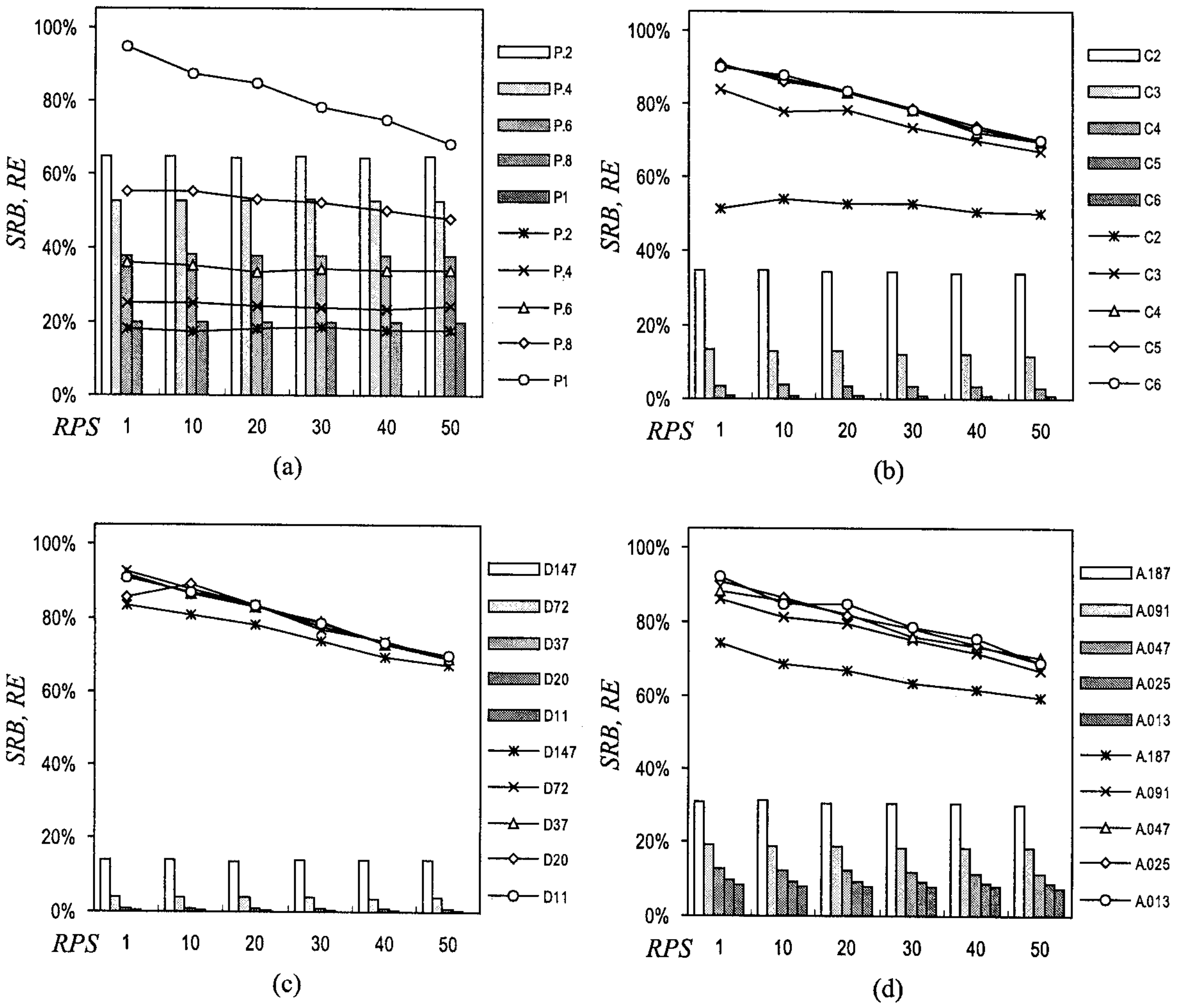

Figure 17. The effect of load on *RE* and *SRB* in a 9 × 9: (a) probabilistic scheme, (b) counter-based scheme, (c) distance-based scheme, and (d) location-based scheme.

References

[1] S. Alagar, S. Venkatesan and J. Cleveland, Reliable broadcast in mobile wireless networks, in: *Military Communications Conference (MILCOM), Conference Record*, Vol. 1 (1995) pp. 236–240.

[2] D.J. Baker and A. Ephremides, The architecture organization of a mobile radio network via a distributed algorithm, IEEE Transactions on Communications COM-29(11) (November 1981) 1694–1701.

[3] R. Bar-Yehuda, O. Goldreich and A. Itai, Efficient emulation of single-hop radio network with collision detection on multi-hop radio network with no collision detection, Distributed Computing 5(2) (1991) 67–72.

[4] R. Bar-Yehuda, O. Goldreich and A. Itai, On the time-complexity of broadcast in multi-hop radio networks: An exponential gap between determinism and randomization, Journal of Computer and System Sciences 45(1) (August 1992) 104–126.

[5] R. Bar-Yehuda, A. Israeli and A. Itai, Multiple communication in multi-hop radio networks, SIAM Journal on Computing 22(4) (August 1993) 875–887.

[6] S. Basagni, I. Chlamtac, V.R. Syrotiuk and B.A. Woodward, A distance routing effect algorithm for mobility (DREAM), in: *Proc. IEEE/ACM International Conference on Mobile Computing and Networking (MOBICOM)* (1998) pp. 76–84.

[7] J. Broch, D.B. Johnson and D.A. Maltz, The dynamic source routing protocol for mobile ad hoc networks, Internet Draft (work in progess) (1998) `draft-ietf-manet-dsr-00.txt`

[8] J. Broch, D.A. Maltz, D.B. Johnson, Y.-C. Hu and J. Jetcheva, A performance comparison of multi-hop wireless ad hoc network routing protocols, in: *Proc. IEEE/ACM Interference Conference on Mobile Computing and Networking (MOBICOM)* (1998) pp. 85–97.

[9] I. Chlamtac and A. Faragó, Making transmission schedules immune to topology changes in multi-hop packet radio networks, IEEE/ACM Transactions on Networking 2(1) (February 1994) 23–29.

[10] I. Chlamtac and S. Kutten, On broadcasting in radio networks – problem analysis and protocol design, IEEE Transactions on Communications COM-33(12) (December 1985) 1240–1246.

[11] I. Chlamtac and S. Kutten, Tree-based broadcasting in multihop radio networks, IEEE Transactions on Communications COM-36(10) (October 1987) 1209–1223.

[12] I. Chlamtac and O. Weinstein, The wave expansion approach to broadcasting in multihop radio networks, IEEE Transactions on Communications COM-39(3) (March 1991) 426–433.

[13] R. Dube, C.D. Rais, K.-Y. Wang and S.K. Tripathi, Signal stability based adaptive routing (SSA) for ad-hoc mobile networks, Technical report CS-TR-3646, University of Maryland, College Park (August 1996).

[14] M. Gerla and J.T.-C. Tsai, Multicluster, mobile, multimedia radio network, Wireless Networks 1(3) (1995) 255–265.

[15] Z.J. Haas and M.R. Pearlman, The zone routing protocol (ZRP) for ad hoc networks, Internet Draft (work in progess) (1998) `draft-ietf-manet-zone-zrp-01.txt`

[16] M. Jiang, J. Li and Y.C. Tay, Cluster based routing protocol (CBRP) functional specification, Internet Draft (work in progess) (1998) `draft-ietf-manet-cbrp-spec-00.txt`

[17] J.-H. Ju and V.O.K. Li, An optimal topology-transparent scheduling method in multihop packet radio networks, IEEE/ACM Transactions on Networking 6(3) (June 1998) 298–306.

[18] E.D. Kaplan (ed.), *Understanding GPS: Principles and Applications* (Artech House, Boston, MA, 1996).

[19] Y.-B. Ko and N.H. Vaidya, Location-aided routing (LAR) in mobile ad hoc networks, in: *Proc. IEEE/ACM International Conference on Mobile Computing and Networking (MOBICOM)* (1998) pp. 66–75.

[20] LAN MAN Standards Committee of the IEEE Computer Society, IEEE Standard 802.11-1997, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications (November 1997).

[21] C. Lee, J.E. Burns and M.H. Ammar, Improved randomized broadcast protocol in multi-hop radio networks, Technical report GIT-CC-93-14, College of Computing, Georgia Institute of Technology (February 1993).

[22] J.P. Macker and M.S. Corson, Mobile ad hoc networking and the IETF, ACM Mobile Computing and Communications Review 2(3) (July 1998) 7–9.

[23] A. Michail and A. Ephremides, Energy efficient routing for connection-oriented traffic in ad-hoc wireless networks, in: *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications* (2000) pp. 762–766.

[24] E. Pagani and G.P. Rossi, Reliable broadcast in mobile multihop packet networks, in: *Proc. IEEE/ACM International Conference on Mobile Computing and Networking (MOBICOM)* (1997) pp. 34–42.

[25] C.E. Perkins and E.M. Royer, Ad hoc on demand distance vector (AODV) routing, Internet Draft (work in progess) (1998) `draft-ietf-manet-aodv-02.txt`

[26] S. Ramanathan and E.L. Lloyd, Scheduling algorithms for multihop radio networks, IEEE/ACM Transactions on Networking 2(2) (April 1993) 166–177.

[27] A. Sen and M.L. Huson, A new model for scheduling packet radio networks, Wireless Networks 3 (1997) 71–82.

[28] E.K. Wesel, *Wireless Multimedia Communications: Networking Video, Voice, and Data* (Addison-Wesley, Reading, MA, 1998).

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