

# Leveraging 1-hop Neighborhood Knowledge for Efficient Flooding in Wireless Ad Hoc Networks

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## Abstract

*Flooding is a fundamental and frequently invoked operation in wireless ad hoc networks. Existing flooding techniques either are unreliable, generate overwhelming unnecessary retransmission, or incur excessive network control overhead. In this paper, we address these crucial problems and propose a new flooding technique called Edge Forwarding. The new scheme minimizes the flooding traffic by leveraging location information to limit broadcast retransmission to only hosts near the perimeter of each broadcast coverage. Unlike most existing techniques, Edge Forwarding requires each host to track only neighboring nodes within its one-hop distance. Therefore, it is more adaptive to host mobility and incurs less network control overhead. In particular, it can be easily incorporated into many existing routing protocols without any additional control overhead. Our performance studies indicate that with our strategy, a substantial portion of the unnecessary broadcast retransmission can be eliminated.*

## 1 Introduction

A wireless ad hoc network consists of a number of hosts that communicate with each other through wireless packet relay. In such a network, flooding operation, i.e., sending a message to all hosts, is a fundamental communication primitive and its efficiency is critical to overall network performance. The simplest flooding technique is *simple flooding* [1, 2]. In this scheme, when a host receives a flooding packet, it first checks if it has seen the same packet before. If this is true, it drops the packet; otherwise, it rebroadcasts the packet. This approach guarantees that

a flooding packet can reach all hosts that are reachable from its originator if no packet collision occurs. However, it generates a large amount of network traffic because it requires every host to transmit the data packet once. In the case all hosts are within 1-hop distance to each other, a flooding packet travels each pair of hosts twice. Such overwhelming amount of packet transmission, most of them unnecessary, can quickly exhaust the battery of hosts and may hang up the entire network as a result of severe packet contention and collision [3]. If the hosts have to compete for limited communication bandwidth, the excessive network traffic could cause a significant delay in packet transmission.

To reduce the flooding traffic, many approaches have been proposed. We classify them into three categories and discuss their limitation as follows:

- *0-hop schemes*: Many flooding techniques developed in early time are in this category. These techniques try to reduce flooding cost without any assumption on neighborhood knowledge. For example, one can simply make each host rebroadcast flooding packets with some predetermined probability. This probabilistic-based scheme was first proposed in [3] [4] and further investigated in [5]. Other approaches proposed in [3], including counter-based, distance-based, location-based, and cluster-based flooding schemes, are also in this category. These techniques can effectively reduce the flooding traffic and has the same implementation cost as plain flooding. Their efficiency, however, is achieved at the expense of flooding reachability. In these schemes, a non-redundant retransmission might be dropped in the first few hops; and its effect could propagate to the following hops causing the number of unreachable hosts to amplify quickly hop after hop. Besides the reachability issue, finding a threshold (e.g., retransmission probability, etc.) appropriate for various network situations can also be difficult [6].

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- *1-hop schemes*: The technique called Flooding with Self Pruning (FSP) in [7] is a 1-hop flooding scheme since it requires each host to track its neighbors within 1-hop distance. In this scheme, when a host broadcasts a packet, it includes all of its 1-hop neighbors in the packet header. Upon receiving a broadcast, a host checks its own 1-hop neighbors and if all of them have already been listed in the broadcast packet header, it does not forward the broadcast. Although this technique can reduce the flooding cost and guarantee packet reachability at the same time, its performance improvement is very limited in most network conditions [8].
- *2<sup>+</sup>-hop schemes*: Most existing flooding approaches are in this category and they can be further divided into *reactive* schemes and *proactive* schemes. In proactive schemes [7] [9] [10] [11], a broadcasting host selects some of its 1-hop neighbors as rebroadcasting hosts. When a host receives a broadcast, it drops off the packet if it is not designated as a rebroadcasting host; otherwise, it recursively chooses some of its 1-hop neighbors as rebroadcasting hosts and then forwards the broadcast. In reactive schemes [12] [13] [14] [15] [16] [17] [18] [19], each host determines by its own on whether or not to forward a broadcast packet. In general, these techniques are not adaptive to networks with high mobility and host density. This is due to the fact that when the network topology changes frequently, the overhead of discovering and maintaining local network topology (within two or more hops) for each host increases, and may outweigh the benefit of reduction in retransmission [5] [6]. Furthermore, for those proactive techniques, the task of selecting a suitable set of hosts to forward the broadcasts is not trivial and requires significant computation on the hosts. It was proven in [11] that finding the optimal set of rebroadcasting hosts is NP-hard.

In summary, recent techniques, as discussed above, either compromise flooding reachability, are inefficient in reducing network traffic, or require significant control overhead and intensive computation on hosts. In this paper, we address the aforementioned problems by considering a novel technique called *Edge Forwarding*. In this approach, we divide the transmission coverage of each host into six equal partitions. When a host receives a broadcast, it decides on its own whether or not to forward the broadcast using two different forwarding rules. Under the first rule, a host does not for-

ward a broadcast unless it is *close* to some partition edge of the broadcast coverage. Thus, a significant percentage of redundant broadcast retransmission is eliminated. The second rule further reduces the unnecessary rebroadcast by pushing the forwarding responsibility to the hosts close to the perimeter of the broadcast coverage. While this new technique guarantees the desired flooding reachability, it is highly efficient and scalable to the network size and density. This is due to the fact that the retransmission of a broadcast typically occurs only at the perimeter of the broadcast coverage. Another major advantage of Edge Forwarding is its simplicity: it requires each host to know only its 1-hop neighbors. Since such information is a prerequisite to many routing protocols, Edge Forwarding can be easily incorporated into these routing protocols to boost their performance without incurring additional network control overhead.

The remainder of this paper is organized as follows. We present Edge Forwarding concept in Section 2, and introduce the protocol in Section 3. In Section 4, we describe the simulation model and examine the performance results. Finally, we give our concluding remarks in Section 5.

## 2 Preliminary

### 2.1 Transmission Coverage Partitioning

Given a host, say  $A$ , we partition its transmission coverage into six equal-size regions and identify them as  $A_{P_1}$ ,  $A_{P_2}$ ,  $A_{P_3}$ ,  $A_{P_4}$ ,  $A_{P_5}$ , and  $A_{P_6}$ , respectively. The partitioning and naming rules are illustrated in Figure 1(a). We say a host is  $A$ 's  $P_i$  neighbor, if the host is currently inside partition  $A_{P_i}$ , where  $1 \leq i \leq 6$ . For instance, in Figure 1(b),  $B$  is  $A$ 's  $P_1$  neighbor as  $B$  is located in  $A_{P_1}$ . Given  $A$  at location  $(x_a, y_a)$  and its 1-hop neighbor  $B$  at location  $(x_b, y_b)$ , the distance between  $A$  and  $B$  is  $dist(A, B) = \sqrt{(x_b - x_a)^2 + (y_b - y_a)^2}$ . We can determine which partition of  $A$  contains  $B$  with some simple computation as follows:

- if  $x_a \leq x_b$  and  $y_a \leq y_b$ , then  $B$  is in  $A_{P_1}$  if  $\frac{x_b - x_a}{dist(A, B)} >= \frac{1}{2}$ ; otherwise,  $B$  is in  $A_{P_2}$ ;
- if  $x_a > x_b$  and  $y_a < y_b$ , then  $B$  is in  $A_{P_2}$  if  $\frac{x_a - x_b}{dist(A, B)} \leq \frac{1}{2}$ ; otherwise,  $B$  is in  $A_{P_3}$ ;
- if  $x_a > x_b$  and  $y_a > y_b$ , then  $B$  is in  $A_{P_4}$  if  $\frac{x_a - x_b}{dist(A, B)} >= \frac{1}{2}$ ; otherwise,  $B$  is in  $A_{P_5}$ ;

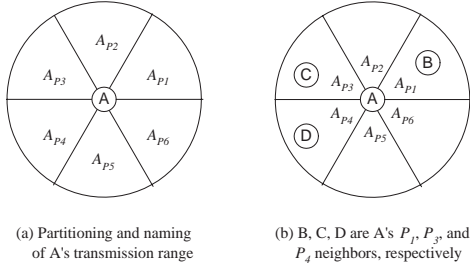


Figure 1: Transmission Coverage Partitioning

- if  $x_a \leq x_b$  and  $y_a \geq y_b$ , then  $B$  is in  $A_{P_5}$  if  $\frac{x_b - x_a}{\text{dist}(A, B)} \leq \frac{1}{2}$ ; otherwise,  $B$  is in  $A_{P_6}$ ;

In the next, we present two *forwarding rules*, by which a host can determine whether or not it should forward a broadcast packet. When a host forwards a broadcast, it adds its ID to the packet header to inform each recipient of the sender of this broadcast. In our discussion, we assume each host knows the accurate position of its 1-hop neighboring hosts. In reality, the location information typically includes some amount of error, as a result of host movement and the inaccuracy caused by the underlying positioning systems. The ideas suggested here, however, can be applied in general - the issue of location uncertainty will be addressed in the next section, where we present our new flooding protocol.

## 2.2 Basic Forwarding

Under this rule, when a host, say  $B$ , receives a new broadcast from another host, say  $A$ ,  $B$  first determines which partition of  $A$   $B$  is currently in. Given  $B$  in  $A_{P_i}$ , where  $1 \leq i \leq 6$ , it forwards the broadcast if there exists at least one partition  $B_{P_j}$ , where  $1 \leq j \leq 6$ , such that no other hosts can be found in  $B_{P_j} \cap A_{P_i}$  (i.e., the overlapping area of  $B_{P_j}$  and  $A_{P_i}$ ).

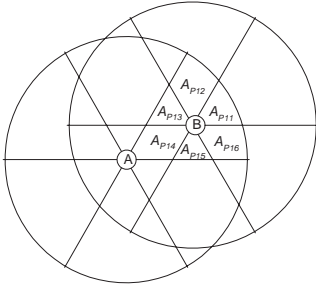


Figure 2: Host  $B$  divides  $A_{P_1}$  into 6 partitions

We use Figure 2 to explain the above forwarding rule. Without loss of generality, we assume  $B$  is in  $A_{P_1}$ .  $B$ 's partition lines divide  $A_{P_1}$  into 6 subpartitions:  $A_{P_{11}}$ ,  $A_{P_{12}}$ ,  $A_{P_{13}}$ ,  $A_{P_{14}}$ ,  $A_{P_{15}}$ , and  $A_{P_{16}}$ , as showed in Figure 2. That is,  $A_{P_{1i}} = A_{P_1} \cap B_{P_i}$ , where  $1 \leq i \leq 6$ . When  $B$  receives a broadcast from  $A$ ,  $B$  first determines if there is anyone of its  $P_1$  neighbors inside  $A_{P_{11}}$ . This can be done by simply checking their distance to  $A$ : a  $B$ 's  $P_1$  neighbor, say  $H$ , is inside  $A_{P_{11}}$  if and only if  $\text{dist}(H, A) \leq R$ , where  $R$  is  $A$ 's transmission radius. If no host can be found in  $A_{P_{11}}$ ,  $B$  forwards the broadcast. Otherwise,  $B$  continues to check its 1-hop neighbors in  $P_2$ ,  $P_3$ ,  $P_4$ ,  $P_5$ , and  $P_6$  sequentially. If there is at least one host in each of  $A_{P_{1i}}$ , where  $1 \leq i \leq 6$ ,  $B$  does not forward the broadcast. The complexity of this procedure is  $O(n)$ , where  $n$  is the number of  $B$ 's 1-hop neighbors. In practice,  $B$  can stop checking a subpartition  $A_{P_{1i}}$  as soon as a host is found in this subpartition. Furthermore, if  $B$  detects an empty subpartition,  $B$  does not need to explore the remaining subpartitions. This strategy is, therefore, very energy efficient.

The above forwarding rule ensures that the broadcast can reach all of  $B$ 's 1-hop neighbors that are outside of  $A$ 's transmission coverage even if  $B$  does not forward the packet. In other words, at least one host in  $A_{P_{1i}}$  will broadcast to cover  $B$ 's  $P_i$  partition, where  $1 \leq i \leq 6$ . This can be proof as follows. Let's say  $B$  does not forward the broadcast in the above example. In this case, it means that there is at least one host in each of  $A_{P_{1i}}$ , where  $1 \leq i \leq 6$ . These hosts must have received the broadcast from  $A$  also since they are within 1-hop distance to  $A$ . Obviously, if there is a host inside  $A_{P_{1i}}$  and it forwards the broadcast, then all hosts inside  $B_{P_i}$  will receive the broadcast. This is due to the fact that all  $B$ 's  $P_i$  neighbors are within 1-hop distance to any host inside  $A_{P_{1i}}$ , as ensured by the nature of our partitioning. We now just need to prove that there is at least one host in each of  $A_{P_{1i}}$ , where  $1 \leq i \leq 6$ , will forward the broadcast.

We first prove that there is at least one host in  $A_{P_{11}}$  that will forward the broadcast. Let's say host  $H^1$  is currently inside  $A_{P_{11}}$ . Then similar to  $B$ , it divides  $A_{P_1}$  into 6 partitions. As  $H^1$  is inside  $A_{P_{11}}$ , partition  $H^1_{P_1} \cap A_{P_1}$  must be contained by  $A_{P_{11}}$ . If there is no host inside  $H^1_{P_1} \cap A_{P_1}$ , then according to the rule,  $H^1$  must forward the broadcast. Otherwise, there must have at least one host inside  $H^1_{P_1} \cap A_{P_1}$ . Let host  $H^2$  be such a host. Again, it divides  $A_{P_1}$  into 6 partitions and partition  $H^2_{P_1} \cap A_{P_1}$  must be contained by  $H^1_{P_1} \cap A_{P_1}$ , because  $H^2$  is inside  $H^1_{P_1} \cap A_{P_1}$ . If  $H^2$

does not forward the broadcast, then let  $H^3$  be a host inside  $H_{P_1}^2 \cap A_{P_1}$ , ..., and so forth. These steps proceed recursively and eventually a host, say  $H^i$ , will find out that there is no hosts inside  $H_{P_1}^i \cap A_{P_1}$  and need to forward the broadcast: as the value of  $i$  increases, the overlapping area  $H_{P_1}^i \cap A_{P_1}$  becomes smaller and smaller and each time the number of hosts it contains, which is limited, is reduced at least by 1. Similarly, we can prove that in each of the remaining regions,  $A_{P_{12}}$ ,  $A_{P_{13}}$ ,  $A_{P_{14}}$ ,  $A_{P_{15}}$ , and  $A_{P_{16}}$ , there is at least one host that will forward the broadcast.

### 2.3 Advanced Forwarding

As we can observe in Figure 2, a large portion of  $B$ 's  $P_3$  partition has already been covered by  $A$ 's broadcast; and if there is any host inside the uncovered area, then very likely it is within 1-hop distance to all hosts inside  $A_{P_{12}}$ . If this is true, then it is not necessary to have some host inside  $A_{P_{13}}$  to cover  $B_{P_3}$  partition. Obviously, partition  $B_{P_5}$  is in a similar situation. In addition, we do not need to consider the hosts inside  $B_{P_4}$  since this partition is completely covered by  $A$ 's broadcast. Based on this observation, we develop an *advanced* forwarding rule -  $B$  does not need to forward a broadcast from  $A$  if the following three conditions are satisfied:

1. there is at least one host in each of  $A_{P_{11}}$ ,  $A_{P_{12}}$ , and  $A_{P_{16}}$ ;
2. all  $B$ 's  $P_3$  neighbors beyond 1-hop distance to  $A$  are within 1-hop distance to all hosts inside  $A_{P_{12}}$ ;
3. all  $B$ 's  $P_5$  neighbors beyond 1-hop distance to  $A$  are within 1-hop distance to all hosts inside  $A_{P_{16}}$ .

We have already discussed how to determine if there is any host inside each of  $A_{P_{1i}}$ , where  $1 \leq i \leq 6$ . If there is no hosts in  $A_{P_{13}}$ , then we find out all  $B$ 's  $P_3$  neighbors whose distances to  $A$  are larger than the transmission radius  $R$ . For each of these hosts, say  $H_x$ , we check its distance to all hosts inside  $A_{P_{12}}$ . If there exists any host, say  $H_y$ , inside  $A_{P_{12}}$ , such that  $dist(H_x, H_y) > R$ , then the second condition is violated and  $B$  needs to forward the broadcast. The complexity of this procedure is  $O(m * n)$ , where  $m$  is the number of  $B$ 's  $P_3$  neighbors not covered by  $A$ 's broadcast and  $n$  is the number of hosts inside  $A_{P_{12}}$ . If the second condition is satisfied, we then continue to check the third condition in a similar way.

We note that under the basic forwarding rule, a host does not need to forward a broadcast unless it is *close*

to the edge of some broadcast partition. This characteristic eliminates a significant portion of unnecessary broadcast forwarding. The advanced forwarding rule enhances this by pushing the forwarding responsibility to only the hosts close to the transmission perimeter. This strategy, however, incurs more computation.

### 2.4 Handling Host Heterogeneity

The above discussion implicitly assumes that all hosts have the same transmission radius. In the presence of host heterogeneity, we can add a host's true transmission radius in its heartbeat broadcast and modify the basic forwarding rule as follows: Given host  $B$  in host  $A$ 's partition  $P_i$ , where  $1 \leq i \leq 6$ ,  $B$  must forward a broadcast from  $A$  if there exists at least one  $B$ 's partition  $B_{P_j}$ , where  $1 \leq j \leq 6$ , such that any one of the following conditions is satisfied:

- no hosts can be found in  $B_{P_j} \cap A_{P_i}$ ;
- there is at least one host inside  $B_{P_j} \cap A_{P_i}$  whose transmission cannot cover some of  $B$ 's  $P_j$  neighbors beyond 1-hop distance to  $A$ .

Similarly, we can revise the advanced forwarding rule to handle heterogeneous hosts. Thus, our protocol presented in the next section can be used in general.

## 3 Proposed: Edge Forwarding

In Edge Forwarding, each flooding packet is associated with a life process. Upon receiving a flooding packet, a host spawns a new process to handle the packet if this packet has not been received before. The process first determines if it should forward the packet according to one of the above two forwarding rules and then puts itself into either one of the following two waiting scenarios. The waiting is an *overhearing* period if the underlying forwarding rule requires the host to rebroadcast the packet; otherwise, it is a *confirming* period. We will discuss shortly the settings of these two stages and the rationale behind them. During the waiting period, the host might receive the duplicated packets forwarded by other hosts. These packets are put into an internal queue of this process. At the end of the waiting period, the process checks the list of its 1-hop neighbors and for each one of them, determines if the neighbor can be reached by some broadcast in the queue. This can be done by simply calculating the distance between the neighbor and the sender of each broadcast. If there is at least one neighbor not covered by any received broadcasts, the process forwards the

packet immediately and then terminates. This process is illustrated in a flowchart shown in Figure 3.

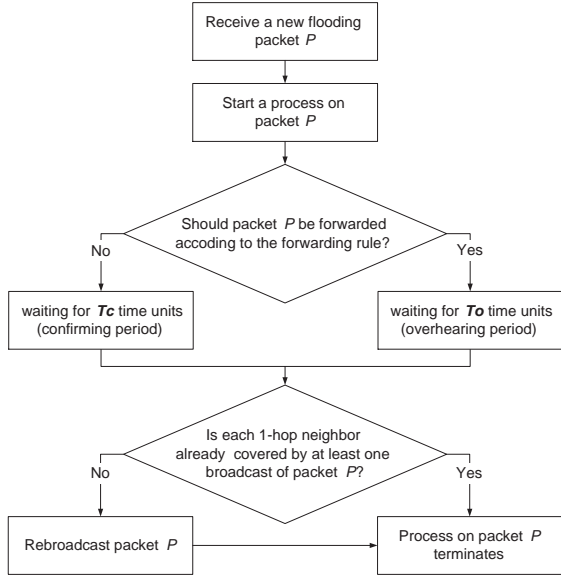


Figure 3: Flowchart of processing a new flooding packet

### 3.1 Setting Overhearing Period

We use the overhearing period to make broadcast retransmission occur in a more orderly manner. Given a broadcast, we prefer the hosts closer to its coverage perimeter to forward the broadcast in order to minimize the flooding. For example, in Figure 4, if both  $B$  and  $C$  are required by the forwarding rule to forward a broadcast from  $A$ , then  $C$  should forward the broadcast prior to  $B$ . Since  $B$  becomes aware of this forwarding, it might not need to forward the same packet.

In Edge Forwarding, each host sets and dynamically adjusts its overhearing period for a flooding packet. When a host  $A$  receives a new packet from another host  $B$ ,  $A$  initializes the overhearing period for this packet to be  $B.R - dist(A, B)$  time units<sup>1</sup>. Before the overhearing period expires, the host could receive duplicated packets from other hosts. For each of these packets, the overhearing period is adjusted as follows. If the duplicated packet arrives  $t$  time units later from a host  $C$ , where  $0 \leq t \leq B.R - dist(A, B)$ , host  $A$  adjusts its overhearing period for this packet to  $max(B.R - dist(A, B) - t, C.R - dist(A, C) - t)$  time units. We note that a similar overhearing period

<sup>1</sup>Given a host, say  $H$ , its transmission radius is denoted as  $H.R$

is used in [6, 20] to arrange broadcast retransmission. In their schemes, a host sets its overhearing period for a flooding packet only once (i.e., when the packet was received at its first time). Thus, the setting of overhearing period is static for each flooding packet. In our case, the setting of overhearing period is dynamic. The dynamic adjustment of overhearing period allows a host, say  $A$ , to further delay a packet forwarding in order to collect duplicated packets from more neighboring hosts. This increases the chance that all of  $A$ 's neighbors have been covered by some previous broadcast of the same packet; and therefore  $A$  need not forward the packet. For example, in Figure 4, after host  $A$  broadcasts a packet, the initial forwarding order is host  $C$ ,  $B$ , and then  $D$ . After  $A$  forwards, the adjustment of the overhearing periods for the packet at host  $B$  and  $D$  makes  $D$  forward before  $B$ , since  $B$  is closer to  $C$ . Since  $B$ 's transmission coverage is enclosed by the combined coverage of  $A$ ,  $C$ , and  $D$ ,  $B$  will not need to forward the packet.

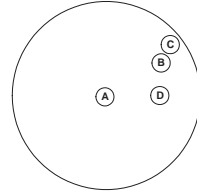


Figure 4: Dynamic setting of overhearing period

### 3.2 Setting Confirming Period

An inherent feature of wireless ad hoc networks is host uncertainty, such as host fragility and broadcast energy fading. In the applications involved of mobile hosts, host location is another uncertain factor. Due to the continuous movement of mobile devices, a host may have inaccurate position information about its neighbors. Such uncertainty can make a host unreliable in terms of sending and receiving packet as expected. In Edge Forwarding, we minimize the effect of host uncertainty with a new concept called *confirming period*, by which a backup packet is transmitted in the case an expected retransmission fails. The concept works as follows. If a host, say  $B$ , determines that it needs not forward a new flooding packet from another host, say  $A$ , then  $B$  sets its confirming period for this packet to be  $A.R + (A.R - dist(A, B))$  time units. We take the distance of the two hosts into consideration (i.e.,  $A.R - dist(A, B)$ ) to avoid bursts of backup retransmission.

## 4 Performance Study

For the purpose of performance study, we have implemented a detailed simulator for four reachability-guaranteed flooding techniques: *Plain Flooding* (PF), *Flooding with Self-Pruning* (FSP), *Basic Edge Forwarding* (BEF), and *Advanced Edge Forwarding* (AEF). In our study, we focus on their average flooding costs. The cost of flooding a data packet is defined to be the total number of hosts involved in the packet retransmission. The sum of the individual flooding costs is divided by the number of floodings over a simulation run to determine the average flooding cost. We note that FSP requires a host to include its 1-hop neighbors in all packets it broadcasts. This cost is ignored in our performance study. We do not compare with other flooding techniques because they either do not ensure flooding reachability, or require each host to track the changing of network topology beyond 1-hop distance. Nevertheless, it is possible to compare these schemes indirectly with our Edge Forwarding strategy through their performance difference with the plain flooding, which is commonly used as the benchmark for flooding performance.

### 4.1 Simulation Model

For each simulation run, we generate a certain number of hosts and place them randomly on a square domain. These hosts take turn to flood one data packet using different flooding techniques. Only one flooding occurs at any one time. As we are mainly interested in the reduction in redundant broadcast retransmission, we did not simulate the communication synchronization among the hosts, and assumed that a host could acquire a clear channel whenever it needed. For each flooding, we record the individual flooding costs and compute their average. Since we want to compare the performance of the four different flooding techniques under the same snapshot of the network, we make each host remain static during each flooding operation. As the radio transmission propagates at the speed of light, we feel that given the size of the network we simulate, it is reasonable to assume that a flooding packet can be received by all hosts at the same time, although in reality it might pass through several hops. Thus, the flooding costs we collected in each simulation should fairly reflect their true costs in a real network. In particular, the performance difference of these techniques should be quite accurate.

## 4.2 Simulation Results

In the next subsections, we study how the performance metrics of the proposed techniques are affected by these three parameters: *network area*, *host density*, and *transmission radius*. Table 1 summarizes the parameter values used in the performance study. Roughly, we simulated a small community network, a domain region about 5 to 20 hops with a number of hosts ranging in between 500 to 5000.

Parameter	default	variation	unit
host density	500	100 - 1000	$meter^2/host$
network area	500,000	$10^5 - 10^6$	$meter^2$
trans. radius	100	50 - 150	$meter$

Table 1: Parameters

### 4.2.1 Effect of Network Area

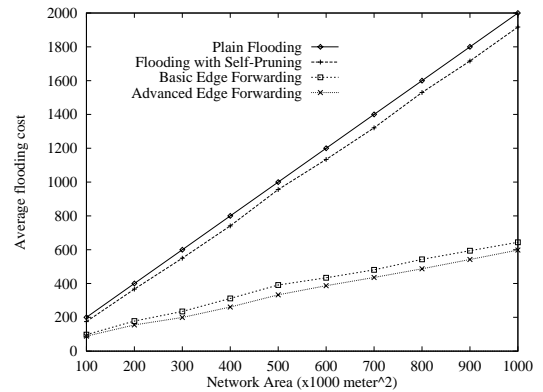


Figure 5: Effect of Network Area

In this study, we increased the area of the network region, from 100,000 to 1,000,000  $meter^2$ , in each simulation run and fixed the host density at 500  $meter^2/host$ . The generated hosts are placed randomly on the network square domain. We fixed the radio transmission radius at 100 meters. The performance data are plotted in Figure 5. We observe that Flooding with Self-Pruning performs almost the same as plain flooding. This confirms that the forwarding rule used in FSP is very restricted - a host can rarely be exempted from forwarding a broadcast as a result of that all of its 1-hop neighbors are already covered by the broadcast transmission. In contrast, the flooding costs under both Edge Forwarding techniques are just a small fraction of that under plain flooding. In particular, their performance gaps become large with the in-

crease of the network domain area. For example, when the network area is  $100,000 \text{ meter}^2$  (i.e., 500 hosts), the basic version of Edge Forwarding incurs about 50% of the sending cost than the plain flooding; when the network area increases to  $1,000,000 \text{ meter}^2$  (i.e., 5000 hosts), the flooding cost under the basic Edge Forwarding is only about 25% of that under the plain flooding. This indicates that both Edge Forwarding schemes are highly scalable with respect to the size of network domain. As for the performance comparison between the two Edge Forwarding schemes, the figures show that the advanced version consistently outperforms its basic counterpart. Obviously, this is due to the less-restricted forwarding rule it uses.

#### 4.2.2 Effect of Host Density

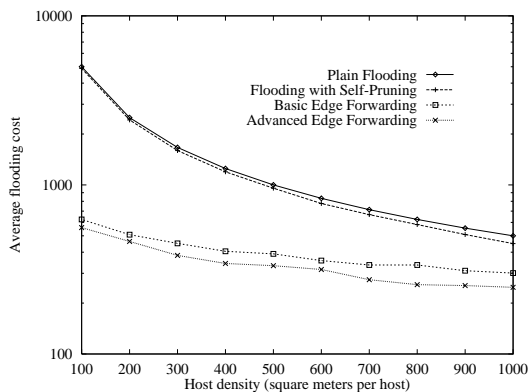


Figure 6: Effect of Host Density

In this study, we fixed the radio transmission radius at 100 meters and generated a certain number of hosts, from 500 to 5000, in each simulation run and placed them randomly on a square region of  $500,000 \text{ meter}^2$ . In other words, we reduced the host density from average  $100$  to  $1000 \text{ meters}^2/\text{host}$ . The performance data are plotted in Figure 6. Again, we observe that the performance of FSP is almost the same as that of the plain flooding; and in contrast, both Edge Forwarding schemes can effectively reduce the redundant broadcast retransmission and outperform the plain flooding many times. Notably, we observe that the percentage of the performance improvement becomes large and large with increasing host density. For example, when the host density is  $1000 \text{ meter}^2/\text{host}$ , the sending cost under the basic scheme is about 50% of that under the plain flooding; when the host density is increased to  $100 \text{ meter}^2/\text{host}$ , the corresponding sending cost is reduced to about 10%. This indicates that the per-

formance of Edge Forwarding solution is not very sensitive to the host density. This characteristic can be explained as follows. First, the number of broadcast retransmission required to cover a network with a fixed domain area is largely not affected by the host density. Second, under Edge Forwarding, only the hosts close to some partition edge are required to forward a broadcast. As a result, the performance of Edge Forwarding solution is not very sensitive to the host density. We note that this performance study, together with the previous one, indicate that our new techniques are particularly suitable for flooding in large scale wireless ad hoc networks.

#### 4.2.3 Effect of Transmission Radius

In this study, we varied the radio transmission radius, from 50 to 150 meters, in each simulation run and randomly placed 1000 hosts on a square region of  $500,000 \text{ meter}^2$ . The simulation results are plotted in Figure 7. The curve of the send cost for the plain flooding is flat since each host has to forward a flooding packet once and we have the same number of hosts in each simulation run. As for Flooding with Self-Pruning, the figures again show that it cannot reduce the redundant rebroadcast effectively - under all scenarios, its flooding cost is very close to that of plain flooding. On the contrary, both Edge Forwarding schemes incur significantly less flooding cost with a larger transmission radius. This can be explained intuitively as follows. When the transmission range is very small, very few hosts can be found in each of its transmission partitions. In the worst case, all hosts would find themselves close to some partition edge and have to forward a broadcast. As its transmission coverage enlarges, more and more hosts will be contained in each of its partitions. Thus, there is more chance that a host can find itself surrounded by some other hosts within the same partition and does not have to forward a broadcast.

## 5 Concluding Remarks

We have presented an efficient and low-cost flooding strategy based on the partitioning of each host's radio broadcast coverage. We call the new technique as *Edge Forwarding*, alluding to the fact that it allows hosts to be exempted from forwarding a broadcast unless they are close to some partition edge of the broadcast coverage. In our solution, each host can determine on its own whether or not it should forward a broad-

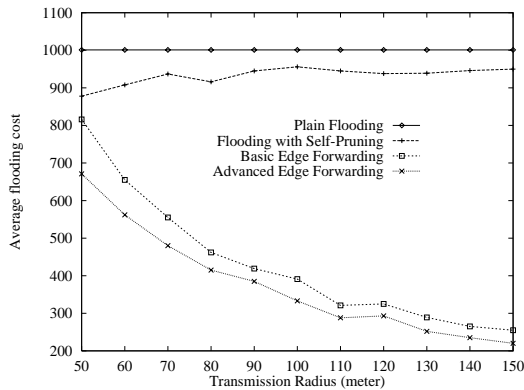


Figure 7: Effect of Transmission Radius

cast. Our technique allows a host to drop off a packet only when its 1-hop neighbors can receive the same packet from other hosts. Thus, the new scheme guarantees that a flooding packet is able to reach all hosts that are not isolated from the network. Many existing flooding techniques require hosts to keep track of their neighboring hosts within 2-hop distance. In contrast, our technique requires each host to know only its 1-hop neighbors. Therefore, the new technique is more adaptive to the host mobility and incurs much less overhead in terms of control-related network traffic and computation. Since such 1-hop neighborhood information is a prerequisite to many existing routing algorithms, Edge Forwarding can be incorporated into their implementation easily without additional control overhead. In our performance study, we compare the new technique with two existing flooding schemes using simulation. Our study shows that under all network settings we simulated, our new technique performs many times better.

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