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PAPER

Flooding Schemes for Clustered Ad Hoc Networks

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SUMMARY This paper presents novel flooding schemes for wireless mobile ad hoc networks. Clustering of nodes is assumed as a basic ad hoc network structure. GWF (Gateway Forwarding) and SGF (Selected Gateway Forwarding) are presented based on clustering. A new protocol, termed FGS (Flooding Gateway Selection) protocol, between a cluster head and its gateways to realize SGF is presented. It is shown that SGF significantly improves the packet delivery performance in ad hoc networks by reducing flooding traffic.

key words: *ad hoc network, flooding, clustering, gateway selection*

1. Introduction

The number of subscribers in mobile telecommunication services is significantly increasing all over the world. This growth is expected to continue in the near future. One person may have several wearable mobile communication devices and many systems and facilities may use mobile communication devices. The number of mobile communication devices will continue to grow and various new applications will be developed for mobile devices. Conventional mobile telecommunication technology may not be sufficient to meet such huge demands due to limited radio facility resources.

Under these circumstances, wireless mobile ad hoc networking is one of the most promising concepts. In mobile ad hoc networking, neighboring nodes communicate directly without a base station and a wired network. Distant nodes mutually communicate through multi-hopping on intermediate nodes. Direct communication between neighboring nodes can be carried out with low power, which limits the area of interference. Thus, a communication bandwidth can be spatially reused.

Ad hoc networking has been used for various applications recently with the popularization of wireless LAN and PHS, including systems for supervising and managing widely spread facilities, for distributing teaching material in a classroom, and for spreading parking lot vacancy information to drivers in the neighborhood. Most of these applications assume closed networks used in groups for specific and temporary purposes.

It should be noted, however, that ad hoc networking is promising for the realization of a new communication environment, which conventional mobile networking cannot cover, and is a field in which wider applications are expected in the near future. In this context, a concept of the next-generation ad hoc network has been proposed [1].

This paper focuses on the most fundamental protocol for information distribution in a network, that is, flooding. Flooding is often used in mobile ad hoc networks. For example, flooding may be used to discover the path (route) from a source to the destination. Multicast routing protocols may use flooding to advertise multicasting groups and their membership. Moreover, flooding may be more efficient than multicast routing, when the number of destinations is relatively large and node mobility is relatively high. Under these circumstances, an improvement in flooding performance will have major benefits.

We assume clustering is used in the network [2]. Clustering is a popular mechanism in the field of mobile ad hoc networking and may enhance various aspects of network performance such as code separation (among clusters), channel access, routing, power control, and bandwidth allocation [3], [4]. On the other hand, clustering introduces overhead for the network. Control packets required for clustering consume bandwidth. This overhead would increase with node mobility, because the clustering interval must be sufficiently short to properly reconfigure clustering. Routing protocols for clustered ad hoc networks have been proposed [5], [6]. This study explores the improvement of flooding performance for clustered networks. Specifically, we allow broadcasting in the process of flooding only to a selected group of nodes, which are called the flooding nodes hereafter. The remaining nodes are not allowed to broadcast for flooding, thus unnecessary traffic can be kept to a minimum. Preliminary research on this approach was reported in ref. [7]. A similar method for nonclustered networks has been proposed in ref. [8].

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The rest of the paper is organized as follows. Sect. 2 describes conventional clustering and flooding schemes, and presents two enhanced flooding schemes. Sect. 3 describes a flooding gateway selection protocol. Sect. 4 evaluates the number of flooding nodes with different node density. Sect. 5 compares the performance of different flooding schemes based on simulation. Sect. 6 summarizes the results and discusses items for further study.

2. Clustering and Flooding Schemes

2.1 Clustering Algorithms

Various distributed clustering algorithms have been proposed including Lowest-ID algorithm or Linked Cluster Algorithm (LCA) [2] and Highest-Connectivity Algorithm (HCA) [4]. We assume that nodes travel independently in an area. Typically, each node periodically broadcasts its ID and IDs it can hear to the neighboring nodes to form clusters of nodes in a distributed fashion. Each cluster has its cluster head. A node, which belongs to a cluster, is a cluster member. Each cluster member has a direct link with its cluster head (can communicate directly with its cluster head). A noncluster node, which does not belong to any cluster, may exist. A cluster member, which has a direct link with another cluster head, cluster member or noncluster node, is a gateway. The conventional definition of a gateway [4], [9] describes a gateway as a cluster member having a direct link with other cluster heads, while a distributed gateway is a cluster member having a direct link with other cluster members but not with other cluster heads. In our definition, a gateway may be a gateway or distributed gateway in the conventional definition.

According to a clustering algorithm, each node can identify itself either as a cluster head, gateway, inner node (cluster member except gateway), or noncluster node.

We assume that node IDs can be ordered. In LCA, a node, whose ID is less than that of any adjacent (one-link reachable) node, becomes the cluster head. In HCA, a node whose degree is more than that of any adjacent node becomes the cluster head. If two adjacent nodes have the same degree and satisfy the above condition except with respect to each other, the node with the smaller ID becomes the cluster head.

We consider why noncluster nodes may appear as the results of clustering, taking HCA as an example. We focus on nodes n_i, n_j, n_k, and n_l, where n_i and n_j are within transmission range, n_j and n_k are within transmission range, and n_k and n_l are within transmission range. Let degrees of nodes n_i, n_j, n_k, and n_l be d_i, d_j, d_k, and d_l . We assume that $d_i < d_j < d_k < d_l$ and d_l is selected as a cluster head. In this case, d_i and d_j cannot become a cluster head and may not be included by any cluster. We confirm the existence of noncluster nodes through computer simulations in Sect. 4.

We assume the use of clustering as a common basis regardless of the flooding protocols. Specifically, clustering is used to control time slot assignment for members in the cluster. The details are presented in Sect. 5.1.

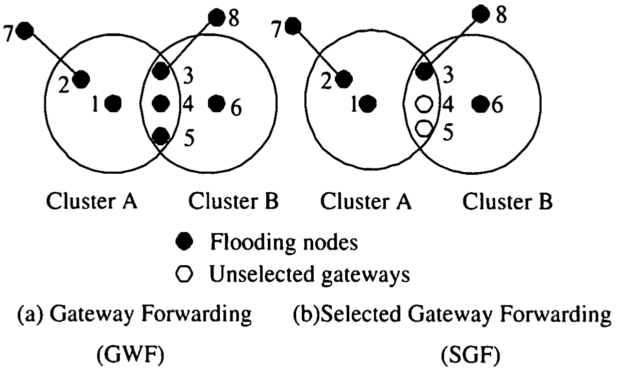
2.2 Pure Flooding

In conventional flooding (pure flooding), a node broadcasts a data packet to the neighboring nodes. Each node receiving that packet checks if it has received the same packet (duplicated packet) before. If so, it discards the packet. If not, it re-broadcasts the packet. This process continues and all nodes in a network are eventually expected to receive the same packet. Flooding is a simple method of distributing information in the network. A disadvantage of flooding is that it will create a large amount of traffic in the network because all nodes in the neighborhood try to forward packets to each other by broadcasting them, which is called Every Node Forwarding (ENF) hereafter. It is required to reduce unnecessary load due to flooding as much as possible. In ENF, clustering is not used to control flooding. However, clustering is used to control time slot assignment in each cluster as mentioned in Sect. 2.1.

2.3 Efficient Flooding for Clustered Ad Hoc Networks

We introduce two enhanced flooding schemes. In the first scheme, cluster heads, gateways, and noncluster nodes become the flooding nodes. That is, inner nodes are exempted from working as the flooding nodes. This scheme is termed Gateway Forwarding (GWF). A similar method has been proposed in ref. [10], but it does not assume the existence of noncluster nodes or distributed gateways. In the second scheme, in addition to inner nodes, a part of the gateways are excluded from the flooding nodes to avoid redundant flooding. That is, cluster heads, gateways, which are selected by each cluster head (representative gateways), and noncluster nodes become the flooding nodes. This scheme is termed Selected Gateway Forwarding (SGF).

An example of clustering as well as flooding node selection in GWF and SGF is shown in Figs. 1(a) and (b), respectively. Black nodes are the flooding nodes in each figure. Node 2 has a direct link with node 7, which is shown by the straight line connecting them. Node 3 has a direct link with node 8. Connectivity within a cluster is not shown for simplicity. As shown in Fig. 1(a), nodes 1-8 are the flooding nodes in GWF, while nodes 4 and 5 are not flooding nodes in SGF as shown in Fig. 1(b). Note that node 3 should be selected from among nodes 3-5 as the flooding node to assure connectivity with node 8.



(a) Gateway Forwarding (GWF) (b)Selected Gateway Forwarding (SGF)

Fig. 1 Example of clustering with forwarding schemes.

We need a well-defined algorithm and protocol between a cluster head and its gateways to properly select the representative gateways as the flooding nodes in a distributed fashion. This protocol is termed the "flooding gateway selection protocol (FGS protocol)" and is presented in the next section. Gateway selection is also discussed for routing [2], where a single node is a destination, but gateway selection for flooding is a different problem.

3. Flooding Gateway Selection Protocol

An example of a clustered ad hoc network is shown in Fig. 2. We focus on cluster k in the following. The FGS protocol is described as follows:

Step 1: According to the clustering protocol, each node periodically broadcasts its ID and IDs it can hear (an ID list) to the neighboring nodes to form clusters of nodes in a distributed fashion. That is, each node collects the one-hop and two-hop neighboring nodes information. We modify this conventional clustering protocol as follows:

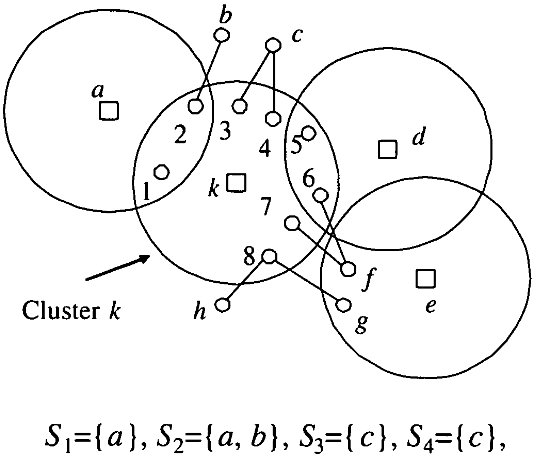
(1) Each node identifies itself either as a cluster head, gateway, inner node, or noncluster node according to a clustering algorithm.

(2) If a node identifies itself as a cluster head or noncluster node, its ID is marked respectively in the ID list, which is broadcast to the neighboring nodes.

(3) Each node can identify two-hop neighboring cluster head IDs, based on the ID lists with marking received by the neighboring nodes. The ID list, which each node broadcasts to the neighboring nodes, includes two-hop neighboring cluster head IDs in addition to the ID of itself and IDs it can hear.

(4) As a result, each node collects the one-hop neighboring nodes, two-hop neighboring nodes and in addition, three-hop neighboring cluster heads information.

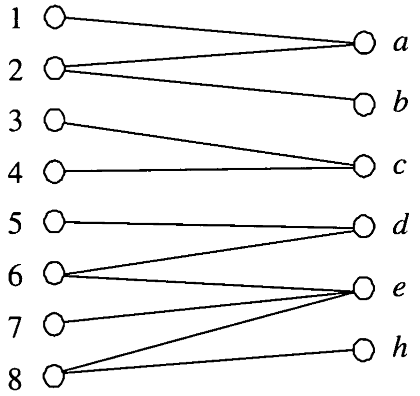
For example, an ID list from node f includes the ID of node e marked as a cluster head. This list is received by node 7. Node e is a two-hop neighboring cluster head for node 7. Therefore an ID list from node 7 includes the ID of node e as a two-hop neighboring cluster head. This list is received by node k. Thus, node k recognizes node e as a three-hop neighboring cluster head.



$S_1=\{a\}, S_2=\{a, b\}, S_3=\{c\}, S_4=\{c\},$

$S_5=\{d\}, S_6=\{d, e\}, S_7=\{e\}, S_8=\{e, h\}$

Fig. 2 Example of clustering.



$A_k = \{1,2,\cdots,8\} \qquad \bigcup_{i=1}^{8} S_i = \{a,b,c,d,e,h\}$

Selected gateways $B_k = \{2,3,6,8\}$

$S_2 + S_3 + S_6 + S_8 = \bigcup_{i=1}^{8} S_i$

Fig. 3 Example of selecting gateways.

Step 2: As a result, cluster head k has a list of peer cluster head IDs reachable by two-hop or three-hop paths and noncluster nodes reachable by two-hop paths. Let S_i (i=1,$\cdots$,v) bbe a set of cluster heads or noncluster nodes, reported by the ID list sent from gateway i, where gateways include both conventional gateways and distributed gateways as mentioned in Sect. 2.1. An example of S_i is given in Fig. 2.

Step 3: Cluster head k makes a bipartite graph (Fig. 3), where the left-hand side nodes are lists of gateways and the right-hand side nodes are the elements of the set of $\bigcup_{i=1}^{v} s_i$. Each left-hand side node (gateway i) is connected to each element of the set S_i by an edge.

Cluster head k selects a minimum number of nodes from the left-hand side nodes so as to cover all of the nodes in the set of $\bigcup_{i=1}^{v} s_i$. This is the well-known set cover problem, which is NP complete [11]. A greedy algorithm can be used to obtain a solution [12]-[14]. These selected gateways are the representative gateways for the cluster head k.

Step 4: Cluster head k informs each selected representative gateway to act as the flooding node. This message includes IDs of the peer cluster head, for which the selected gateway has an edge in the bipartite graph in Fig. 3. If the informed gateway is a distributed gateway, it then forwards this message to the peer gateway, which has a link to the informed peer cluster head so that the peer gateway also becomes the flooding node. These messages can be piggybacked on the ID list.

4. Evaluation of the Number of Flooding Nodes

4.1 Definitions and Assumptions

In Sect. 3, we described two schemes, GWF and SGF. In this section, we consider the number of flooding nodes in both schemes. We define the following variables:

N: Number of nodes.

r: Number of clusters.

m_k : Number of inner nodes of cluster $k (k = 1, ..., r)$.

A_k : A set of gateways of cluster k.

B_k : A set of the selected gateways of cluster k in SGF.

In GWF, the number of flooding nodes is given by $N - \sum_{k=1}^{r} m_k$, while it is $N - \sum_{k=1}^{r} m_k - \left|\bigcup_{k=1}^{r} A_k\right| + \left|\bigcup_{k=1}^{r} B_k\right|$ in SGF. The latter equation is actually a lower bound, because it may not include the peer gateways as the flooding nodes, which are required when the distributed gateways are selected as the flooding nodes.

We evaluate the values of the number of flooding nodes to determine whether of not our approach is potentially effective. Our evaluation is based on computer simulation, assuming the following conditions.

(1) Nodes are randomly distributed in an area, which is a regular square with size 1,000m × 1,000m.

(2) Transmission range of each node is 100m.

(3) A unique number is given as an ID to each node.

(4) Nodes are stationary.

For a given number of nodes, we generate 1,000 patterns of node placement in the area, using different seed numbers. For each node placement pattern, clustering algorithms, LCA or HCA are applied to facilitate node clustering, and as a result, the number of the flooding nodes is calculated. The average percentage of the flooding nodes is then obtained for each number of nodes.

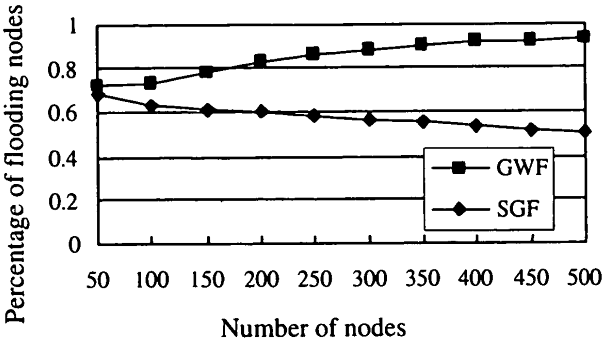


Fig. 4 Reduction in the number of flooding nodes (LCA, Transmission range : 100 m).

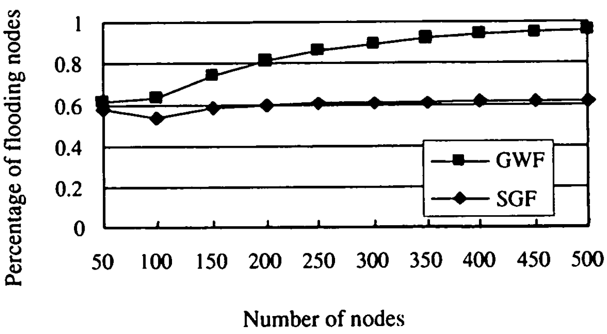


Fig. 5 Reduction in the number of flooding nodes (HCA, Transmission range : 100 m).

4.2 Results

Figure 4 compares the numbers of flooding nodes normalized by the number of nodes for GWF and SGF, where LCA is used for clustering. The case of ENF corresponds to 1.0, where all nodes are flooding nodes.

It is shown that GWF can reduce the number of flooding nodes compared with ENF but its effect decreases as the number of nodes increases. On the other hand, SGF appears to be more effective in reducing the number of flooding nodes than GWF, and its effect increases with node density. Thus, a significant decrease in the number of flooding nodes (up to 30-50%) is expected in the wide range of node density in the case of SGF compared with ENF. This is an encouraging result, since the reduction in the number of flooding nodes directly contributes to the reduction in network traffic.

We obtain similar results when HCA is used for clustering as shown in Fig. 5. As in LCA, GWF can reduce the number of flooding nodes compared with ENF but its effect decreases as node density increases. Again, SGF appears to be extremely useful in reducing the number of flooding nodes (up to 40%).

We have analyzed the simulation results above, focusing on the clustering performance of LCA and HCA. The main results are summarized as follows:

(1) Clusters do not completely cover the entire area, resulting in noncluster nodes as mentioned in Sect. 2.1. In fact, we confirm that the number of clusters converges to a constant number as the number of nodes increases. Under our numerical conditions mentioned in Sect. 4.1, the average number of clusters converges to 36 when the number of nodes is more than 200 in LCA, and to 13 when the number of nodes is more than 450 in HCA.

(2) As the number of nodes increases, the percentage of inner nodes decreases. This is natural because the number of clusters does not increase and a node in a cluster may have a higher chance of becoming a gateway, as the number of nodes increases. As a result, the percentage of flooding nodes in GWF increases as shown in Figs. 4 and 5.

(3) Since the number of clusters is fewer in HCA than that in LCA when clustering is converged, the percentage of noncluster nodes is higher in HCA, resulting in a higher percentage of flooding nodes in GWF, as shown in Figs. 4 and 5.

(4) The percentage of cluster heads decreases as the number of nodes increases, because the number of clusters converges. This is the major reason why the percentage of flooding nodes in SGF decreases in Fig. 4. The number of gateways also increases, as the number of nodes increases, but this increase does not directly work to increase the percentage of flooding nodes because of gateway selection in SGF.

(5) The observation in point (4) above is valid also in the case of HCA, but its effect is limited in the case of HCA, because the percentage of cluster heads is lower than that in LCA. The number of clusters does not yet converge and continues to decrease, as the number of nodes increases up to 450 in Fig. 5. As a result, the percentage of noncluster nodes increases as the number of nodes increases. This is the major reason why the percentage of flooding nodes is almost constant but still very slightly increases in Fig. 5.

(6) As mentioned in point (3) above, the percentage of noncluster nodes is lower in LCA than in HCA when clustering is converged. This is the major reason why the percentage of flooding nodes in SGF is lower in LCA than in HCA. The number of cluster heads and gateways is higher in LCA, but its effect is limited because of gateway selection and does not cancel the gains mentioned above.

The above results show that the clustering algorithm influences the performance of SGF as well as that of GWF. LCA appears to be superior in terms of the reduction of the number of flooding nodes compared with HCA as the node density is high. More importantly, SGF is promising for decreasing the flooding nodes regardless of the clustering algorithms.

Note that the evaluated number of flooding nodes in SGF is actually a lower bound. We have only confirmed the potentiality of SGF in reducing the number of flooding nodes. We also need to evaluate the effect of node mobility, which is considered in the following section.

5. Performance Evaluation

5.1 Assumptions

The flooding performance of three forwarding schemes, ENF, GWF and SGF is investigated using simulation. We do not explicitly treat packet transmission for broadcasting ID lists and its effect in bandwidth consumption. Since all schemes use a common underlying clustering algorithm, we can evaluate at least their relative performance, even if we ignore packet transmission for broadcasting ID lists in the simulation. This approach is also justified, assuming that a different channel is used for packet transmission for broadcasting ID lists, which is beyond the scope of the following simulation.

We, however, assume clustering is performed periodically and take the effect of this clustering interval into consideration. We assume all nodes have the same clustering interval, but these intervals may not be synchronized. For example, in Fig. 2, node k receives ID lists from neighboring nodes at different time points. Node k runs the clustering algorithm based on ID lists received from one-hop neighboring nodes during the past interval. The result of this clustering is reflected in an ID list broadcast by node k. We assume that the node processing time for clustering and for selecting gateways, and the time for broadcasting an ID list are negligible compared to the clustering interval. This assumption may be justified if the clustering interval is a few hundred ms, assuming that the time for broadcasting an ID list may be less than 1 ms.

We further assume that adjacent clusters use different frequencies or spreading codes [4]. Gateways and noncluster nodes have multiple radio interfaces so as to be able to simultaneously receive packets from cluster members which belong to different clusters, or noncluster nodes. A cluster head controls the time slot assignment for nodes in the cluster. For example, a cluster head generates a time frame, which is composed of a time slot reservation field and data packet transmission field. Each node in a cluster which has a data packet sends a time slot request using a time slot reservation field based on random access mode to reserve a time slot in a data packet transmission field. As a result, data packet collision can be avoided. Therefore, we ignore packet collision in our simulations.

Each simulation runs until 1100 data packets are completely delivered. We perform 20-40 repetitions of the simulation. In each simulation, packet delivery time and packet delivery rate (percentage of nodes receiv-

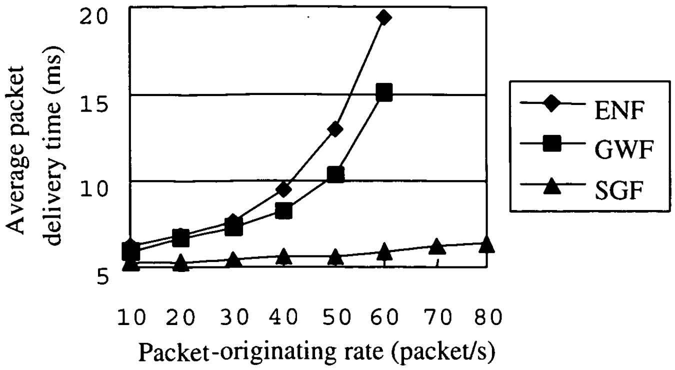


Fig. 6 Average packet delivery time versus packet-originating rate.

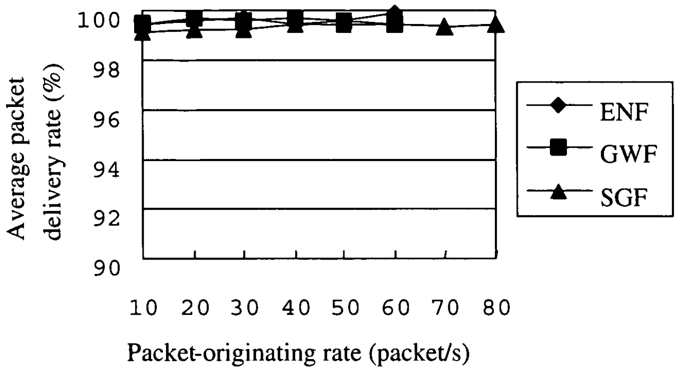


Fig. 7 Average packet delivery rate versus packet-originating rate.

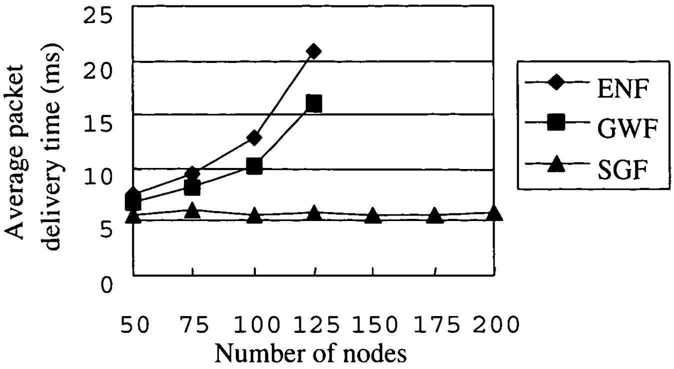


Fig. 8 Average packet delivery time versus number of nodes.

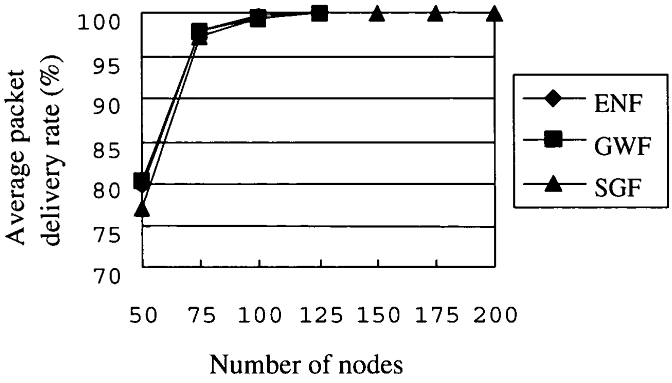


Fig. 9 Average packet delivery rate versus number of nodes.

ing a data packet) are measured for 100-th to 1100-th packets. As a result, the average packet delivery time and the average packet delivery rate are obtained. We have confirmed that the above simulation conditions are sufficient to obtain stable and consistent simulation results.

5.2 Simulation Parameters

Simulation parameters are listed as follows:

(1) A fixed number (one hundred in most cases) of nodes are initially distributed at random in an area which is a regular square of 500 m × 500 m. The area size is selected based on the default number of nodes, 100. The node density in this case corresponds to 400 nodes in the area of 1,000 m × 1,000 m, which is used in the analysis in Sect. 4.

(2) Each node travels in the area. It goes straight in a given direction at constant speed until it arrives at the edge of the area. A new direction is, then, selected at random so that the node continues to travel in the area.

(3) Packet originates uniformly at each node with Poisson distribution.

(4) Data packet length is constant and 10 kbits.

(5) Each node has a sufficient buffer size to store and forward packets.

(6) Transmission range of each node is 100 m.

(7) LCA is used as the clustering algorithm.

(8) Radio bandwidth is 10 Mbps.

5.3 Results

Figure 6 shows the average packet delivery time versus packet-originating rate (the total rate for the network), where the number of nodes is 100, node mobility is 10m/s and clustering interval is 0.1 sec. We do not assume any particular applications in our simulation. However, a node mobility of 10 m/s may be reasonable in the case of vehicles, which is considered as one of the applications in mobile ad hoc networks. It is shown that the effect of GWF in reducing the average packet delivery time is limited. On the other hand, it is shown that a significant gain is achieved by using SGF. This gain increases with the packet-originating rate. Figure 7 sshows the corresponding packet delivery rate. There is only a slight degradation in the packet delivery rate for SGF. Thus SGF improves packet delivery time at the cost of an insignificant degradation in packet delivery rate.

Figure 8 hows average packet delivery time versus node density, where the packet-originating rate is 50 packet/s, node mobility is 10 m/s and clustering interval is 0.1 sec. Figure 9 shows the corresponding average packet delivery rate. It is shown that SGF is

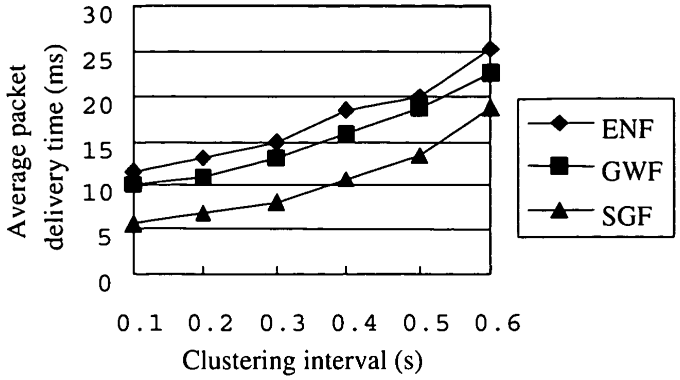


Fig. 10 Average packet delivery time versus clustering interval.

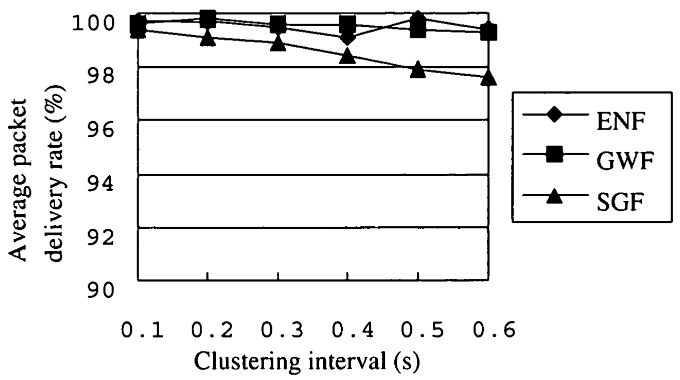


Fig. 11 Average packet delivery rate versus clustering interval.

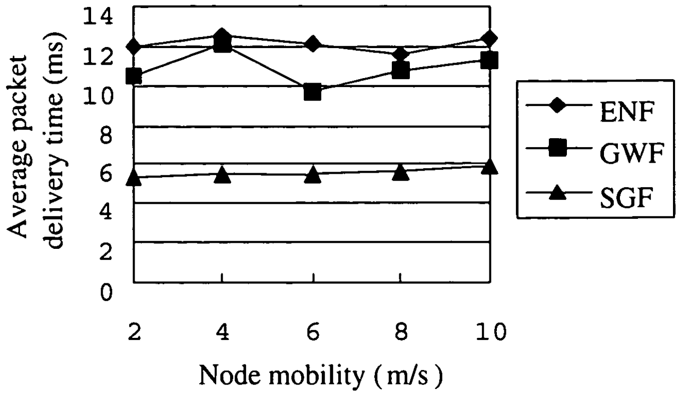


Fig. 12 Average packet delivery time versus node mobility.

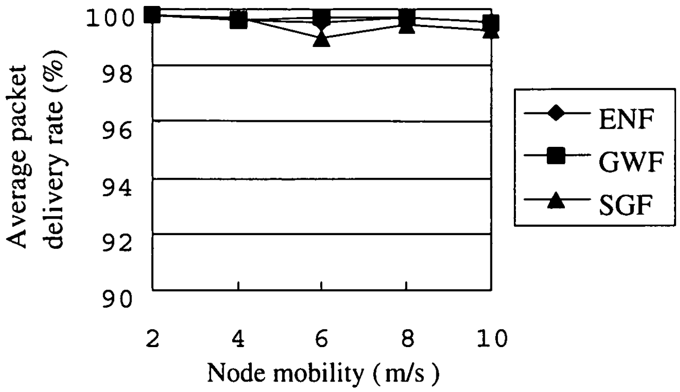


Fig. 13 Average packet delivery rate versus node mobility.

effective in reducing the packet delivery time, as the node density increases, without significant degradation in the packet delivery rate. In particular, note that the average packet delivery time increases with node density in ENF as well as in GWF, while it remains almost constant in SGF. This suggests that the freedom of gateway selection increases with node density, and more adequate selection is possible in SGF.

Figure 10 shows average packet delivery time versus clustering interval, where the number of nodes is 100, packet-originating rate is 50 packet/s and node mobility is 10 m/s. Figure 11 shows the corresponding average packet delivery rate. It is shown that the packet delivery time increases with clustering interval in all schemes, ENF, GWF and SGF. With longer clustering interval, each node cannot maintain the latest and accurate information on neighboring nodes. The results of the clustering therefore may not reflect actual node positions, as the clustering interval increases. As a result, a node may not be within transmission range of its cluster head. In this case, this node cannot send its packets because it fails to receive the time slot from its cluster head. This is a common factor in all schemes to increase packet delivery time.

Again, the effect of GWF in reducing the average packet delivery rate is limited. SGF is quite effective in reducing the packet delivery time for a wide range of the clustering interval. However, the percentage of improvement in the average packet delivery time decreases and degradation in the packet delivery rate increases as the clustering interval increases. A longer clustering interval affects the gateway selection performance in the case of SGF, because many nodes are erroneously selected as flooding nodes.

Figure 12 shows average packet delivery time versus node mobility, where the number of nodes is 100, packet-originating rate is 50 packet/s and clustering interval is 0.1 sec. Figure 13 shows the corresponding average packet delivery rate. It is shown that SGF is effective in reducing the packet delivery time, for a wide range of node mobility, without significant degradation in packet delivery rate. The average packet delivery rate very slightly decreases as the mobility increases in all schemes. This is because each node may not perform accurate clustering and gateway selection may not work correctly in SGF due to higher mobility.

In the following, we discuss node mobility and clustering interval selection, focusing on SGF. The required average packet delivery rate may depend on the application. If we assume that 99% is required, the clustering interval should be 0.1-0.2 sec, when node mobility is 10 m/s from the results in Figs. 11. If 98% iis required, the clustering interval could be extended up to 0.4 sec. The results in Fig. 13 suggest that the clustering interval could be further extended if the node mobility is lower. We have confirmed this assumption through additional simulations. The results are summarized as follows: If a 99% packet delivery rate is required, the clustering interval should be 0.5 sec, when node mobility is 2m/s. If 98% is required, the clustering interval could be extended up to a few seconds.

In our simulation, clustering overhead is not counted as mentioned in Sect. 5.1. Therefore, we cannot discuss the optimal clustering interval based on the above results. However, clustering overhead is a common element for all cluster-based ad hoc networks as mentioned in Sect. 2.1, and the above results suggest that if a proper clustering interval is selected to meet the given node mobility, then SGF achieves a significantly higher performance compared with ENF and GWF.

Based on the simulation results and discussions so far, we next consider the capacity of the ad hoc network with flooding. The capacity is defined as the maximum throughput obtainable by each node. It depends on many factors including radio bandwidth, transmission range, number of nodes, node mobility, and communication patterns. Some previous works analyzed the capacity of the ad hoc networks, where point-to-point communication is assumed [15], [16]. In our simulation scenario, the radio bandwidth, the transmission range, and the number of nodes are given. Therefore, the capacity can be defined as follows:

$$C = \lambda \times \theta / N, \quad (1)$$

where C, λ, θ, N represent capacity, the maximum packet-originating rate (the total rate for the network), average packet delivery rate, and number of nodes. This definition is on the lines of the conventional definitions for point-to-point communication, and is adequately modified to cope with flooding. The maximum packet-originating rate depends on the level of acceptable average packet delivery time. If we allow 10 sec for example, the maximum packet-originating rate λ is about 40 in the case of ENF, and about 50 in the case of GWF, while it is more than 80 in the case of SGF as seen from Fig. 6. Note that there are no significant differences in average packet delivery rates regardless of the flooding methods and packet-originating rates used, as shown in Fig. 7. It is therefore clear from Eq. (1), that capacity C is determined only by λ. From these results, it is obvious that SGF is superior to ENF and GWF, in terms of network capacity.

6. Conclusion

This paper presents an efficient flooding scheme based on clustering, which is termed SGF (Selected Gateway Forwarding). A new protocol, termed the FGS (Flooding Gateway Selection) protocol, between a cluster head and its gateways is introduced to realize SGF. It is shown that SGF significantly improves the packet delivery performance in ad hoc networks by reducing the flooding traffic. In particular, SGF is effective when node density and packet arrival rate are high.

This paper roughly compares the flooding performance of basic flooding strategies in clustered ad hoc networks. We avoid detailed modeling in medium access control, time slot assignment and radio propagation for simplicity. Thus, we may need more accurate modeling when considering practical applications. Further studies should also include an optimal clustering algorithm as well as an optimal clustering interval for realizing efficient flooding.

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