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A SURVEY OF MULTIPOINT RELAY BASED BROADCAST SCHEMES IN WIRELESS AD HOC NETWORKS

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ABSTRACT

Almost every routing protocol in mobile ad hoc networks (MANETs) depends on a broadcast scheme to disseminate routing information. For this reason, creating an efficient broadcast scheme is important and a large variety of approaches have been proposed. Among them, multipoint relay (MPR) is one of the distributed broadcast schemes which is efficient and simple. Based on the MPR concept, many broadcast schemes have been proposed, which generally focus on different performance issues. In this article we present a comprehensive survey of MPR-based broadcast schemes, classified into three categories based on their objectives. Different heuristics are described, and the evaluation of their performances is provided in light of their costs. Advantages and limitations of different broadcast schemes are also highlighted.

Mobile ad hoc networks (MANETs) [1] have gained much attention in recent years due to their self-organizing and infrastructure-free characteristics. Unlike cellular networks, which rely heavily on a wired infrastructure, MANETs can form temporary networks without any centralized administration or support from base stations. Each node in a MANET can act as a router to receive and forward packets, allowing seamless communications between people and devices. Hence, MANETs have great application potential in various scenarios such as battlefield communications, emergency services, disaster recovery, environmental monitoring, personal entertainment, and mobile conferencing [2, 3].

In a MANET, nodes can randomly move around, leave the network, or switch off. Moreover, new nodes may join the network unexpectedly. These characteristics make MANET an unstable network, where links between nodes may break frequently. Therefore, nodes in a MANET have to generate and distribute control messages regularly in order to update their connection states. However, the wireless nature of the medium implies the limited bandwidth capacity available in a frequency band. Every protocol that is going to use wireless links has to keep its unnecessary traffic to a minimum. Hence an efficient message distributing mechanism is essential for transmitting packets throughout the network.

Broadcasting has been used widely in wired and wireless networks to disseminate data and topology information. In MANETs, many routing protocols such as On-demand Distance Vector (AODV) [4], Dynamic Source Routing (DSR) [5], and the Optimized Link State Routing protocol (OLSR) [6, 7] rely on a flooding mechanism to broadcast data and control packets throughout the network in order to establish routes between each source-destination pair. The simplest way of broadcasting a packet to all nodes in the network is basic flooding or blind flooding [8], which allows each node to retransmit a packet to its neighbors only if it has not received this packet before. This rebroadcasting continues until all nodes in the network have received a copy of the packet. The main advantage of basic flooding is that it can always find the shortest path between sources and destinations, since topology packets have been through every possible path in parallel. However, the basic flooding mechanism can trigger a large number of packets forwarded in MANETs which will eventually overwhelm the network. Figure 1 illustrates this problem. After source S sends out a new packet, all its one-hop neighbors broadcast copies of it at almost the same time to all two-hop neighbors of S. This results in overly redundant rebroadcasting (some nodes receive the same packet more than once), contention and collision, which are referred to as the broadcast storm problem [9].

To achieve efficient broadcasting and solve the broadcast storm problem, many methods have been proposed [10, 11]. In general, these broadcast protocols are categorized into three classes: *probability-based methods*, which are similar to basic flooding, except that each node rebroadcasts packets

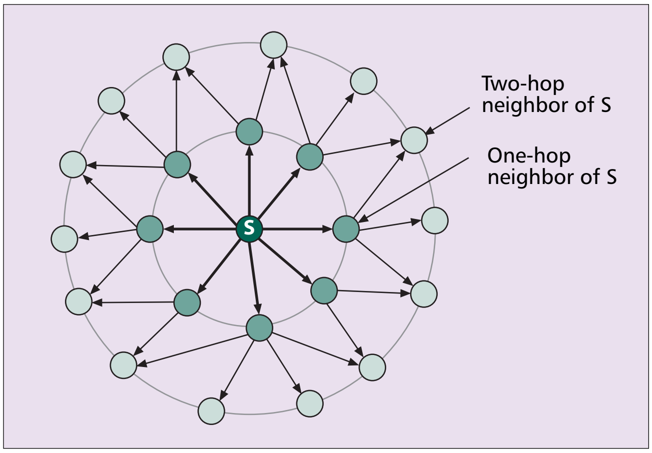


Figure 1. *Basic flooding problem.*

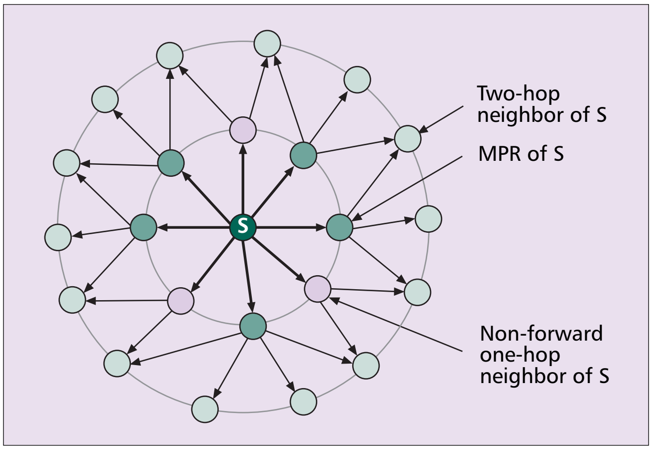


Figure 2. *MPR flooding heuristic.*

with a predetermined probability. This mechanism might work in dense networks when multiple nodes have similar neighbor coverages, but it will not have a significant effect in sparse networks; in *area-based methods*, a node rebroadcasts a packet based on the distance between itself and the node from which that packet is received. A rebroadcast occurs only when the distance is longer than a predefined threshold, so that a larger additional area can be reached. However, area-based methods do not consider whether some nodes actually exist within that additional area, which can lead to inefficient broadcasting; and *neighbor knowledge methods*, which can be further classified as *neighbor-designated methods* and *self-pruning methods*. In neighbor-designated methods, a node that transmits a packet specifies which one of its one-hop neighbors should forward the packet, while in self-pruning methods, a node receiving a packet will decide whether or not to transmit the packet by itself.

Among these broadcasting protocols, we particularly focus on multipoint relay (MPR), which is a neighbor designated method that exhibits both efficiency and simplicity. Compared to other neighbor knowledge broadcasting protocols, MPR uses a simple algorithm to calculate the forwarding nodes which makes it easy to implement. It can also significantly reduce the redundant broadcasting, thus efficiently delivering broadcast packets in both sparse and dense networks. For these reasons, MPR has been successfully employed by many routing protocols in wireless ad hoc networks as the mechanism of packet distribution. Several novel broadcasting techniques have also been proposed based on MPR. However, to our knowledge no overview of MPR and MPR-based broadcast schemes has been published in the research literature. In this article we attempt to fill this gap by presenting a comprehensive survey of MPR-based broadcast schemes in ad hoc networks. We classify these schemes by their objectives, and evaluate the performances of their heuristics based on their costs.

Overview of MPR

What is MPR?

The concept of MPR was first introduced in the High-Performance Radio Local Area Network (HIPERLAN) type 1 standard [12], which was a MAC layer protocol developed by the European Telecommunications Standards Institute (ETSI) to provide a substitute for wired LAN. It was then successfully extended to MANETs and effectively implemented in the OLSR routing protocol, which is a proactive routing protocol ratified as a request for comments (RFC) in the Internet Engineering Task Force (IETF) MANET chapter [13]. The goal of MPR is to reduce the flooding of broadcast packets in the network by minimizing redundant retransmissions locally. Each node in the network selects a subset of its one-hop neighbor nodes, called multipoint relays (MPRs), as the forwarding node set to retransmit broadcast packets. Other nodes that are not in the MPR set can read but not retransmit broadcast packets. The MPR set guarantees that all two-hop neighbor nodes of each node receive a copy of the broadcast packets and, therefore, all nodes in the network can be covered without retransmissions by every single node.

An example of an MPR set is shown in Fig. 2, where source node *S* in the center selects only a subset of its one-hop neighbors (the grey nodes) as MPRs to forward the broadcast messages, so that all two-hop neighbor nodes of *S* can be covered by the selected five MPRs. Upon receiving a broadcast message, a node forwards it if and only if the message is received for the first time and the sender of the message has selected the node as an MPR. This scheme can dramatically reduce the number of retransmitters thus decreasing the rebroadcast and overall redundant messages in the network. Furthermore, the link state messages disseminated throughout the network only contain the information of a node's MPR selectors (i.e., other nodes that have selected the node as their MPR). Therefore, only partial link information is included in the messages, which makes the overhead of control traffic relatively low. Because of these important merits, the MPR mechanism produces efficient routing schemes. It provides shortest-path routes for routing protocols while at the same time minimizing the flooding of broadcast messages and reducing the overhead of control traffic. Hence, the MPR scheme is also favored in other routing protocols such as the Multipoint Relay Distance Vector (MPRDV) protocol [14] and MPR-based hybrid routing (MPR-HR) [15].

Original MPR Selection Heuristics

From the previous section we can see that the main gain obtained by introducing an MPR set is that broadcast can be completed by using only a small set of nodes in the network and the redundant retransmissions are greatly reduced. The smaller the MPR set is, the fewer retransmissions that will occur. Unfortunately, it has been proved in [7] that finding a minimum size of an MPR set is NP-complete [16]. There are some proposed heuristics to select an MPR set with good approximation compared with the optimal one. Here we discuss the MPR selection heuristic currently presented in the OLSR routing protocol as described in [6]. We refer to it as "the original MPR selection heuristic."

The original MPR selection heuristic follows a greedy algorithm [17] which works well for computing an MPR set. To

Groups	Objectives
Pure MPR schemes	Still based on the concept of the original MPR selection heuristic. Several extensions are applied in order to improve some specified performances such as the size of the MPR set, collision avoidance, and power usage efficiency.
MPR-based CDS schemes	To reduce the number of forwarding nodes by generating a Connected Dominating Set (CDS) based on the original MPR selection heuristic.
QoS-based MPR schemes	Consider quality-of-service (QoS) constraints in the network by selecting MPRs that meet some QoS requirements, so that real-time applications such as voice and video can be better supported by providing paths with larger bandwidth and lower delay.

Table 1. *Summary of three groups of MPR schemes.*

select the multipoint relays for a node x, first we define the set of all one-hop neighbors of x as $N(x)$, and the set of all two-hop neighbors of x as $N^2(x)$. We also note the definition of *out-degree* $D(y)$, which represents the number of two-hop neighbors of x that can be covered by y where y is an one-hop neighbor of x. Let the selected MPR set of node x be MPR(x). The heuristic of the MPR(x) calculation operates as follows:

- Start with an empty MPR set MPR(x).
- Calculate $D(y)$ for each node in N(x).
- Add to MPR(x) those nodes in N(x), which are the *only* nodes to provide reachability to some nodes in $N^2(x)$. For example, if node a in $N(x)$ is the only neighbor of node b in $N^2(x)$, then add node a to MPR(x). Remove nodes from $N^2(x)$ which are now covered by nodes in MPR(x).
- While there are still some nodes in $N^2(x)$ which are not yet covered by the nodes in MPR(x):
  –For each node in $N(x)$ which is not yet selected as the MPR, calculate the number of the two-hop neighbor nodes of x it can cover which are not yet covered by the nodes in MPR(x).
  –Add a node to MPR(x) which covers maximum number of remaining two-hop neighbors of x. In case of multiple choices, select the node as MPR whose $D(y)$ is larger. Remove nodes from $N^2(x)$ which are now covered by nodes in MPR(x).
- To optimize the MPR(x), remove the node in MPR(x) if all its covered two-hop neighbor nodes can also be covered by the remaining nodes in MPR(x). In other words, there is no effect on MPR(x) if this redundant node is removed.

In order to recognize neighbor nodes and calculate $D(y)$ for each one-hop neighbor, a *HELLO message* has to be exchanged between one-hop neighbors periodically. A HELLO message from a node may contain information such as its node ID, MPRs it has selected, and all related information about its one-hop neighbors. These HELLO messages are exchanged in a fixed time period so that necessary information for the MPR calculation can be obtained and the status of the network can also be updated.

In the original MPR selection heuristic, it is worth noting that the third step, which selects some one-hop neighbors that solely cover some two-hop neighbors, can be omitted because these two-hop neighbor nodes can be covered sooner or later based on the fourth step. The purpose of the third step is to optimize the MPR set calculation by removing some two-hop neighbors at the beginning of the iterative procedure in the fourth step.

How to Classify MPR Schemes

Currently, many schemes have been proposed to calculate the forwarding node set based on the original MPR selection heuristic. These schemes are put forward to improve different aspects of broadcasting performance in MANETs such as the number of forwarding nodes, collision avoidance, efficient power usage and quality of service (QoS). These schemes can be classified into different groups based on various criteria. In this article we classify different MPR schemes into three groups based on their objectives. Table 1 shows the classifications and their objectives.

Pure MPR schemes [18–21] aim to extend the original MPR selection heuristic to reduce transmit collisions and improve the efficiency of power usage in MANETs. The collision problem is mainly due to the large size of the MPR set and the overlapping coverage between MPRs. It can significantly reduce the ratio of successful information transmission thus degrading the overall system performance. Power consumption in MANETs is always an important issue, since efficient use of power in a network cannot only prolong the life of batteries, but also increase the ratio of successful communications.

MPR-based CDS schemes [22–25] try to find a connected dominating set (CDS) based on MPR schemes. They also aim to reduce the number of forwarding nodes in order to minimize retransmission overheads in the network.

QoS-based MPR schemes [26, 27] consider the QoS requirements in the network and attempt to find an MPR set that meets the QoS criteria. Because QoS metrics such as bandwidth and delay are essential for real-time applications, finding an MPR set that can guarantee these QoS conditions is the preliminary for better supporting QoS in mobile ad hoc networks.

Based on this classification, we can precisely analyze and compare different schemes. Similarities and differences of each scheme in the same group or between different groups will be easily indicated. This will provide a systematic clear overview of all schemes in this survey.

Costs of MPR Schemes

In order to evaluate different schemes, we define the costs of MPR-based broadcast schemes here. For each heuristic, in order to implement the calculation of the forwarding node set, a certain number of procedures and information are required. These requirements form the costs and can be evaluated for comparisons between different schemes. In this article, we evaluate four costs of MPR-based schemes described as follows:

- In order to calculate the forwarding node set, a certain number of processes need to be conducted. These processes may take different time to complete depending on the algorithms they used. For each MPR scheme, the time required to complete the forwarding node calculation is referred to as the *time complexity* or *computation complexity* of that MPR heuristic, which can be used to

Cost	Definition and Description
Time complexity	The maximum number of steps required in the worst case of a heuristic. Here we ignore the message transmission time and only calculate the time to run each step in a heuristic. For some heuristics that do not present detail procedures, the time complexity will be based on assumptions. Furthermore, we only consider the time for each node to complete the heuristic; therefore, the time complexity in our article is a local value. However, since each node follows the same calculation processes, this local time complexity is sufficient to evaluate the overall system.
Message complexity	The maximum number of messages used in the worst case for a heuristic to obtain necessary information, so that the calculation can be conducted. Here we assume the message has a constant size and each message sent by a node can be heard by all its one-hop neighbor nodes. We only consider the message complexity of each node to complete the heuristic.
Information range	To run a heuristic, different hops of neighbor's information is required, which we refer to as the information range of the heuristic. The larger information range a heuristic requires, the higher time and message complexity it will have.
Source dependent	If a scheme is source dependent, a forwarding node needs to know whether or not messages it received are from its MPR selectors before it relays them. If a scheme is source independent, a forwarding node will broadcast all messages that are received for the first time.

Table 2. *Description of the cost terms of MPR heuristics.*

evaluate the efficiency of a heuristic. A heuristic that requires much time to run the calculation may be too complex to be deployed. Furthermore, when the network topology changes rapidly, the frequency of a forwarding node calculation also increases, and thus the time consumption of the calculation is huge for a complex heuristic. Hence, an efficient heuristic that consumes less time is essential for the MPR set generation.

- For each MPR scheme, a number of HELLO messages may need to be exchanged between nodes in advance. These HELLO messages contain the necessary information for a heuristic to implement the forwarding node set calculation. Schemes in different groups or even in the same group may require a different number of HELLO messages. However, frequent information exchange will consume the limited bandwidth in wireless networks and also accelerate the energy consumption of mobile nodes. Therefore, the number of HELLO messages exchanged, which is regarded as the message complexity or communication complexity, can significantly affect the performance of an MPR scheme.
- The MPR-based schemes need to collect neighboring nodes' information in order to calculate MPR sets. Referring to the original MPR scheme demonstrated in Fig. 2, source node *S* has to know all neighbors in its one-hop neighborhood in order to identify all its two-hop neighbors and to decide which one-hop neighbor has covered the largest number of two-hop neighbors. In other words, node *S* has to obtain node information of its one-hop and two-hop neighbors in order to operate the MPR calculation. We refer to this node information requirement as the *information range* of an MPR scheme, and thus the original MPR scheme has an information range of two hops. Depending on different schemes, the information range can be different. Generally, the larger information range a scheme requires, the more time and message exchange it will need. Hence, an information range up to four hops may not be efficient for an MPR scheme because messages need a long time to be transmitted to the source node and the information they carry may be outdated by then.
- Some MPR schemes are *source dependent*, they need to know from which node the packet was received in order to determine whether or not to retransmit this packet. For example, in the original MPR selection heuristic discussed earlier, a node will transmit a broadcast message if it has not received this message before and the message is from its MPR selectors. It will only read, but not rebroadcast, other messages that are not from its selectors. This requirement increases the complexity of both the message sending and receiving process in a scheme.

These costs reflect the efficiency and scalability of different MPR schemes, such that the merits and drawbacks of each scheme can be clearly highlighted by analyzing these costs. A summary of terms of costs and their definitions are shown in Table 2. In the following study, we will analyse these costs for each scheme so that readers can gain a better understanding and make a thorough evaluation of MPR-based schemes.

Classifying MPR Schemes

In this section we will describe and analyze different MPR schemes in each group shown in Table 1. Summarized heuristics will be given as well as advantages and disadvantages of each scheme. Finally, a summary will be presented based on the costs listed in Table 2 for each group to compare different schemes so that readers can gain clear understanding of characteristics of each scheme.

Pure MPR Schemes

Based on the conception of the original MPR selection heuristic, pure MPR schemes [18–21] try to modify the MPR selection in order to choose nodes as MPRs that have some special effects such as minimum collisions and efficient power consumption.

Mans and Shrestha's Heuristics — Mans and Shrestha proposed four heuristics in [18, 19] which aim to reduce the cardinality of MPR set and limit collisions in the network.

The first heuristic, namely, in-degree MPR (ID-MPR), puts forward the concept that the complexity of the original MPR selection heuristic is mainly due to the maximum value of the out-degree *D* of one-hop neighbor nodes. Considering this property, a new concept called in-degree denoted as *Din* was presented in this heuristic as a new criterion for MPR selection. The value of the in-degree of a node *y* is the num-

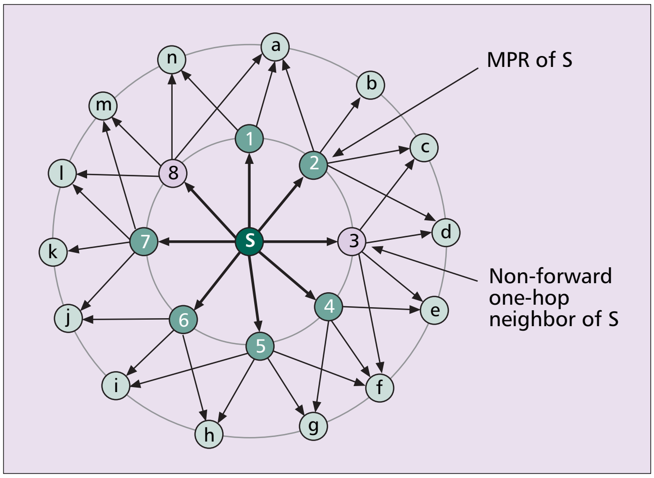


Figure 3. *In-degree MPR heuristic.*

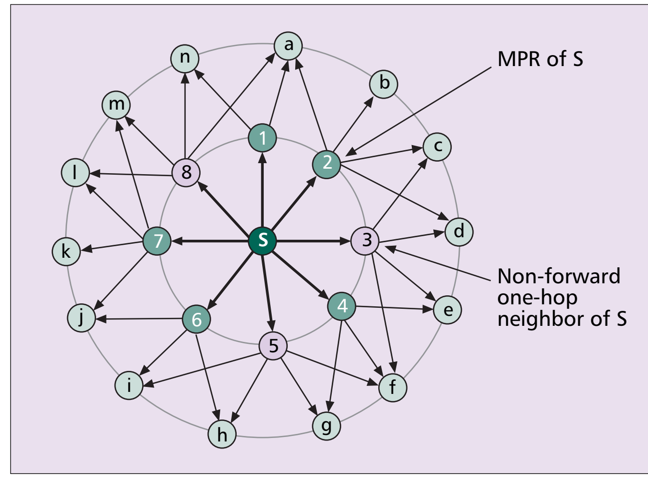


Figure 4. *Minimum overlapping MPR heuristic.*

ber of shared neighbors between node y and node x, where x is a one-hop neighbor of source node S and y is a two-hop neighbor of S. Due to the intrinsic connectedness, wireless networks may be dense and highly clustered. In such case, it is believed that the maximum value of the in-degree $Din(y)$ of a two-hop neighbor node y is likely to be smaller than the maximum value of the out-degree $D(x)$ of a one-hop neighbor node x. When applies the in-degree to the MPR selection, the computational complexity might be lower than the original MPR heuristic.

The proposed scheme is still based on the original MPR selection heuristic. For a source node S that needs to calculate the MPR set, apply first three steps used in the original MPR selection heuristic to cover some two-hop neighbors that are solely covered by some one-hop neighbors. If there are still some uncovered two-hop nodes, randomly pick up a node among those uncovered two-hop nodes, from all the one-hop neighbor nodes of source node S, which can cover this two-hop node and have not been selected as MPRs, select a node as an MPR that has minimum number of uncovered two-hop neighbors. Repeat this step until all two-hop neighbor nodes have been covered. Figure 3 depicts this heuristic. First, one-hop neighbor nodes 2 and 7 will be chosen as MPRs because they solely cover two-hop nodes b and k, respectively. Among the uncovered two-hop neighbors, randomly pick up a node, assume node i. Based on the in-degree heuristic, node 6 will be selected as the MPR, because it covers less uncovered two-hop neighbors of source S. The rest ot the MPRs are selected following the same strategy when two-hop neighbor nodes f, n, and e are randomly picked.

The initial aim of this proposed heuristic is to reduce the computational complexity by introducing in-degree to the original MPR heuristic. It has the merit that the in-degree of each two-hop node of source S is a smaller value compared to the out-degree of each one-hop node of S, so that less time is spent on the MPR calculation for each two-hop neighbor. However, this scheme increases the size of the MPR set. As shown in Fig. 3, the number of MPRs in this scheme is six, whereas only five MPRs (node 2, 4, 5, 7, and 8) are required when the original MPR heuristic is used. The additional MPR node is due to the iterative step in the heuristic which selects an one-hop neighbor that covers minimum number of uncovered two-hop neighbors of source S. Intuitively, this increases the size of the MPR set. We believe a possible way to compensate this drawback is to use maximum number of uncovered two-hop neighbors instead of minimum to enlarge the coverage, so that more two-hop neighbors will be covered by an MPR in average, and thus less number of MPRs are needed to cover all the two-hop neighbors.

The second heuristic, referred to as the minimum overlapping MPR (MO-MPR), tries to minimize overlaps between MPRs. The overlap is defined as the shared two-hop neighbors that are covered by two or more MPRs. For example, in Fig. 3, both MPR 5 and MPR 6 cover two-hop nodes i and h. This overlap is detrimental to the message reception when considering the signal interference. The received signal at nodes i and h might be greatly interfered if both MPRs broadcast messages simultaneously. To reduce overlaps, the heuristic tries to spread MPRs as evenly as possible around the source node, thus limiting the overall interference in the network.

In this heuristic, instead of using the out-degree, a covering ratio of a one-hop neighbor is employed to determine an MPR set. The covering ratio is defined as the ratio of covered two-hop neighbors over uncovered two-hop neighbors that a one-hop neighbor has. Similar to the previous heuristic, the minimum overlapping MPR heuristic also follows the first three steps used in the original MPR scheme. After these first three steps, if there are still some uncovered two-hop nodes, among those one-hop neighbors that are not selected as MPRs, the heuristic chooses a node with the minimum covering ratio as the MPR. If multiple choices exist, randomly pick one as an MPR. Repeat this step until all two-hop neighbors of source S are covered. Figure 4 illustrates this heuristic.

This heuristic cannot reduce the maximum amount of overlaps per node due to the fact that the overlaps per node mainly depends on the topology which can change arbitrarily. However, it is possible to limit the impact of overall overlapping in a network. As shown in Fig. 4, nodes a and j are overlapping nodes which are covered by some one-hop neighbors of S. Whereas node a, f, g, i, and m are the overlapping nodes when the original MPR heuristic is applied to the same graph and node 2, 4, 5, 7, and 8 are selected as MPRs. It is obvious that the overall overlapping in the network is reduced by the proposed heuristic. Nevertheless, the minimal overlapping comes with other prices. It increases the number of MPRs in some scenarios. For instance, if node x has a higher covering ratio than node y, x will be chosen as the MPR. However the number of uncovered two-hop neighbors of x might be smaller than the one of y. This leads to more time to finish the MPR set calculation and also increases the number of MPRs generated. Another drawback of this scheme is that, during the beginning of the heuristic there may be numerous nodes with the same covering ratio. In this case, the heuristic randomly chooses one node as the MPR, which might not cover the most number of uncovered two-hop nodes. The worst scenario is that all randomly-selected MPRs cover the smallest number of uncovered two-hop nodes. This obviously increments the

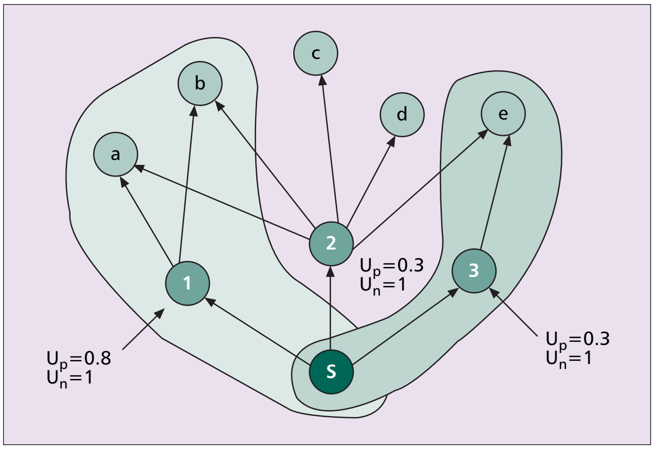


Figure 5. *UMPR heuristic.*

size of the MPR set. One possible solution is to choose the node as the MPR that can cover the most number of uncovered two-hop nodes if multiple nodes have the same covering ratio.

For the sake of minimizing the overlaps in the original MPR scheme without increasing the number of MPRs, two heuristics are proposed, namely, prioritized MPR (P-MPR) and random prioritized MPR (RP-MPR). Both of them follow the same steps of the original MPR heuristic except for the tie breaking procedure. In P-MPR, when there are multiple one-hop nodes that can cover the same number of uncovered two-hop nodes, instead of using the maximum out-degree, a node with a minimum out-degree is selected as the MPR. In RP-MPR, while multiple choices exist, randomly choose a node as the MPR.

The two proposed heuristics are the combinations of the original MPR heuristic and the minimum overlapping MPR heuristic discussed previously. In the original MPR heuristic, the reason to use the maximum out-degree as the tie breaker is to add some redundancy to the network, therefore nodes can still be covered even if some MPRs are temporarily away. This strategy can stabilize the performance of the network when the topology changes rapidly. However, such redundancy might lead to a large degree of overlapping thus increasing the number of collisions. P-MPR scheme tries to minimize the degree of overlapping by sacrificing the redundancy in the network while RP-MPR aims to balance both properties.

Lipman's UMPR — Lipman [20] proposed a distributed broadcast scheme based on the original MPR heuristic referred to as utility-based MPR (UMPR) flooding. It aims to reduce the unnecessary retransmission by limiting the rebroadcasting to only essential nodes in a similar fashion to the original MPR scheme. Furthermore, it intends to extend the lifespan of the network by fully utilizing the energy of nodes. In the UMPR, the network is assumed to be heterogeneous, wireless mobile devices can have different characteristics even if all devices consist identical hardwares. By considering this characteristic, the UMPR tries to distribute the broadcasting load to the *most suitable* nodes, so that the overall energy in the network can be efficiently used. In order to decide the desirability of a node, the UMPR calculates a *forwarding utility* for each one-hop neighbor of source node S. A forwarding utility U_f is a function that consists of an one-hop node's power utility U_p and neighbor utility U_n. The function is defined as follows:

$$U_f = U_p U_n \quad (1)$$

The power utility U_p gives the value of the remaining power of a node. The larger the value is, the more remaining power a node has. However, how to monitor the remaining power of a device is not presented in the article. The neighbor utility U_n represents the ratio of uncovered two-hop nodes over all two-hop nodes that a one-hop neighbor node covers. The value of forwarding utility will be updated each time when a node is allocated into the MPR set.

The heuristic of the UMPR is still based on the original MPR scheme. It applies first three steps used in the original MPR heuristic. When there are still some uncovered two-hop nodes, from those one-hop neighbors of source S that have not yet been chosen as MPRs, it selects a node as an MPR that has the highest forwarding utility. This step is repeated until all two-hop neighbors are covered.

The proposed heuristic can achieve an efficient use of the overall energy in a network by choosing relay nodes with higher remaining power. Furthermore, the neighbor utility U_n makes the UMPR be prone to choose nodes that are less overlapping thus reducing the number of collisions in the network. Due to these characteristics, the UMPR can provide better performance than the original MPR in terms of average lifespan in a mobile ad hoc network. However, the scheme may increase the number of MPRs. This is due to two reasons. First, the nodes with more remaining power may not cover many uncovered two-hop nodes. Second, the neighbor utility U_n can introduce more MPRs to the network. An example is shown in Fig. 5 where all one-hop nodes (node 1, 2, and 3) are selected as MPRs. Assume that all three one-hop nodes initially have the same neighbor utility U_n. Based on the forwarding utility function U_f, node 1 will be firstly chosen as the MPR because it has the highest remaining power. Then the U_n is recalculated for the residual one-hop nodes. In this case, node 3 has a higher U_n than node 2 and it is selected as the MPR. Finally, in order to cover all the two-hop neighbors, node 2 is selected as the MPR. However, as we can see, a better MPR set in this network should only contain node 2, because it can sufficiently cover all two-hop nodes. We believe that this kind of situation is likely to happen at the beginning of the MPR selection when none of two-hop nodes are covered yet.

Lipman's UBF — Lipman [21] later proposed another flooding scheme called the utility-based flooding (UBF), which intends to extend the UMPR to provide full resource awareness. It points out a problem in the UMPR that nodes selected by the first three steps used in the original MPR heuristic tend to dominate the MPR set and limit the use of the forwarding utility. The UBF avoids this problem by eliminating these steps used in UMPR. Therefore, nodes selected as MPRs are solely based on the forwarding utility. It guarantees that each node in the MPR set is selected based on the remaining energy and the overlapping, so that a more efficient energy consumption can be achieved.

The heuristic of the UBF is similar to the UMPR except in the first step. At the beginning of the MPR set calculation, source node S will choose a one-hop node with the highest forwarding utility as the MPR. 15 This step is repeated until all two-hop nodes are covered. Although the modified heuristic can gain more resource awareness, it still has the same drawback as the UMPR. Furthermore, without applying the first three steps, which are used to optimize the heuristic, the UBF may need more time to calculate the MPR set.

Summary of Pure MPR Schemes — The objectives of schemes discussed previously are summarized in Table 3. For the purpose of comparison, the original MPR scheme will also be included in this summary. Generally, objectives of pure MPR schemes are to find out a small set of one-hop neighbor

Approach	Objectives
Original MPR	To reduce the flooding of broadcast packets throughout the network by limiting the number of transmitters in the network.
In-degree MPR	MPR To exploit the fact that the maximum value of in-degree of two-hop nodes is likely to be smaller than the value of maximum uncovered node degree. This might be likely to reduce the computational complexity, thus improving the speed of the MPR selection calculation.
Minimum overlapping MPR	To spread as evenly as possible MPR nodes around the source to reduce the overlapping coverage, so that the overall number of collisions in the network can be limited.
Prioritized MPR	To reduce the possibility of overlapping in the original MPR heuristic by changing the tie-breaking criterion. Thus the overall overlapping degree in the network can be reduced without increasing the number of MPRs.
Random prioritized MPR	Has the same aim as the prioritized MPR but balances the redundancy and overlapping in some degree.
UMPR	To minimize the rebroadcast in a similar fashion as the original MPR scheme, and meanwhile consider some characteristics of nodes such as the remaining power and the neighbor utility in order to select the most suitable nodes as MPRs. Therefore, the overall energy in the network can be efficiently used.
UBF	To achieve full resource awareness by extending the UMPR scheme, so that forwarding utility is considered for each node in the MPR set.

Table 3. *Summary of pure MPR schemes.*

nodes based on the original MPR heuristic to forward broadcast messages, so that all nodes within two hops from the source node can receive the messages eventually. For different schemes in this group, the objective also varies. Mans and Shrestha's heuristics focus on the collision problem in the network and try to produce a set of MPR that can minimize the overall overlapping. Among proposed schemes, the in-degree heuristic is the one that tries to reduce the computational complexity of the MPR selection by introducing the in-degree concept. Lipman proposed two schemes and both of them aim to prolong the lifetime of the network by efficiently using the power of mobile nodes. The UMPR applies the forwarding utility as the criterion to select nodes as MPRs. Thus it can spread the traffic loads to nodes with higher remaining power and less overlapping. The UBF, which can be seen as the extension of UMPR, improves the energy awareness performance by considering the forwarding utility for all MPRs.

The cost comparison of pure MPR schemes is shown in Table 4. The symbol Δ represents the maximum number of one-hop neighbors of a node, $|N_2|$ represents the maximum number of two-hop neighbors of a node, and M represents the maximum number of MPR selected by a node. In this article we only focus on the costs for a source node to complete the MPR set calculation so that all two-hop neighbors of the source node can be covered. When we calculate the time complexity, only the internal computational time (the time used to calculate the MPR set for a heuristic) is considered. We also assume that the out-degree value D for each one-hop node is known to the source node. For simplicity, we assume that each message has a constant size, so that the message complexity of each scheme only depends on the number of necessary messages sent before the calculation by all nodes within two-hop from the source node. However, the actual message overhead of schemes are different because information required might be varied between schemes. This difference will also be pointed out in the summary. For comparison, costs of the original MPR scheme will also be discussed.

Since all schemes in this group are based on the original MPR selection heuristic, they might share some characteristics and have the same value for some costs. For each scheme in the pure MPR group, both one-hop and two-hop node information is required for the MPR calculation. For example, in the original MPR scheme, in order to produce an MPR set, knowledge of one-hop and two-hop neighbors is required for the MPR calculation so as to decide which one-hop node covers the most number of uncovered two-hop nodes. Furthermore, source information is also needed for all schemes in this group to determine whether or not a node needs to rebroadcast a message. An MPR selected in these schemes can rebroadcast a message if and only if the message is received for the first time and it comes from this MPR's selectors.

In the original MPR heuristic discussed previously, the time used to calculate the MPR set is dominated by iterative steps. In step 3, we assume that $O(\Delta)$ time might be needed at most to find out all one-hop neighbors that solely cover some two-hop nodes. In step 4, the heuristic iteratively calculates the remaining one-hop neighbors until all two-hop nodes can be covered. The first substep in step 4 needs $O(\Delta)$ time while the second substep needs $O(2\Delta)$ for each round. The iteration takes M rounds to complete, and thus step 4 needs at most $O(3\Delta M)$ time in total and the overall time complexity of the original MPR heuristic is $O(3\Delta M + \Delta)$. In Mans and Shrestha's four heuristics, except for the in-degree MPR, similar steps are used to calculate the MPR set. Therefore, the same time complexity can be achieved for the minimum overlapping MPR, the prioritized MPR, and the random prioritized MPR. For the in-degree MPR heuristic, because a different iterative step is used to calculate remaining one-hop neighbors, it has a different time complexity value. After applying the step 3 used in the original MPR, the in-degree MPR heuristic randomly chooses an uncovered two-hop node to calculate an MPR. Unlike the original MPR heuristic, this iteration might take Δ rounds to complete, and it might need $O(2\Delta^2)$ time to finish in the worst case. So the overall time complexity of the in-degree MPR is $O(2\Delta^2 + \Delta)$. Lipman's two heuristics calculate a forwarding utility as the criterion of MPR selection instead of the number of uncovered two-hop nodes. For simplicity, we assume both criteria need the same time to be calculated. Because the UMPR follows steps used in the original MPR scheme, it takes the same time to complete the MPR set calculation. Intuitively, due to the lack of

Schemes	Information range	Source dependent	Time complexity	Message Complexity	Summary of the heuristic
Original MPR	2 hops	Yes	$O(3\Delta M + \Delta)$	$O(\Delta + \|N_2\|)$	First, select as MPRs one-hop neighbors of source S if they solely cover any two-hop neighbors of S. Second, select one-hop neighbors of the source S as MPRs if they cover the maximum number of remain uncovered two-hop neighbors of S. In case of a tie, choose a node with the maximum node out-degree.
ID-MPR	2 hops	Yes	$O(2\Delta^2 + \Delta)$	$O(\Delta + \|N_2\|)$	Apply the first phase used in the original MPR. When there are still some uncovered two-hop neighbors of source S, randomly pick up a two-hop neighbor y, and from all S's one-hop neighbors that cover y, select a node as an MPR that has the minimum number of uncovered two-hop neighbors of S.
MO-MPR	2 hops	Yes	$O(3\Delta M + \Delta)$	$O(\Delta + \|N_2\|)$	Apply the first phase used in the original MPR. When there are still some uncovered two-hop neighbors of source S, select a neighbor of S as an MPR that has the minimum covered over uncovered two-hop nodes ratio. In case of multiple choices, randomly choose a node as the MPR.
P-MPR	2 hops	Yes	$O(3\Delta M + \Delta)$	$O(\Delta + \|N_2\|)$	Apply the same phases used in original MPR except the tie-breaking step. Other than the maximum number of one-hop neighbors, a node with a minimum number of one-hop neighbors which are also two-hop neighbors of S is selected as the MPR.
RP-MPR	2 hops	Yes	$O(3\Delta M + \Delta)$	$O(\Delta + \|N_2\|)$	Apply the same phases as the original MPR except the tie-breaking step. If there is a tie, randomly choose a node as the MPR.
UMPR	2 hops	Yes	$O(3\Delta M + \Delta)$	$O(\Delta + \|N_2\|)$	Apply the same phases as the original MPR except the tie-breaking step. If there is a tie, randomly choose a node as the MPR.
UBF	2 hops	Yes	$O(3\Delta M)$	$O(\Delta + \|N_2\|)$	Eliminate the first phase applied in the UMPR. Use the utility based algorithm to calculate all one-hop neighbors of source S. Select nodes with the highest forwarding utility as MPRs until all two-hop neighbors of S are covered.

■ Table 4. *Cost comparison of pure MPR schemes.*

the third step used in the original MPR heuristic, the time complexity of UBF can be $O(3\Delta M)$.

In order to implement heuristics, necessary information, such as one-hop neighbors and the remaining node power, has to be collected by the source node. This information is included in *HELLO* messages and sent by all nodes in the network. In the original MPR scheme, to collect this information, each two-hop node has to send out a certain number of HELLO messages to inform its neighbors about itself. After receiving these messages, all one-hop nodes have knowledge of their neighbors, then they also send out HELLO messages to inform their neighbors. The source node will eventually receive all the HELLO messages from its one-hop neighbors and start the MPR calculation. Therefore, the total number of messages sent within two hops in the original MPR is $O(\Delta + |N^2|)$. In the pure MPR group, different node information can be piggybacked into HELLO messages, and each scheme in the group only needs node information within two hops. Therefore, they all have the same message complexity of $O(\Delta + |N^2|)$. However, we come to this result by ignoring the message overhead of the different schemes. Actually, the overhead might be varied depending on different node information contained in HELLO messages. For example, the UMPR and the UBF have a larger message overhead because they require extra information of the remaining node power inside their HELLO messages.

From the time and message complexity analysis, we notice that most of the schemes in this group have a similar performance. A special case is the in-degree MPR, whose time complexity is among the highest all. This result contradicts to the aim of the scheme, which tries to reduces the computational complexity. The result indicates that the heuristic needs more time to complete, and it generates more MPRs than others. The simulation results in [18] also show that the performance of the in-degree MPR is inferior to others in terms of the average number of MPRs and the total number of retransmissions in the network. The drawbacks are mainly due to two reasons. First, the in-degree heuristic randomly chooses a two-hop node to begin the MPR calculation; second, it selects a one-hop node with minimum uncovered two-hop nodes as the MPR. Such strategies might lead to choosing all one-hop nodes as MPRs in the worst case. However, the concept of the in-degree provides a new thought to calculate an MPR set, and we believe that it is still worthy to be considered while a suitable strategy is applied. Regarding the other schemes proposed by Mans and Shrestha, they all increase the

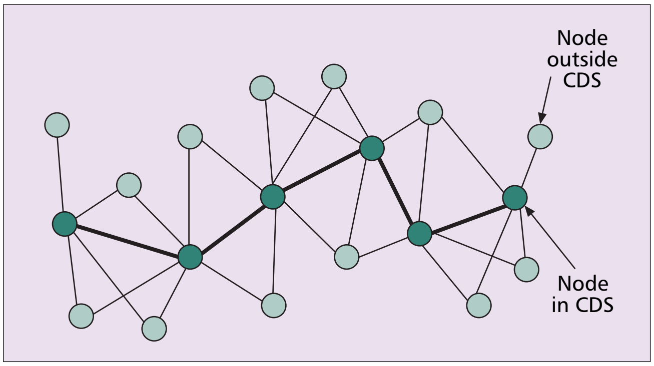


Figure 6. *CDS flooding.*

size of the MPR set to some degree, thus increasing the number of retransmissions in the network. It is also noticeable that despite using different heuristics, the performances of all the heuristics vary only slightly. This can be explained by the fact that all the proposed heuristics apply the initial phase used in the original MPR scheme, which aims to pick up one-hop nodes that solely cover some two-hop nodes. This initial phase attempts to occupy a large part of the MPR set, and thus each heuristic can only vary among a small number of MPRs. The significance of this conclusion is that it points out a way to further improve some heuristics. By ignoring the initial phase, a heuristic can select each MPR based on the same criteria thus achieving better performance. The UBF is an example that takes this advantage and gains full resource awareness.

MPR-Based CDS Schemes

One efficient broadcast method for wireless ad hoc networks is to formulate a small connected dominating set (CDS) where only the nodes in the set relay messages. A dominating set (DS) is a subset of nodes in the network where every node is either in the subset or has at least one neighbor in the subset. A DS is called CDS if the subgraph induced by the DS is connected. An example is shown in Fig. 6 where nodes connected by thick lines form a CDS, and other nodes in the network are one-hop neighbors of the nodes inside the CDS. Upon receiving a broadcast message, only nodes inside the CDS broadcast it regardless where it comes from, and eventually all nodes in the network will receive a copy of that message from their neighbors in the CDS. It has been proven that finding the smallest CDS in a given network is NP-complete [16]; therefore, many heuristics have been presented to produce a CDS with a good approximation. In this section we discuss MPR-based CDS schemes that aim to generate a small CDS from a resultant MPR set.

Adjih's MPR-CDS — Adjih *et al.* [22] proposed a novel heuristic called an MPR connected dominating set (MPR-CDS) to compute a CDS for a given network. It elects a CDS based on the existing MPR set generated using the original MPR heuristic. It points out that the idea of the MPR technique is to compute a kind of local dominating set formed by a source node and its MPRs. By applying some strategies to this local CDS, a global CDS can be generated in the network. In the MPR-CDS scheme, the information required for a given node to implement the heuristic is the IDs of one-hop and two-hop neighbors of the node and the MPR selectors of the node. All the information can be piggybacked into HELLO messages and sent periodically by every node in the network. It is also worth noting that the source node information is not necessary for schemes in this group, because nodes in a CDS will relay whatever messages they received for the first time.

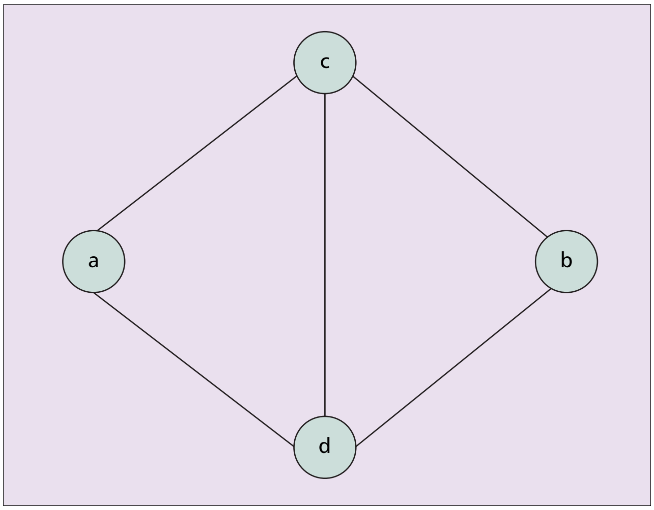
The strategy of the MPR-CDS is to apply two rules to the original MPR heuristic in order to generate a CDS in a network. A node x announces itself in the CDS if and only if it met following rules:

Rule 1: It has the smallest node ID among its one-hop neighbors

Rule 2: It has been selected as an MPR and its selector has the smallest node ID among x's one-hop neighbors

Specifically, the first rule is applied to all nodes in the network while the second one is used only by nodes inside MPR sets. In the MPR-CDS heuristic, the original MPR scheme will be conducted first to generate MPR sets. All nodes then will inform their one-hop neighbors about the MPRs they selected. Upon receiving this message, nodes that have been selected as MPRs apply the second rule to decide whether or not they are the *dominating nodes* (nodes inside a CDS). Furthermore, all nodes in the network also apply the first rule to evaluate themselves. Finally, a CDS is formed by all the dominating nodes in the network. It can be seen that the original MPR heuristic is a special case of the MPR-CDS where the only node elected by the first rule is the source node. The merit of the MPR-CDS heuristic is that it does not need any distributed knowledge of the global topology to generate a CDS in a network. This makes the heuristic very attractive for wireless mobile networks since it needs only local updates at each detected topology change. Furthermore, because of the lack of the source node information in the HELLO messages, the implementation of the heuristic is eased. However, the MPR-CDS heuristic may increase the number of MPRs in the network. This is due to the Rule 1 applied in the network, which elects extra nodes into the CDS. When the node ID is ordered arbitrarily, each node might be elected by Rule 1 with a probability of $1/\Delta$, where Δ is the maximum number of one-hop neighbors of a node. The average number of nodes elected by Rule 1 will be N/Δ, where N is the total number of nodes in the network. In such a case, the original MPR will perform better than the MPR-CDS in terms of the number of forwarding node generated.

Wu's EMPR — Although the MPR-CDS heuristic can efficiently generate a connected dominating set without any distributed global information, it increases the number of forwarding nodes and retransmissions in the network. Wu [23] considered this problem and tried to extend the MPR-CDS heuristic to construct a smaller forwarding node set without additional cost. In the extended heuristic, namely, enhanced MPR (EMPR), two drawbacks of the MPR-CDS are pointed out. First, Rule 1 is unnecessary in many cases, nodes selected based on Rule 1 are not essential for a CDS. Second, the original MPR forwarding node selection does not take advantage of Rule 2. The first drawback can be explained by Fig. 7 where nodes a and b are selected in the CDS based on Rule 1. However, we can see that node c alone is sufficient to cover all nodes in the network. Hence Rule 1 is not suitable in this occasion. The essence of the second drawback is that the MPR-CDS does not take the advantage of Rule 2 to provide fault tolerance. Because only MPRs whose selectors have the smallest node ID can be chosen into the CDS, other selectors with a larger node ID will have no effect on the CDS calculation. Therefore, a node that does not have the smallest ID among its one-hop neighbors can choose these one-hop neighbors as MPRs without any extra cost. This strategy can enhance the ability of fault tolerance in a mobile ad hoc network. Figure 8 illustrates this enhancement. In this network, node r is only selected as an MPR by node i, which has the smallest node ID among r's one-hop neighbors. If node i is turned off or it leaves the network, node r will eliminate itself



■ Figure 7. *First drawback of MPR-CDS.*

from the CDS, and this may cause network to break. However, if node *j* also selected *r* as an MPR, on the one hand, it will not affect *r*'s decision to be in the CDS; on the other hand, node *r* will be still in the CDS without node *i*, thus stabilizing the network. Such nodes as node *r* are called *free neighbors* of node *j* which is a novel concept introduced in the EMPR.

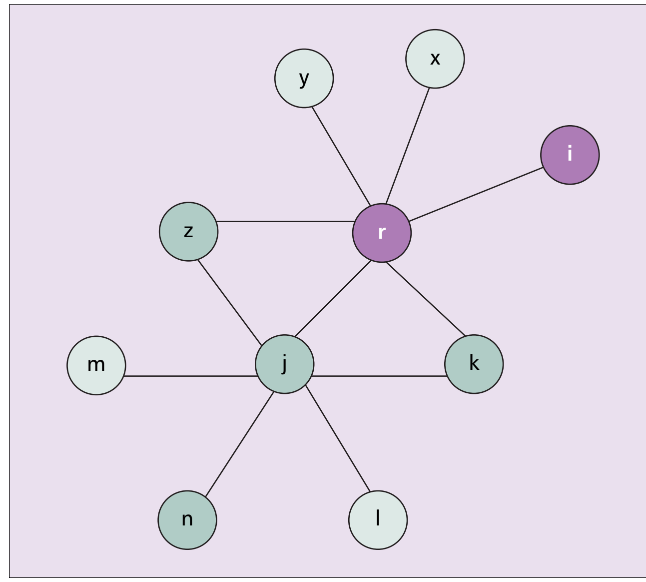
The heuristic of the EMPR extends the MPR-CDS in two phases shown as follows:

Enhanced Rule 1: The node has the smallest ID among all its one-hop neighbors and it has two unconnected neighbors.

Enhanced Original MPR Heuristic: Initially, add all free neighbors of source node *S* to the MPR set and eliminate two-hop nodes that are covered by these free neighbors. Then apply the original MPR heuristic to the residual one-hop neighbors to cover all remaining two-hop nodes. Use the node ID to break a tie when two nodes cover the same number of uncovered two-hop nodes.

In essence, the enhanced original MPR heuristic has already included the function of Rule 2, and thus the forwarding nodes selected by the heuristic are indeed in the CDS. Combining with the enhanced Rule 1, the EMPR can generate a smaller CDS in a given network than the MPR-CDS heuristic.

Although the gains of two extensions are not explicitly given in this article, based on our analysis, we believe that both the enhanced Rule 1 and the enhanced original MPR heuristic contribute to the reduction of the size of the forwarding node set. For the enhanced Rule 1, it adds more constrains to the original Rule 1, and thus it reduces the chance of generating a forwarding node. With regard to the Enhanced original MPR heuristic, the introduction of free neighbors can also reduces the number of forwarding nodes. This is due to the fact that free neighbor nodes may have already covered a large number of two-hop nodes, and hence fewer number of forwarding nodes are needed to cover residual two-hop nodes. An extreme case is that all two-hop nodes are covered by free neighbors. Therefore, no MPR calculation is needed to generate any forwarding nodes. The gains of two extensions are also confirmed by simulation results presented in the article, where the EMPR outperforms the MPR-CDS by producing less number of forwarding nodes in the network. However, the comparison between the EMPR and the original MPR is not given, which we believe is valuable and need to be conducted in the future research. In the article the author also points out that, instead of the node ID, other criteria such as the node remaining power can be used as the node priority. Therefore, the resultant CDS can provide some special features like power awareness and mobility awareness.



■ Figure 8. *Second drawback of MPR-CDS.*

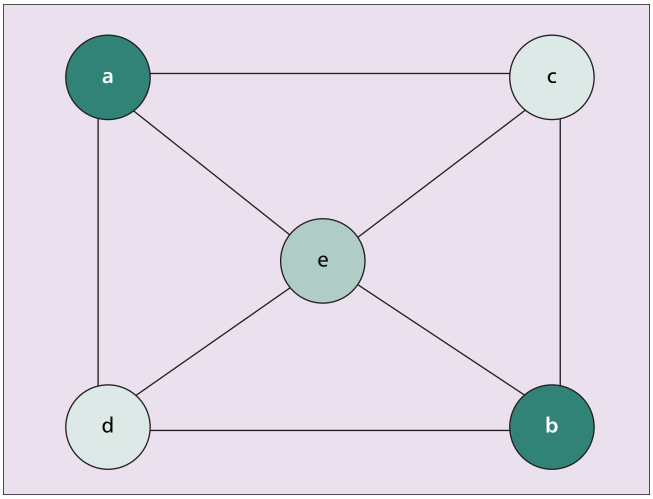
Chen and Shen's DEMPR — Chen and Shen [24] studied the MPR-based CDS schemes presented previously and tried to further reduce the size of the CDS. They observed that the node degree (the number of one-hop neighbors of a node) is more related to the size of a CDS than the node ID, and thus it should be given a higher priority. The node ID can be used whenever a tie happens. Based on this concept, previous schemes can be further improved to produce a smaller forwarding node set. In their article, three improvements are put forward. Here, we only present the improved scheme based on the EMPR which we refer to as degree-based enhanced MPR (DEMPR). The heuristic of DEMPR is the same with the EMPR except it applies two extended rules:

Extended Rule 1: A node is in the CDS if it has the largest node degree among all its one-hop neighbors and it has two unconnected neighbors.

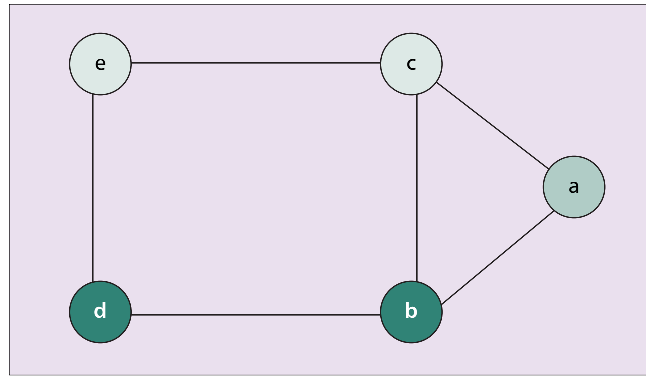
Extended Rule 2: A node is in the CDS if it has been selected as an MPR and its selector has the largest node degree among its one-hop neighbors.

Based on these two rules, the notion of free neighbors also needs to be changed correspondingly. The one-hop free neighbors of source node *S* are its one-hop neighbors who have at least a one-hop neighbor that has larger node degree than *S*. Among these two rules, we believe the main contribution to reducing the size of a CDS is the extended Rule 1. This is because the Rule 1 intends to choose a node as an MPR if it covers the largest number of nodes among all its one-hop neighbors, so all these one-hop neighbors will not be elected as forwarding nodes by Rule 1, and therefore fewer nodes have left in the network and fewer forwarding nodes will be generated consequently. The result can be seen in Fig. 9. In such a network, nodes *a* and *b* will be chosen as forwarding nodes by rule 1 if node ID has a higher priority. However, only node *e* will be selected when the node degree is considered first.

Wu and Lou's EEMPR — Wu and Lou [25] extended the notion of coverage used in previous schemes and attempted to enhance EMPR to generate a smaller CDS for a given network. The proposed heuristic, referred to as the extended enhanced MPR (EEMPR), uses three-hop neighbor informa-



■ Figure 9. *Extended Rule 1 in DEMPR.*



■ Figure 10. *A pair of MPRs in EEMPR.*

tion to cover all two-hop neighbors of each source node. The only additional node information it requires is the one-hop neighborhood information of all two-hop neighbors of the source node. The basic idea behind this heuristic is that it tries to cover more two-hop neighbors with a pair of MPRs, which are two serially connected MPRs in the one-hop and two-hop neighborhoods of the source node, respectively. These two MPRs are either directly selected or indirectly selected by the source node. Figure 10 depicts this heuristic. In the original MPR heuristic, both nodes *b* and *c* will be selected by source node *a*, since they both solely cover a two-hop node. However, it is worth noting that node *d* can also cover node *e* if *d* is chosen as an MPR of *b*. Therefore, all two-hop nodes of a can be covered eventually if node *b* and d are selected as a pair of MPRs. In such a case, node *b* is directly selected by node *a*, while node *d* is indirectly selected by node *a*. Similar to the EMPR, free neighbors are also used in the EEMPR as they contribute additional coverage without any cost. However, the conception of the free neighbor is varied from the EMPR. A two-hop free neighbor *y* of source node *S* is a node in *S*'s two-hop neighbors where the node ID of *S* is not the smallest among *y*'s one-hop neighbors.

The proposed heuristic still applies the Rule 1 used in the EMPR while an enhanced Rule 2 is used to evaluate each pair of MPRs. The eenhanced Rule 2 operates as follows:

Enhanced Rule 2: Node *x* is in the CDS if:

1 It has been selected directly as an MPR and its selector has the smallest node ID among *x*'s one-hop neighbors.

2 It has been selected indirectly as an MPR and its selector has the smallest node ID among *x*'s one-hop neighbors

The heuristic of the MPR calculation is also extended in the EEMPR. Initially, all one-hop and two-hop free neighbors are added to the MPR set, and all two-hop nodes they covered are removed. Then, among the one-hop and two-hop nodes that remain connected, pick up a pair of connected nodes as MPRs if they cover the most number of uncovered two-hop neighbors of the source node. Use the node ID to break a tie if multiple selections exist. Since the heuristic introduces free neighbors, it has already included the function of the Enhanced Rule 2, therefore, MPRs generated by the heuristic are essentially in the CDS.

Obviously, the gain for using additional node information is that fewer MPRs are generated by each source node. The reduction can be explained by referring to the problem in the original MPR selection heuristic discussed earlier, where MPRs chosen by the initial phase tend to dominate the MPR set. The strategy used in the EEMPR may avoid this problem, because a pair of MPRs may have a chance to cover those solely covered two-hop nodes, and thus fewer nodes are selected as MPRs to particularly cover those two-hop nodes. However, the drawback of this strategy is that each source node has to reconsider all pairs of MPRs to cover their two-hop neighbors without taking the advantage of the forwarding nodes that have already been selected. This may prolong the calculation process and increase the number of the forwarding nodes in the network. Because for each source node, some forwarding nodes in its two-hop neighborhood may have already been chosen into the CDS, these forwarding nodes can be excluded when the one-hop neighbors of the source begin to calculate their forwarding nodes. That is to say, one should treat these forwarding nodes as the free neighbors, even though they do not meet the free neighbor criterion. To further improve the heuristic, the tie-breaking procedure also needs to be enhanced in order to optimize MPRs selected in two-hop neighborhood. In comparison to the node ID, we believe the node degree of the second hop MPR is more suitable as the tie-breaking criterion to reduce the size of the CDS. When multiple pairs of MPRs are available, the pair that has higher node degree of the second hop MPR should be given the priority. This strategy is prone to choose a second hop MPR that has a larger coverage, and thus when the MPR is included as a free neighbor of a node, more two-hop nodes can potentially be covered and fewer forwarding nodes a source will generate.

Summary of MPR-Based CDS Schemes — Table 5 summarizes objectives of four MPR-based CDS schemes. Generally, all schemes that appear in this group aim to calculate a connected dominating set (CDS) in a network based on the original MPR heuristic. Because the CDS is source-independent, nodes inside a CDS do not require the source node information from broadcast messages, thus reducing the complexity of processing a broadcast packet. Sequentially, each scheme in this group tries to improve the performance of the previous one by generating a smaller size of CDS. Among them, Wu and Lou's EEMPR provides an novel concept that can effectively reduce the cardinality of the CDS. However, this achievement needs to sacrifice the simplicity of the heuristic.

Table 6 shows the cost comparison of these four schemes. $|N_3|$ represents the maximum number of three-hop neighbors of a node. Among four schemes, only the EEMPR uses the three-hop node information. The extra node information contributes to more knowledge of a two-hop neighbor of the source; hence, MPRs can be more wisely selected to have a larger two-hop node coverage. However, the extra information also leads to the high latency and inaccuracy in the network. Therefore, the EEMPR achieves better performance by sacrificing time and computational simplicity.

Since two rules are applied to the original MPR heuristic, schemes in this group generally need more time to complete the calculation and have larger time complexity. Since all

Approach	Objectives
MPR-CDS	The original MPR scheme needs source information in order to decide whether or not an MPR should broadcast messages. This source information may be difficult to obtain considering broadcasting in IP level. The proposed scheme aims to resolve this problem by producing a connected dominating set (CDS) based on the original MPR heuristic.
EMPR	Try to produce a smaller CDS by extending the MPR-CDS heuristic. The scheme shows two drawbacks in the MPR-CDS and tries to avoid them without increasing extra costs.
DEMPR	Try to reduce the size of the CDS generated by previous schemes. Point out that the node degree is more related to the size of a CDS and should be used instead of the node ID.
EEMPR	Further extend the MPR-CDS to produce a smaller number of forwarding nodes. The scheme considers the dominating effect of the initial phase in the original MPR heuristic, and tries to avoid it by using three-hop node information to generate a pair of MPRs that can cover more two-hop neighbors.

Table 5. *Summary of MPR-based CDS schemes.*

nodes can operate each rule at the same time, the time complexity of the two rules is only determined by their internal calculation steps, and the overall time complexity for each MPR-based CDS scheme is the time for each source node to complete forwarding node calculation. In the MPR-CDS scheme, the original MPR selection heuristic is still used to generate the MPR set for each source node. The extra costs in the scheme are the two rules that determine a node's forwarding status. In Rule 1, a node has to find out whether its node ID is the smallest among all its one-hop neighbors. This iterative step can be finished within $O(\Delta)$ time for all nodes in the network. In Rule 2, an MPR node needs to know whether any of its selectors has the smallest node ID among all its one-hop neighbors, and this takes at most $O(\Delta)$ time to complete for all MPRs. Therefore, the overall time complexity of the MPR-CDS is $O(3\Delta M + 3\Delta)$, referring to the fact that the time complexity of the original MPR heuristic is $O(3\Delta M + \Delta)$. In the EMPR scheme, two extensions are introduced to the Rule 1 and the MPR selection heuristic respectively, both of them add extra costs to the scheme. Because the detail of the heuristic is not presented in this article, we cannot deduce the explicit time complicity of these extra costs. However, we estimate that the step to add all free neighbors to the MPR set will take $O(\Delta^2)$ time to run in the worst case, and it might be the dominant part of the extra costs. Therefore, the time complexity of the EMPR should be larger than $O(3\Delta M + \Delta^2 + 3\Delta)$. In Chen and Shen's DEMPR, the only change is the criterion of the two rules. Instead of node ID, the node degree is used to determine a node's forwarding state. This change will not increment the cost of the heuristic, so it has the same time complexity as the EMPR. In Wu and Lou's EEMPR, more computational complexity is introduced in the heuristic to achieve better performance in terms of the size of a CDS. It adds both one-hop and two-hop free neighbors in the MPR set, which might take $O(\Delta^2 + |N_2|\Delta)$ time to complete. The MPR set selection heuristic has also been extended, which chooses a pair of MPRs at each round. However, how to choose such a pair of MPRs is not specified in this article; we can only estimate that it may use more time to run this heuristic than the EMPR. Although the Rule 2 in the EEMPR is enhanced, it only affects two-hop nodes of the source node. Since every node can individually apply two rules at the same time, the enhancement will not increment the time complexity of the Rule 2. Thus, the overall time complexity of the EEMPR could be larger than $O(3\Delta M + |N_2|\Delta + \Delta^2 + 2\Delta)$. This result is in accord with the previous analysis, which indicated that the EEMPR is the most sophisticated scheme in this group.

In this group, except for the EEMPR, the process of the MPR set calculation is the same as the original MPR selection heuristic, so that the number of HELLO messages exchanged within two hops of these schemes is also the same as the original MPR scheme. However, Rule 2 in each MPR-based CDS scheme requires source node to send out an additional HELLO message to its one-hop neighbors in order to inform its MPR decisions. This makes the overall message complexity a little bit higher than schemes in the pure MPR group. A special case is the EEMPR, which generates a pair MPRs in each round of MPR calculation. This process needs an information range of three hops, and thus it requires each three-hop neighbors of the source to send a HELLO message. Furthermore, Rule 2 in this scheme forces all one-hop MPRs to send a HELLO message to inform nodes that they have chosen as MPRs. Therefore, in order to implement the heuristic, the EEMPR needs $O(\Delta + |N_2| + |N_3| + M + 1)$ messages in advance. This result again proves that EEMPR has sacrificed its simplicity to achieve a better flooding performance.

From the above analysis, we can see that all schemes in this group more or less increase the time and message complexity. Among them, the EEMPR is the most complex heuristic; in return, it produces the smallest size CDS in this group. The gain for all schemes in this group is that the source-independent flooding strategy is achieved which reduces the difficulty in implementing a heuristic. Among all the schemes in this group, we notice that the DEMPR requires node degree information from one-hop neighbors, which cannot be obtained from the usual contents in a HELLO message. Extra information that contains the value of the largest node degree among all one-hop neighbors and the corresponding node ID should be appended into the HELLO message. It is also remarkable that the enhanced Rule 1 is only effective when the network is sparsely distributed. This is due to the fact that in a dense network, the probability of having two unconnected neighbors raises as the number of neighbors increase, and thus more nodes are selected as MPR by Rule 1. Considering this effect, we believe that node degree used in the DEMPR is a better choice and should be used to replace node ID in Rule 1, and thus the extra condition of finding two unconnected neighbors can also be eliminated. Such an improved Rule 1 will not be affected significantly by the topology changes and can be deployed to any scheme in this group.

QoS-based MPR Schemes

Quality-of-service (QoS) is an important issue in the traditional wired network and has been deployed more that ten years. Inevitably, it will also be a key feature in mobile ad hoc networks to provide multimedia service. To support QoS, the link state information, such as bandwidth and delay, should be

Schemes	Information range	Source dependent	Time complexity	Message complexity	Summary of the heuristic
MPR-CDS	2 hops	No	$O(3\Delta M + 3\Delta)$	$O(\Delta + \|N_2\| + 1)$	First, run the original MPR heuristic to calculate an MPR set for each source node. Then deploy Rule 1 to all nodes in the network and Rule 2 to all MPRs to further select a subset of nodes as the forwarding nodes.
EMPR	2 hops	No	$> O(3\Delta M + \Delta^2 + 3\Delta)$	$O(\Delta + \|N_2\| + 1)$	First, put all free neighbors of the source node into MPR set. Then apply the same phases used in the original MPR selection heuristic. However, use the node ID to break a tie. Finally, deploy an extended Rule 1 and the original Rule 2 to all nodes and MPRs, respectively, to select a subset of nodes as the forwarding nodes.
DEMPR	2 hops	No	$> O(3\Delta M + \Delta^2 + 3\Delta)$	$O(\Delta + \|N_2\| + 1)$	Extend the previous heuristic by replacing the minimum node ID to the maximum node degree. Use node ID when there is a tie.
EEMPR	3 hops	No	$O(3\Delta M + \|N_2\|\Delta + \Delta^2 + 2\Delta)$	$O(\Delta + \|N_2\| + \|N_3\| + M + 1)$	First, put all the one-hop and two-hop free neighbors of source node *S* into MPR set. Then choose a pair of nodes that are a one-hop neighbor and a two-hop neighbor of source *S* as MPRs if they cover the most number of uncovered two-hop neighbors of *S*. Node ID will be used to break a tie. Finally, deploy Rule 1 used in the EMPR and an extended Rule 2 to all nodes and MPRs, respectively, to select a subset of nodes as the forwarding nodes.

■ Table 6. *Cost comparison of MPR-based CDS schemes.*

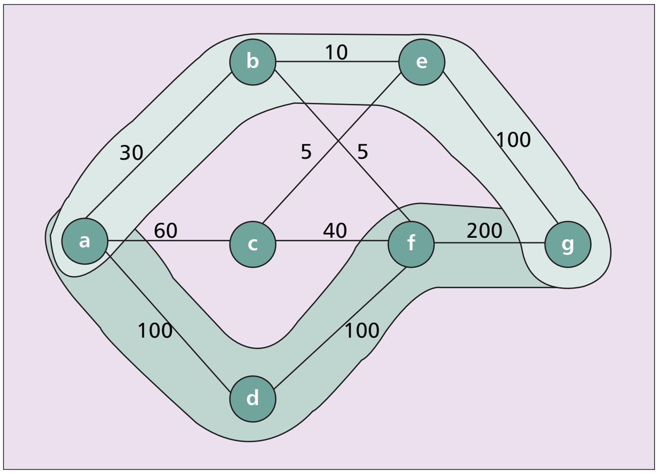
available and manageable. This requires broadcast schemes in a wireless network to be able to efficiently disseminate the QoS information throughout the network. Regarding the original MPR scheme, where MPRs are chosen based on non-QoS criteria and each MPR can only propagate information of links between it and its MPR selectors, good quality links may be hidden to other nodes in the network. Figure 11 illustrates this problem in the original MPR scheme. The number above each link represents the corresponding bandwidth. In such a network, node a will select node *b* as the MPR because it covers more uncovered two-hop neighbors and has a smaller node ID. Following the same heuristic, node *b* will choose node *f* as the MPR. Hence, node *g* knows that it can reach node a via the route {g, f, b, a} which has the bottleneck bandwidth of 5. However, it is obvious that a better route should be {g, f, d, a} which has the bottleneck bandwidth of 100. This high bandwidth route is hidden from node *g* by using the original MPR heuristic. Therefore, the MPR selection has to consider QoS information such as bandwidth and delay in order to provide suitable links for some specific applications. Here we discuss the QoS-based MPR schemes that aim to select MPR sets based on some QoS requirements.

Badis's QoS-based MPR Heuristics — Badis *et al.* [27] proposed two heuristics for the MPR selection based on QoS measurements. The purpose of these new MPR schemes are to extend the QoS routing protocol proposed in [28]. The essence of these two MPR heuristics is to utilize QoS conditions, such as bandwidth and delay of links between one-hop neighbors, to select MPRs that can provide better QoS environment. Additional QoS information can be piggybacked into HELLO messages and exchanged between neighbors, and thus no extra control messages are generated.

The first proposed heuristic, referred to as the QoS-based MPR-1 (QMPR-1), still follows the same steps as the original MPR heuristic, but it modifies the tie-breading procedure in order to provide QoS prioritized MPRs. Instead of a maximum node out-degree, a node with higher bandwidth is chosen when multiple choices exist. In case there is another tie in the above step, a node with minimum delay is selected. This heuristic has a higher chance to pick up MPRs with larger bandwidth, but the improvement is only marginal. Thus, it cannot guarantee to find the optimal links. Referring to Fig. 11, path {g, f, c, a} will be revealed based on QMPR-1 because node *c* has a larger bandwidth compared with node b. However, this result is still not the best one in terms of higher bandwidth.

The second heuristic, referred to as QMPR-2, tries to improve the QoS performance of QMPR-1. It also follows the same steps as the original MPR heuristic but selects nodes with higher bandwidth as MPRs, and the delay is used when there is a tie. In case of another tie in the above step, a node that covers the most number of uncovered two-hop neighbors will be chosen. This heuristic enlarges the effect of QoS criteria in the MPR selection; hence, more MPRs will be chosen based on their QoS conditions and, consequently, a better chance can be achieved to find the optimal links between a given pair of source and destination. As we can see in Fig. 11, the path with the highest bandwidth is found finally by using this heuristic.

These two schemes, especially the second one, can find MPRs with better QoS conditions, thus providing suitable links for QoS requirements. However, both schemes might increase the number of MPRs. This is due to the fact that MPR nodes which have higher bandwidth or lower delay might cover few uncovered two-hop nodes. Hence, more



■ Figure 11. *QoS problem in original MPR heuristic.*

MPRs have to be selected to covered all two-hop nodes of the source. As shown in Fig. 11, nodes *d* and *g* are selected as MPRs of node *f* in QMPR-2; however, node *b* alone is sufficient to cover all two-hop neighbors of *f* and will be selected as an MPR in the original MPR heuristic. It is also noticeable that not all MPRs are selected based on the QoS conditions. This is because that the initial phase in the original MPR is applied to both proposed heuristics, and it might generate most of the MPRs. Therefore, both heuristics can only have effect on a small part of the MPR set. A possible solution for this problem is to use a pair of MPRs to cover more two-hop neighbors as used in the EEMPR discussed in the previous section. However, this also introduces more complexity into the heuristic and make it difficult to be implemented.

Ge's QoS-based MPR Heuristics — Ge *et al.* [26] tried to integrate the QoS feature into the original OLSR routing protocol [7]. They also investigated the limitation of the original MPR heuristic and realized that good quality links could be hidden to other nodes in the network. Considering this limitation, three revised MPR selection heuristics are proposed to compute the MPR set based on QoS criteria. The first two heuristics are similar to Badis's but without considering the delay. The third heuristic, referred to as the QoS-based MPR-3 (QMPR-3), further improves the QoS performance. It points out a drawback in QMPR-2 that not all two-hop neighbors have optimal links to reach the source node. Referring to Fig. 11, it is observed that node *g* will select node *f* as the MPR based on QMPR-2. Hence, node *b* will have the knowledge that it can reach node *g* via *f* after *f* relays *g*'s broadcast messages. Obviously, a larger bandwidth link {b, e} is hidden from node *b*. QMPR-3 solves this problem by using a heuristic similar to the in-degree MPR scheme discussed in the pure MPR group.

The idea of the heuristic is to let all two-hop nodes have an optimal bandwidth path through MPRs to the source node. Here, the optimal bandwidth path is the path with the highest bottleneck bandwidth. For each two-hop node *x*, source node *S* chooses a one-hop neighbor node as the MPR if it covers *x*, and the bottleneck of the path is the largest among all available paths from *x* to *S*. Each two-hop node has to go through this calculation until is finds an optimal path to the source node.

The QMPR-3 heuristic further increases the chance of finding a route with higher bandwidth, since each two-hop node is linked to the source node using an optimal path. However, the heuristic generates a greater number of MPRs than the other two QoS-based MPR heuristics, which results in more retransmissions in a network. One can possibly think that, in the worst case, every one-hop neighbor of the source node can be chosen as the MPR for different two-hop nodes. We estimate that it will be too costly to ensure that every two-hop node has an optimal path to the source node. An alternative way is to consider a weighted value, which can be a ratio of the overall bandwidth of all links that a node has on the number of links. A one-hop node with the highest weight should be selected as the MPR. Therefore, two-hop nodes may have a higher chance to obtain larger bandwidth paths to the source node via fewer MPRs.

Summary of QoS-based MPR Schemes — The summary of objectives of different schemes in this group is shown in Table 7. In general, all schemes in this group aim to revise the original MPR selection heuristic to achieve QoS awareness. Among them, QMPR-3 has a better performance of finding the optimal routes in the network. However, it also generates more MPRs compared with other QoS-based MPR schemes thus increasing the overall retransmissions in the network.

Table 8 presents a cost comparison of the different schemes. Because all the schemes in this group are still based on the original MPR heuristic, they have the information range of two hops. Furthermore, all schemes require a source node information to be included in broadcast messages in order to decide whether or not an MPR needs to relay the message.

The first two schemes proposed by Badis *et al.* only modify the tie-breaking procedure and the MPR selection criterion of the original MPR heuristic; therefore, no extra costs are introduced in the heuristics, and thus they have the same time complexity as the original MPR scheme. Although Ge *et al.* have proposed three schemes, two of them are essentially the same as the Badis's, and thus they are not further analyzed here. The third scheme, which guarantees that each two-hop node has an optimal bandwidth path to the source node, uses different strategy from the original MPR heuristic. Since each two-hop node has to run the heuristic to compute an MPR in order to setup a path to the source, the heuristic can be completed at least in $O(|N_2|)$ time, where $|N_2|$ denotes the maximum number of two-hop nodes for a given source node. Due to the lack of details of the heuristic, we cannot explicitly

Approach	Objectives
QMPR-{1, 2}	Try to resolve the limitation of the original MPR selection heuristic that it has no guarantee to find the optimal path in terms of QoS requirements. The new heuristics tend to select MPRs based on QoS criteria such as bandwidth and delay so that good-quality paths have higher chance to be revealed to nodes in the network.
QMPR-3	Aim to ensure that all two-hop neighbors have an optimal bandwidth path to the source node, so that the chance to find a better route for a given pair of source and destination can be further increased. The heuristic selects a node as the MPR if it provides the highest bandwidth path to the source node for a given two-hop neighbor node.

■ Table 7. *Summary of QoS-based MPR schemes.*

Schemes	Information Range	Source Dependent	Time Complexity	Message Complexity	Summary of the Heuristic
QMPR-1	2 hops	Yes	$O(3\Delta M + \Delta)$	$O(\Delta + \|N_2\|)$	Apply the same steps used in the original MPR selection heuristic. When there is a tie, choose a node as the MPR that provides a larger bandwidth. In case of another tie, select the node with lower delay as an MPR.
QMPR-2	2 hops	Yes	$O(3\Delta M + \Delta)$	$O(\Delta + \|N_2\|)$	First, apply the initial phase used in the original MPR scheme. When there are still some uncovered two-hop neighbors, select the node with higher bandwidth as an MPR. In case of a tie, select a node with lower delay. In case of another tie, select the node as an MPR that covers the most number of uncovered two-hop neighbors of the source node.
QMPR-3	2 hops	Yes	$O(2\|N_2\|\Delta)$	$O(\Delta + \|N_2\|)$	For each two-hop neighbor of source node *S*, select as MPR a one-hop neighbor of *S* that covers this two-hop neighbor if it has the largest bottleneck bandwidth path to *S*. Repeat this step until all two-hop neighbors are covered.

Table 8. *Cost comparison of QoS-based MPR schemes.*

deduce the time complexity of this scheme. Here, we assume that the heuristic has the following steps. First, for each two-hop 34 node, the bottleneck bandwidth of all its available paths to the source node are calculated. This step takes $O(\Delta)$ time to complete in the worst case when a two-hop node is reachable by all one-hop nodes. Second, for each two-hop node, pick up a node as the MPR that can provide the largest bottleneck bandwidth. This step takes $O(\Delta)$ time to run. Since these two steps have to be operated for all two-hop neighbors, the total time complexity of the heuristic can be $O(2|N_2|\Delta)$. This result points out that in most of the cases, the scheme is more complex than others in this group. However, it performs better in terms of finding optimal bandwidth path for a given two-hop node.

In this group, all schemes have the information range of two hops, so they have the same message complexity as the original MPR heuristic. However, extra information, such as bandwidth and delay, is piggybacked into HELLO messages in order to disseminate QoS conditions of links. Hence, all schemes in this group have a larger message overhead than the original MPR scheme.

From the analysis above, it is clear that all schemes in this group have similar time and message complexity to the original MPR heuristic. This is due to the fact that they only partially modify the original MPR heuristic by introducing some QoS measurements. This puts forward an idea that one can also use QoS conditions to modify MPR-based CDS schemes in the purpose of generating a connected dominating set that can provide a better QoS environment without increasing the complexity of the heuristics. In such a case, we believe that the velocity of a node is necessary to be considered as one of the QoS criteria during the CDS selection in order to stabilize the network.

A Comparative Analysis of Three Groups

So far we have discussed 14 MPR-based broadcast schemes and categorized them into three groups based on their objectives. Referring to Table 1, schemes in the pure MPR group mainly attempt to solve the broadcast storm problem and achieve efficient flooding. Schemes in the MPR-based CDS group try to further reduce the size of the forwarding node set in order to perform optimized flooding. They extend the original MPR scheme and attempt to produce a CDS based on the original MPR heuristic. QoS-based MPR schemes consider the bandwidth and the end-to-end delay of links, and try to generate an MPR set based on these requirements, so that QoS can be better supported in the network.

Schemes in different groups also have different costs. Referring to Tables 4, 6, and 8, one can see that the schemes in the MPR-based CDS group are the most costly in both time and message complexity, while other two groups share similar complexity. This is due to the fact that MPR-based CDS schemes utilize more complex heuristics in the forwarding node calculation. In return, they also generate a smaller forwarding node set compared to other schemes. It is also worth noting that all MPR-based CDS schemes are source independent, whereby nodes do not need to identify the last hop transmitter to decide their own retransmission state. Therefore, one might be able to use MPR-based CDS schemes to replace the original MPR scheme in order to simplify the rebroadcasting process in the network. However, due to the complexity of heuristics, MPR-based CDS schemes may not achieve efficiency in mobile ad hoc networks, where nodes move frequently and the forwarding node calculation is conducted rapidly. In such cases, MPR-based CDS schemes could only be suitable for fixed networks. We believe that this issue is important and should be addressed in future research.

Besides the costs presented in this article, another significant criterion for evaluating broadcast schemes is the overall system performance, which is generally referred to as the network throughput [29] and the end-to-end delay. When applied to the same routing protocol that requires a broadcast mechanism to distribute data and control packets, different broadcast schemes may have different impacts on the overall system performance, and a broadcast scheme is considered to be better than the others if it achieves the largest network throughput and/or the lowest end-to-end delay. Unfortunately, among all the MPR-based broadcast schemes surveyed in this article, only Badis's work [27] considers such impact on the overall system performance. The simulation conducted in [27] applies the QMPR-1 and QMPR-2 heuristics to the Optimized Link State Routing (OLSR) protocol [6] and evaluates the resultant network throughput for each. The results show that the network attains almost maximum throughput before saturation for both heuristics. After the saturation, the network using QMPR-2 still retains the maximum throughput while the network using QMPR-1 experiences a gradual drop in the throughput. This result reflects that the QMPR-2 heuristic indeed finds larger bandwidth paths than the QMPR-1 heuristic.

Despite the lack of published system performance results useful for a quantitative comparison, we can still reasonably claim that the QoS-based MPR schemes may yield the best overall system performance because of their bandwidth and end-to-end delay orientated characteristics, while the MPR-based CDS schemes may achieve the poorest overall system performance. This can be due to the fact that the MPR-based CDS schemes produce fewer forwarding nodes, which propagate limited link information throughout the network. Therefore, fewer routes are provided to the routing protocol for each source-destination pair, and thus less optimal paths are generated by the routing protocol in the network. However, the real situation may be far more complex than what we supposed. Because of the transmission contention and the interference among nodes, schemes that produce higher number of forwarding nodes may perform poorly, while schemes operating with fewer forwarding nodes can have better performance. For this reason, comprehensive and systematic studies are necessary for a comparative analysis of the impact of different MPR-based broadcast schemes on overall system performance.

Conclusions

As a prospective technology, MANETs have gained increased research attention in recent years. Efficient broadcast is one of the significant research issues that plays an important role in the performance of MANETs. Many techniques have been presented to minimize redundant rebroadcasting and save the limit energy in MANETs. In this article we have discussed in particular the broadcast schemes based on the multipoint relay (MPR) heuristic, which is one promising broadcast technique proposed recently.

We first presented the fundamental concepts of the original MPR selection scheme, explained the basic idea of this heuristic and its significance, and put forward the definition of the costs of MPR-based broadcast schemes. Then, we classified 14 proposed schemes into three groups, based on their objectives. We discussed the heuristic and performance for each scheme. Merits and drawbacks were shown while possible improvements were also presented for some schemes. A summary was given in each group to compare the schemes in terms of their objectives and costs.

In this survey we have discussed some costs of the proposed heuristics, such as source node information dependency state, information range, HELLO message overheads, computation complexity, and communication complexity. Although schemes in different groups may have different focuses and objectives, these issues always need to be considered because they are important for evaluating the performance and scalability of a given scheme regardless of its objective. From the discussion of these 14 MPR-based broadcast schemes, we can conclude that the original MPR still has relatively lower computation and communication complexity compared with most of the other schemes. This is because schemes that are extended from the original MPR are meant to have additional procedures and require extra information in their heuristics, so that more time and message complexity are expected for them.

Although schemes in different groups have different focuses and objectives, it is still necessary to compare the number of forwarding nodes generated by each scheme in order to estimate the retransmission overheads. We observed that the original MPR selection heuristic still yields a smaller MPR set than most of the others. This is due to the fact that the original MPR scheme mainly focuses on reducing the number of forwarding nodes, while others are interested in different features such as minimum overlapping, efficient energy usage, and QoS conditions. However, the comparisons between the original MPR scheme and MPR-based CDS schemes are not so clear. Although the simulation done in [22] has proven that the MPR-CDS is inferior to the original MPR in terms of the number of forwarding nodes, it is hard to analyze other MPR-CDS schemes, and no simulation has been done thus far to compare these schemes with the original MPR scheme. We believe that it is worth conducting such work in the future to produce a better comparison. Furthermore, the impact on the overall system performance (network throughput and end-to-end delay) for different MPR-based broadcast schemes is also an important issue that needs to be addressed. Schemes in different groups or even in the same group may have varied contributions to the overall system performance, and thus in future work it will be necessary to conduct simulations to compare the overall system performance for different MPR-based broadcast schemes.

From this survey, we can see that the MPR-based broadcast schemes provide different features based on different MPR selection criteria. By using various kinds of node information, one can customize the MPR selection procedures and obtain different broadcast performances as required. QoS-based MPR schemes are such customized schemes which use QoS measurements to modify the original MPR heuristic to achieve QoS-awareness broadcast in the network. Based on this concept, it is possible to extend all MPR-based broadcast schemes by piggybacking extra node information into the HELLO messages and utilizing them to modify the MPR selection criterion.

The aim of this survey is to facilitate a comprehensive understanding of MPR-based broadcast schemes in mobile ad hoc networks, and to present possible improvements for some schemes, which might be a helpful guideline for people who want to further improve them.

References

[1] S. Corson and J. Macker, "Mobile Ad Hoc Networking (MANET): Routing Protocol Performance Issues and Evaluation Considerations," RFC 2501, Jan. 1999, available: http://www.faqs.org/rfcs/rfc2501.html

[2] C. Imrich, M. Conti, and J. Liu, "Mobile Ad Hoc Networking: Imperatives and Challenges," *Ad Hoc Networks*, vol. 1, Jul. 2003, pp. 13–64.

[3] L. Yang *et al.*, Common Wireless Ad Hoc Network Usage Scenarios, Internet Draft, Oct. 2003, available: http://www.flarion.com/ans-research/Drafts/draft-irtf-yang-ans-scenarios-00.txt

[4] C. Perkins and E. Royer, "Ad Hoc On-Demand Distance Vector Routing," *Proc. WMCS'99*, Feb. 1999, pp. 90–100.

[5] D. Johnson and D. Maltz, "Dynamic Source Routing in Ad Hoc Wireless Networks," *Mobile Comput.*, 1996, pp. 153–181.

[6] T. Clausen and P. Jacquet, "Optimized Link State Routing Protocol (OLSR)," RFC 3626, Oct. 2003, available: http://www.faqs.org/rfcs/rfc3626.html

[7] A. Laouiti, A. Qayyum, and L. Viennot, "Multipoint Relaying: an Efficient Technique for Flooding in Mobile Wireless Networks," *35th Annual Hawaii Int'l. Conf. System Sciences HICSS'2001*.

[8] C. Ho *et al.*, "Flooding for Reliable Multicast in Multi-Hop Ad Hoc Networks," *Proc. Int'l. Wksp. Discrete Algorithms and Methods for Mobile Computing and Commun. (DIALM)*, 1999, pp. 64-71.

[9] S.-Y. Ni*et al.*, "The Broadcast Storm Problem in a Mobile Ad

Hoc Network," *Proc. 5th Annual ACM/IEEE Int'l. Conf. Mobile Computing and Network*, 1999, pp. 151–62.
[10] B. Williams and T. Camp, "Comparison of Broadcasting Techniques for Mobile Ad Hoc Networks," *Proc. MOBIHOC*, 2002, pp. 194–205.
[11] J. Wu and F. Dai, "A Generic Distributed Broadcast Scheme in Ad Hoc Wireless Networks," *IEEE Trans. Computers*, vol. 53, Oct. 2004, pp. 1343–54.
[12] E. S.-R. Committee, Radio Equipment and Systems: HYPERLAN type 1, functional specifications ETS 300-652, ETSI, June 1996.
[13] "IETF mobile ad hoc network working group," available: http://www.ietf.org/html.charters/manet-charter.html
[14] G. Allard, P. Jacquet, and L. Viennot, "Ad Hoc Routing Protocols with Multipoint Relaying," 5eme Rencontres Francophones sur les aspects Algorithmiques des Telecommunications, (AlgoTel'2003), available: gyroweb.inria.fr/ viennot/postscripts/algotel2003ajv.pdf
[15] I. Joe and S. Batsell, "Mpr-based Hybrid Routing for Mobile Ad-Hoc Networks," *Proc. 27th Annual IEEE Conf. Local Computer Networks (LCN'02)*, Nov. 6–8, 2002, pp. 7–12.
[16] M. Garey and D. Johnson, Computers and Intractability, a Guide to the Theory of NP-Completeness. W.H. Freeman, 1979.
[17] V. Chvatal, A Greedy Heuristic for the Set-Covering Problem, *Mathematics of Operation Research*, 1979, ch. 4, pp. 233–35.
[18] B. Mans and N. Shrestha, "Performance Evaluation of Approximation Algorithms for Multipoint Relay Selection," *Med-Hoc-Net 2004, 3rd Annual Mediterranean Ad Hoc Net. Wksp.*, Bodrum, Turkey, June 27–30, 2004.
[19] N. Shrestha, "Performance Evaluation of Multipoint Relays: Collision and Energy Efficiency Issues," Macquarie University, Tech. Rep., 6 Apr. 2003.
[20] J. Lipman, P. Boustead, and J. Judge, "Utility-based Multipoint Relay Flooding in Heterogeneous Mobile Ad Hoc Networks," *Proc. Wksp. Internet, Telecommun. and Sig. Proc. (WITSP'02)*, Wollongong, Australia, Dec. 2002, pp. 174-185.
[21] J. Lipman *et al.*, "Resource Aware Information Dissemination in Ad Hoc Networks," *Proc.11th IEEE Int'l. Conf. Networks (ICON 2003)*, Sydney, Australia, Sept. 2003.
[22] C. Adjih, P. Jacquet, and L. Viennot, "Computing Connected Dominated Sets with Multipoint Relays," Technical Report, INRIA, Oct. 2002, www.inria.fr/rrrt/rr-4597.html
[23] J. Wu, "An Enhanced Approach to Determine a Small Forward Node Set Based on Multipoint Relays," *IEEE Trans. Parallel and Distributed Systems*, Sept. 2002, pp. 866–81.
[24] X. Chen and J. Shen, "Reducing Connected Dominating Set Size with Multipoint Relays in Ad Hoc Wireless Networks," *Proc. 7th Int'l. Symp. Parallel Architectures. Algorithms and Networks*, May 2004, pp. 539–43.
[25] J. Wu and W. Lou, "Extended Multipoint Relays to Determine Connected Dominating Sets in MANETs," *Proc. 1st IEEE Commun. Society Conf. Sensor and Ad Hoc Commun. and Networks (SECON)*, 2004.
[26] Y. Ge, T. Kunz, and L. Lamont, "Quality of Service Routing in Ad Hoc Networks using OLSR," *Proc. 36th Hawaii Int'l. Conf. Syst. Sci.*, 2003.
[27] H. Badis *et al.*, "Optimal Path Selection in a Link State QoS Routing Protocol," Proc. IEEE VTC2004 Spring, Italy, May 2004.
[28] A. Munaretto *et al.*, "QoS for Ad Hoc Networking based on Multiple Metrics: Bandwidth and Delay," *Proc. IEEE MWCN2003*, Singapore, Oct. 2003.
[29] A. Zemlianov and G. de Veciana, "Capacity of Ad Hoc Networks with Infrastructure Support," *IEEE JSAC*, vol. 23, Mar. 2005, pp. 657–67.

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