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Performance Evaluation of Broadcasting Protocols for Ad Hoc and Sensor Networks

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Abstract— **In ad hoc and sensor networks, the simplest and most widely used approach to broadcast is blind flooding, which lets every node in the network to rebroadcast a receiving packet to all its neighbors. This causes redundancy of broadcast packets and results in unnecessary collisions and bandwidth waste. To overcome these problems, a number of research groups have proposed more efficient broadcasting schemes with the goal of minimizing the retransmissions, while still guaranteeing that a broadcast packet is delivered to all the nodes in the network. Multipoint relay (MPR) and dominating set (DS) based broadcasting schemes can effectively improve the broadcasting efficiency while providing reliable broadcasting. The neighbor elimination scheme (NES) can improve any broadcasting protocol as an added feature. In this paper, we evaluate the performance of MPR (source dependent), MPR-DS (source-independent MPR), and DS based broadcasting protocols. We add NES to these three schemes separately and evaluate the performance of the resulted protocols. In our experiments, we use the random unit graphs to model the ad hoc and sensor networks. Each of the studied protocols has scenarios under which it has the best performance. Our experiments demonstrate that, without applying neighbor elimination scheme, MPR based protocol requires fewest retransmissions (however, each retransmission is with a longer message including list of forwarding neighbors). DS and MPR-DS schemes benefit significantly from the neighbor elimination technique in terms of the ratio of re-broadcasting nodes and the message redundancy on both transmitting and non-transmitting nodes, while MPR benefits marginally. After adding the neighbor elimination scheme, three new protocols behave almost equally well in terms of rebroadcast message counts. MPR-NES method is narrowly the best when the message that is broadcasted is a very large one, and the network is dynamic. MPR-DS-NES is narrowly the best when the broadcast message is not very large, and the network is stable (this method requires the third round of preprocessing HELLO messages). Overall, DS-NES appears to be the most robust, taking all measurements and parameters into acount, because it remains competitive under all scenarios, and has significant advantages over MPR-DS-NES in dynamic scenarios, and significant advantages over MPR-NES when the broadcast message is not very large, because MPR has overhead in packet lengths.**

I. INTRODUCTION

Wireless ad hoc networks are formed by autonomous mobile devices, which operate in a self-organized manner and communicate together using radio interfaces. As ranges are limited due to physical properties of radio waves, only close hosts can directly communicate to each other. This means that multi-hop routing must be used, and thus each node must alternately act as either a terminal or a router depending on the needs of the system. Sensor networks can be seen as a special case of ad hoc networks, where hosts are mostly static and communications mainly occur between a fixed collector (which gathers sensed data) and some of the sensors.

Among the common problems found in these two kinds of networks is broadcasting, which is commonly used for route discovery, information dissemination or data gathering. It is a well-known *one-to-all* communication task, where one host u whishes to send a given set of data to all the other ones. Since normally the source node is not within transmission radius to all the recipient nodes, many hosts will have to act as routers for the task to be achieved. The easiest way is to have all nodes act as routers and retransmit the messages at least once to their neighborhood: this is a protocol known as *blind flooding*. In networks which are not sparse, it generates a lot of collisions that could possibly prevent the broadcasting from being correctly performed. Moreover, significant energy is consumed by the redundant messages. A number of other schemes have been proposed to replace blind flooding, and they are classified in different categories: simple flooding, probability based, area based and neighbor knowledge methods [1].

In this paper, we aim at evaluating the performances of protocols from the fourth category only. Indeed, for the existing probability and area based protocols, the performances of the protocols are closely related to the predetermined parameters and thresholds for which the best values may depend on network conditions. Moreover, they are not reliable [2]. The reliability of a broadcasting protocol refers to the capability of reaching all the nodes in the network when considering a collision free environment. Neighbor knowledge methods normally provide reliable broadcasting, and can be further divided into self-pruning and neighbor-designating methods, according to whether a node makes a local decision to retransmit a broadcast packet or is told by the upstream sender (either via the packet or via a previously sent control packet) whether it needs to retransmit the packet. We may also refer to these two types of methods as source-dependent and source-independent methods. From these two behaviors, we chose the *multipoint relay protocol* (MPR) [3] and the *generalized self-pruning rule* [4] as they are both efficient and representative. A variant combining MPR and dominating sets, namely MPR-DS [5], is also studied. Secondly, by adding the neighbor elimination scheme [2], [6] to the above mentioned schemes, we are able to illustrate that it improves the performance of any broadcasting protocol as added feature.

The remainder of this paper is organized as follows: in the next section, we provide the definitions needed by our network model, while in Sec. III a review of the examined protocols is proposed. We then provide in Sec. IV the technique, algorithms and procedures used in our simulations, as well as the assumptions made for our experiments and the obtained results. We finally conclude in Sec. V and provide some directions for future research.

II. PRELIMINARIES

We represent an ad hoc network by a graph $G = (V, E)$ where V is the set of nodes and $E \subseteq V^2$ is the set of edges that gives the available communications: (u, v) belongs to E means that v is a physical neighbor of u, i.e. u can directly send a message to v. Let us assume that the maximum range of communication, denoted by R, is the same for all vertices and that $d(u, v)$ is the Euclidean distance between u and v. The set E is then defined as follows:

$$E = \{(u, v) \in V^2 \mid d(u, v) \leq R\}.$$

So defined graph is called the *unit graph*, with R as its transmission radius. Each node $u \in V$ is assigned a unique value to be used as an *identifier* (id), so that the identifier of u is denoted by $\mathrm{id}(u)$. We also define the neighborhood set $N(u)$ of a vertex u as:

$$N(u) = \{v \mid (u, v) \in E\}.$$

The size of this set, $|N(u)|$, is also known as the degree of u. The density of the graph is the average degree for each node. Note that (u, u) is not in E.

The distance between two nodes is measured in term of *number of hops*, which is simply the minimum number of links to cross from a source node to a destination one. In Fig. 1, the distance between a and b is one hop, while the distance between a and k is five hops.

Nodes in a broadcasting protocol may require various neighborhood information. The protocols considered in this article require 2-hop topological information at each node. It may be obtained by two rounds of 'HELLO' messages, to send information about itself to neighbors, and to send collected information about its neighbors so that each node can acquire 2-hop knowledge. One of the selected protocols, MPR-DS, requires the third round of 'HELLO' messages, so that each node can inform all its neighbors about forwarding decisions, which are used later when a broadcasting task emerges.

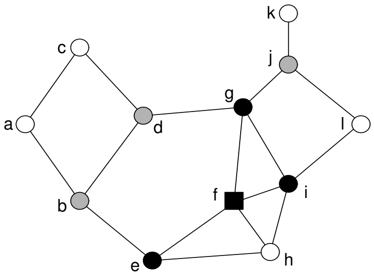


Fig. 1. Application of MPR algorithm: MPR sets are $\{g, e, i\}$ for node f, $\{d, j\}$ for g and $\{b\}$ for e.

III. RELATED WORK

Blind flooding is a traditional solution used to diffuse messages or packets in ad hoc and sensor networks. In this scheme, each receiving node retransmits exactly once the broadcasting message to its neighborhood. The protocol is simple but inefficient, as too many redundant messages are generated if the graph is not sparse.

The only existing article comparing broadcasting methods comprehensively is written by Williams and Camp [1]. They classified the broadcast protocols into: simple (blind) flooding, probability based, area based, and neighbor knowledge methods, and made comparisons between existing broadcasting protocols. Neighbor knowledge methods were claimed to better suit to ad hoc networks than other approaches compared in [1]. Therefore this article justified our focus on these methods. Their comparison, however, did not include dominating set based broadcasting protocols, and did not consider any neighbor elimination scheme. Therefore we believe that the best existing methods were overlooked in [1], which motivated as to perform this comparison.

The *multipoint relay protocol* (MPR) [3] belongs to the family of neighbor-designating methods. In this scheme, the sending node selects neighboring nodes that should relay the message to complete the broadcast. The id's of the selected nodes are recorded in the retransmission packet as a forward list. A neighboring node that is requested to relay the packet again determines its own forward list. This process is iterated until broadcast is completed. Selected nodes are called 'multipoint relays' and form a small subset of neighbors which covers (in terms of 1-hop radio range) the same network region which the complete set of neighbors does. The performances of MPR rely on the manner in which the multipoint relays are selected by each node, the goal being obviously to minimize the number of relays of a given node. The computation of a multipoint relay set with minimal size is a NP-complete problem, as proven in [3]. The greedy heuristics proposed in the latter is as follows: 1-hop neighbors that cover the largest number of uncovered 2-hop neighbors are chosen at each iteration until there are no more uncovered 2-hop neighbors. There exist some other variants of MPR scheme (see [7] for details) that mainly have some tradeofs between the local knowledge required and the size of transmitted message. We did not consider them since none of the variants seem better overall than the original formulation, which also had the closest assumptions to dominating set based approaches. The comparison between the two was the primary motivation of this article.

Consider the example in Fig. 1, where node f is the source of broadcasting. The set of its 1-hop neighbors is $\{e, g, h, i\}$ and and the set of its 2-hop neighbors is $\{b, d, j, l\}$. Node e covers b, node g covers d and j, node i covers l and node h does not cover any node. Since g covers the most nodes, it is selected to rebroadcast packet in the first round. In order to cover b and l, e and i must be selected. Thus the MPR set for node f is $\{g, e, i\}$. Each of these nodes then selects its own multipoint relays. The selection of MPR's can be optimized by ignoring nodes covered by other nodes in the forward list, if these nodes are neighbors. For instance, node g must select 1-hop neighbors d and j to forward packet to 2-hop neighbors b, c and k. Also, g does not need to consider 2-hop neighbor l since it knows that l is covered by i, which is a neighbor of g. Node e will select b to cover a and d. Node i will not select any forward node since all its 2-hop neighbors are already covered. In total, 7 out of 12 nodes are chosen to be MPR's. It thus takes 7 retransmissions for a message to reach all the nodes in the network.

Another possible method to broadcast an information is to use a connected dominating set (CDS). A subset $V_{\mathrm{dom}} \in V$ is said to be dominating if each node either belongs to V_{dom} or has at least one neighboring node that belongs to V_{dom}. It is observed that all nodes will receive the message if it is retransmitted only by nodes that belong to a CDS.

In the MPR based method, the process of selecting multipoint relays, in fact, is an example of creating a CDS which consists of all the relaying nodes and is source-dependent since the relaying nodes are selected by the upstream sender. This method includes a forward list as a part of the message, and therefore has a message overhead and the selection of relaying nodes depends on the source of the broadcast task. It is a competitive solution for broadcasting and routing tasks in network where all nodes are active all the time. In sensor networks, energy efficiency is an important issue. In order to reduce the energy consumption and prolong the lifetime of a sensor network, nodes may periodically go to sleep mode. In this case, MPR based broadcasting is not suitable, while a *source-independent* scheme to elect dominant nodes would be. When this method is applied to a sensor network, during the broadcasting period, the CDS is fixed and the dominant nodes stay active, while the other nodes may turn to sleep mode.

The efficiency of CDS based broadcasting approach depends largely on the process of finding a CDS of minimal size, but unfortunately finding the smallest CDS is NP-complete, even with a global knowledge. Wu and Li [8] proposed a simple and efficient distributed algorithm for calculating connected dominating sets in ad hoc networks. This algorithm has been further improved in term of message overhead by Stojmenović et al. [2], and also in terms of number of dominating nodes by Dai and Wu [4]. The latter considers that each node has a priority which can be simply its unique identifier or a combination of remaining battery power, degree or identifier, and proposes a more general rule where coverage can be provided by an arbitrary number of connected 1-hop neighbors. A modification of this rule has been proposed in [7] in order to avoid similar message exchanges between neighbors. A node u is covered by a set of 1-hop neighbors A_u if A_u is connected, $N(u) \subseteq N(A_u)$ and if each node in A_u has a higher key than u. It has been further computationally simplified by Carle and Simplot-Ryl [9] as follows. First, each node checks if it is intermediate, that is, whether it has at least two neighbors not directly connected. Then each intermediate node u constructs a subgraph G_{h} of its 1-hop neighbors with higher keys. In the graph composed by $N(u)$, each node which has a lower key than u is removed, as well as the corresponding edges. The resulting subgraph is denoted by G_{h}. If the latter is empty or disconnected then u is in the dominating set. If G_{h} is connected but there exists a neighbor of u which is not neighbor of any node from G_{h} then u is in the dominating set. Otherwise u is covered and is not in the dominating set. Dijkstra's shortest path algorithm can be used to test the connectivity (it is performed locally at each node). Non-intermediate nodes are never dominant. CDS concept is illustrated in Fig. 2, considering node g: the set of its 1-hop neighbors with higher priority is $\{h, i, j\}$. This set is not empty, connected, and fully covers $\{c, d, g\}$. Node g thus marks itself as not dominant. CDS consists of nodes f, h, i, j, marked black.

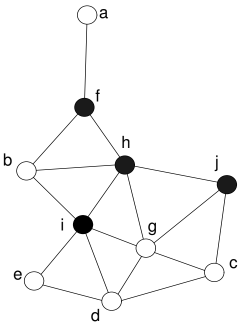


Fig. 2. Applying the Dai and Wu's scheme.

Adjih et al. proposed a connected dominating set election algorithm based on MPR, namely, MPR-DS [5]. Each node computes its multipoint relays and transmits the forward list to its neighbors. This is achieved by the third round of hello messages, after 2-hop neighbor topology is gained. Each node then decides that it belongs to 'MPR-dominating set' (MPR-DS) if and only if either it has the smallest id in its neighborhood (rule 1), or it is the multipoint relay of the neighbor with the smallest id (rule 2). Wu has enhanced both the selection of multipoint relays and the first rule of the above algorithm [10]. When selecting MPR's, free neighbors do not have to be considered: a node u is a free neighbor of v if v is not the smallest id neighbor of u. The rule 1 becomes: if it has the smallest id in its neighborhood and it has at least 2 unconnected neighbors.

In [11], Basagni et al. proposed a performance comparison of various protocols for computing backbones in ad hoc networks, including the previously cited protocols. They measured miscellaneous parameters, like the computation complexity (needed time to create the backbone), the backbone size or even the energy consumption per node in order to determine which protocol suits the best to ad hoc networks. They concluded that Wu and Li's algorithm used in conjunction with the variant by Stojmenović et al. [2] is an excellent compromise with respect to all the considered metrics, and overall far superior than any other approach that exists in literature. We therefore limited our study to listed protocols, refering to [11] for justification for not including other approaches in the study. The primary reason for superior performances of selected protocols is their localized nature, with low overhead for gaining needed neighbor knowledge, and low message overhead involved in constructing and maintaining the underlying backbones.

The neighbor elimination scheme (NES) [6], [12] has been used to improve the performance of existing broadcasting protocols as an added feature. In this scheme, nodes do not retransmit immediately, but wait for a given duration and monitor their neighborhood. When the timeout expires, if all neighbors have been covered by other transmissions, then the retransmission is canceled. The duration can be randomly chosen, but it can also be computed based on several parameters: one solution is to let nodes with more neighbors rebroadcast earlier, so that more nodes can be covered by one transmission. We thus may define the timeout as $\mathrm{timeout} = (1/\mathrm{numberCoverd}, \mathrm{id})$, where $\mathrm{numberCoverd}$ is the number of neighbors that have not received the packet, based on node's knowledge (some neighbors could have received the packet from 2-hop neighbors that are not 1-hop neighbors, thus node may not be aware of this). id is used to decide which node retransmits first in case of ties. When the timeout of a node expires and this node still has some neighbors that have not received the broadcast packet, this node rebroadcasts the packet. This scheme can be applied in any protocol to increase the energy savings while still keeping the reliability.

IV. PERFORMANCES EVALUATION

A. Simulation guideline

We have developed a simulator using JAVA [13]. In our research, the experiments were carried out in two phases. In the first phase, the performance of the basic MPR, CDS and MPR-DS schemes were evaluated. In the second phase, we added a neighbor elimination scheme to these three algorithms and evaluated the performance of the resulting methods.

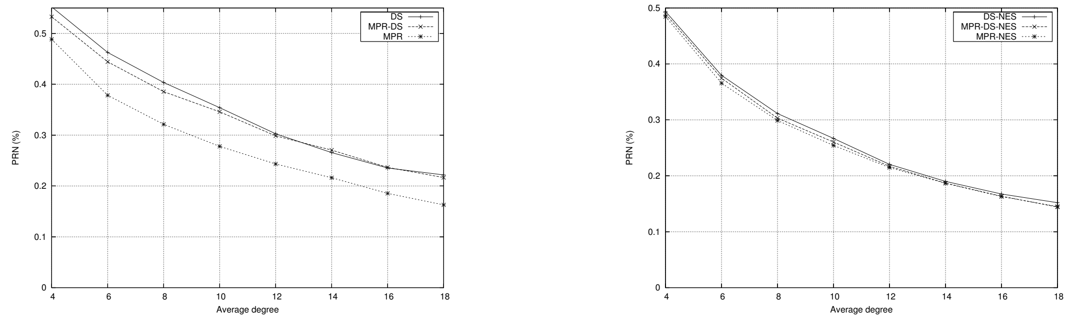
We used commonly adopted random unit disk graphs to model ad hoc and sensor networks. In this model, two nodes communicate with each other if and only if the distance between them is at most R, where R is the transmisison radius, equal for all nodes.

The random unit graphs were generated as follow: each of n nodes is chosen by selecting its x and y coordinates at random in the interval $[0, 200]$. In order to control the average node degree d, we sort all $n(n-1)/2$ potential edges in the network by their length, in increasing order. The radius R that corresponds to chosen value d is equal to the length of $nd/2^{\mathrm{th}}$ edge in the sorted order. Edges that are no longer than R will remain in the graph. Other edges are eliminated from the graph. In order to ascertain the existence of a link from a node to all other nodes in the networks, we ignored the disconnected graphs and considered the connected networks only. In connected graphs, the broadcast packet can reach all the nodes in the network if the considered broadcasting protocol is reliable.

We adopt certain assumptions to appropriately define the area of our study. These assumptions can be summarized as follow:

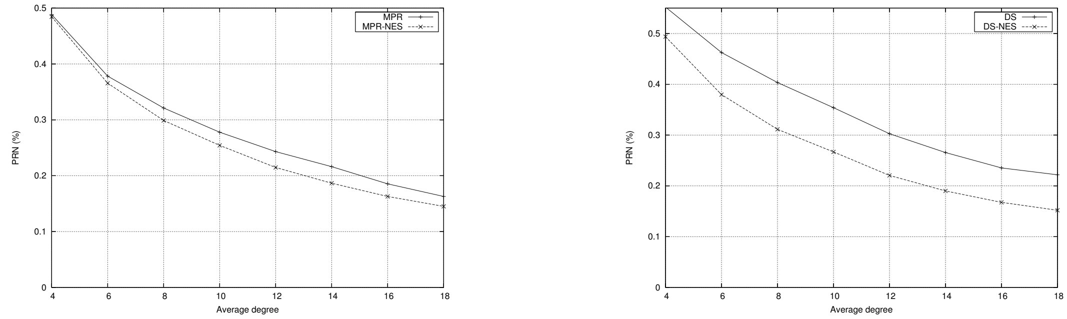
- An ideal MAC protocol, which provides for collision-free broadcasting, is used. The nodes in network are static while broadcasting is in progress. Thus any effect that mobility may have on the protocols is avoided. Because of localized algorithms being applied, it is assumed that relative positions of nodes do not change (sufficiently to impact the protocol performance) while broadcasting is in progress.
- One broadcasting task at a time is in the network and there is no other message traffic while broadcasting is in progress. Thus we avoid the impact of collisions in our experimental data, believing that a protocol that has lower overhead on one broadcasting task reduces collision impact on other tasks, thus is expected to perform better if collision considerations were added.
- Each node retransmits packets (if it has to retransmit according to the protocol) only once.
- There is synchronization among the transmissions. Channel is time-slotted and each transmission takes one slot.
- Each time a node transmits a packet, all its 1-hop neighbors receive this packet with probability 1.
- While a node transmits, none of its neighbors up to 2-hops are transmitting. This assumption was used to eliminate the problem of interference when a node receives two radio transmissions at the same time by two of its neighbors, which are not neighbors themselves.

We used the rule by Dai and Wu to compute CDS's. We define the priority of a node with a record $\mathrm{key} = (\mathrm{degree}, \mathrm{id})$ (this record is proposed for use in CDS in [2]): nodes compare their degrees first and the node with the higher degree has greater chances of being in the connected dominating set. In case of ties, the node with the highest id has priority to be selected. We used the same priority for MPR-DS and the



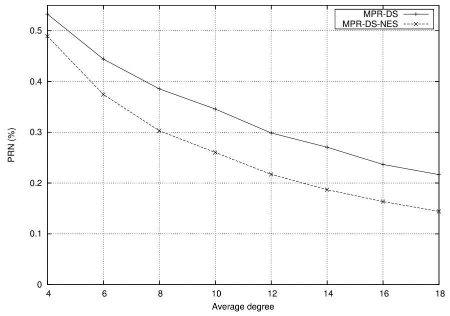
(a) All schemes.

(b) All schemes with NES.



(c) MPR scheme.

(d) DS scheme.

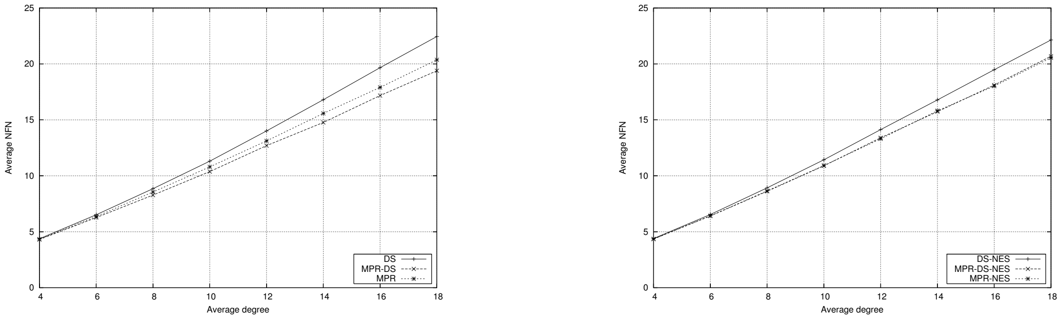


(e) MPR-DS scheme.

Fig. 3. PRN versus average degree.

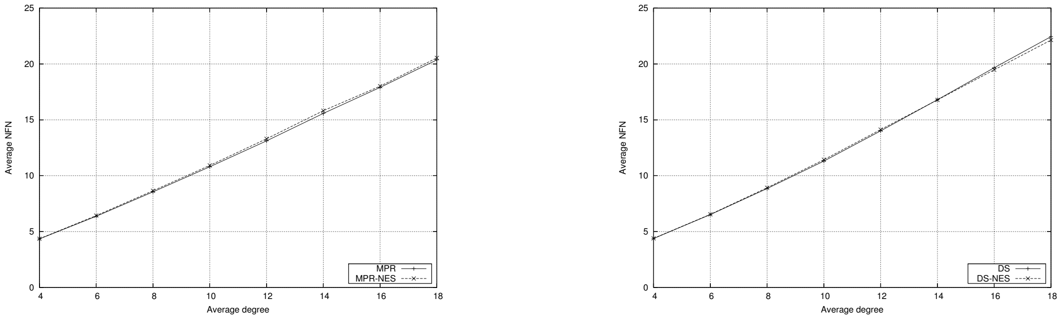
enhancement by Wu.

We call a node that is in multipoint relay set or in connected dominating set a relay candidate. There are two factors that a relay candidate c needs to consider before it relays the broadcast packet when using NES: timeout and forwardingList. Upon the first reception of the broadcast packet, c sets up $\text{timeout} = (1/\text{numberCoverd}, \text{id})$, where numberCovered is the number of 1-hop neighbors who have not received the packet after the same transmission. In case of ties, the node with the lowest id will rebroadcast the packet first. The forwardingList, at first, contains all 1-hop neighbors of c. For each reception of the packet, c eliminates from the forwardingList all neighbors receiving the packet from the same transmission. If c gets a packet from one of its neighbors after its first reception, it may need to adjust its original timeout when the number of uncovered neighbors changes. When timeout expires, c will rebroadcast the packet if its forwardingList is not empty. When adding a neighbor elimination scheme within a multipoint relaying broadcasting protocol, instead of letting all existing MPR's compute their own MPR's, we decided that only the MPR's which relay the packet to their neighbors carry out further computation. That means, if a MPR v has an empty forwarding list, v will not rebroadcast the packet and thus will not compute its own MPR's.



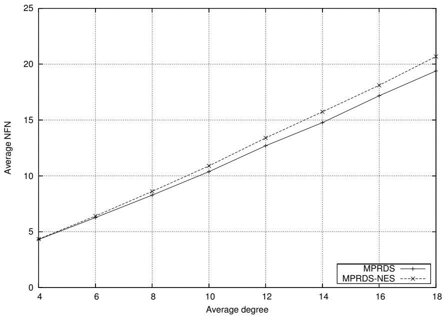
(a) All schemes.

(b) All schemes with NES.



(c) MPR scheme.

(d) DS scheme.



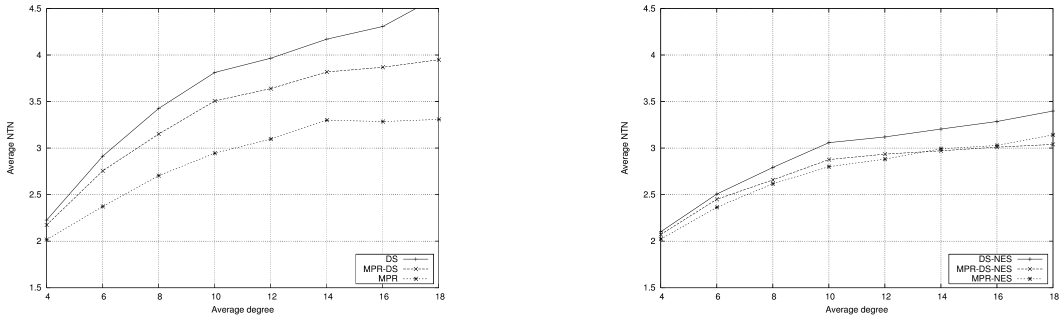
(e) MPR-DS scheme.

Fig. 4. NFN versus average degree.

B. Results

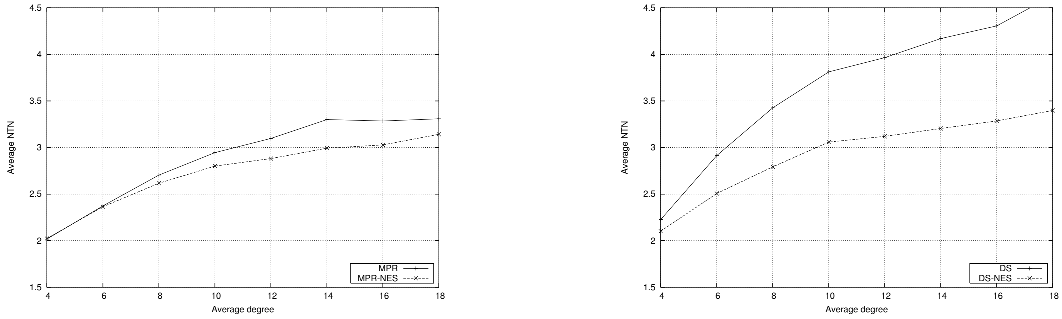
We first measure the percentage of re-transmitting nodes (noted PRN). To do this, the number of nodes that rebroadcasts the message is counted, and compared to the total number of nodes. Fig. 3 illustrates the simulation results. Subfigure 3(a) indicates that MPR has a lower ratio compared to DS and MPR-DS. However, each message in MPR is of longer size and therefore the selection of method with lowest overall packet size depends on the size of broadcast packet with respect to the size of neighbor's id. DS and MPR-DS behave equally well. This observation is consistent with results from [5]. From Fig. 3(c), 3(d) and 3(e) we observe that the neighbor elimination scheme has improved DS and MPR-DS significantly, but does not seem to have a significant impact on MPR when the average node degree is less than 10 and only does trivial improvement to MPR for $d > 10$. It is interesting to note that after adding the neighbor elimination scheme, three new protocols behave almost equally well.

Our result reveals that all algorithms depend on the density of the network. In sparse networks, more nodes need to rebroadcast in order to reach all the nodes in the network. As the density increases, proportionally fewer nodes rebroadcast. This observation differs from the result in [2], where it has been observed that the ratios appear to be relatively stable with respect to degree d. We argue that our result is more reasonable because when the degree d increases, the number of neighbors covered by one transmission increases, consequently the number of retransmissions needed to cover a certain



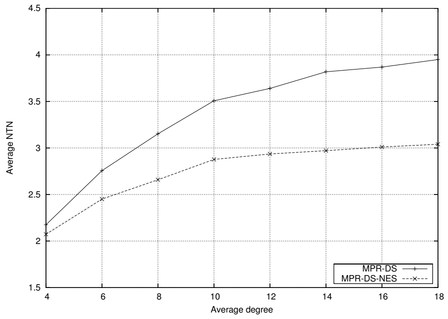
(a) All schemes.

(b) All schemes with NES.



(c) MPR scheme.

(d) DS scheme.



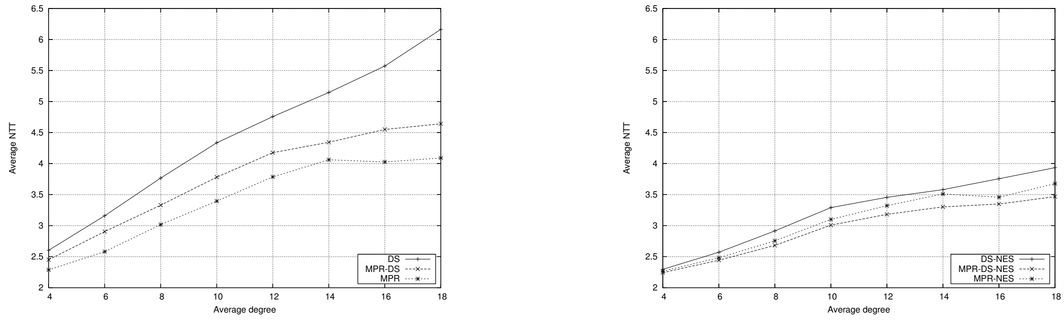
(e) MPR-DS scheme.

Fig. 5. NTN versus average degree.

number of nodes ($n = 100$ in our case) decreases.

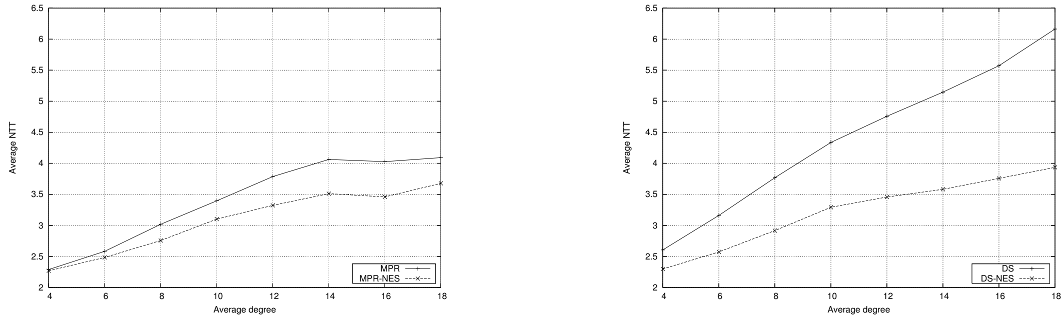
We also measure the number of nodes that each transmission covers. In fact this number is the number of 1-hop neighbors of each transmitting node. An average value on all the transmitting nodes is computed and compared with other methods. In Fig. 4(a) and 4(b), it is observed that NFN increases with respect to the average node degree d for all the methods. This was predictable as theoretically the NFN is closely related to d. DS has shown superiority over MPR and MPR-DS while DS-NES performs a little better than MPR-NES and MPR-DS-NES. Recall that in MPR, a node is chosen to be a multipoint relay because it covers a maximal number of un-covered neighbors. Although this number relies on the node degree to a certain extent, a node which covers the most uncovered neighbors will not necessarily have the highest degree in its neighborhood. However in DS, nodes with higher degrees have a higher priority to be in the connected dominating set. This is also true for MPR-DS most of the time. Notwithstanding the previous statement, in MPR-DS, a node with the highest degree in its neighborhood but without being an intermediate node cannot be in the connected dominating set. Ergo, there is the possibility that node with highest degree is not selected for both MPR and MPR-DS. Consequently, DS has a larger coverage per transmission.

The neighbor elimination scheme does not have significant impact on the average number of nodes covered by each transmitting nodes, as indicated in Fig. 4(c), 4(d) and 4(e). This demonstrates that the neighbor elimination scheme improves



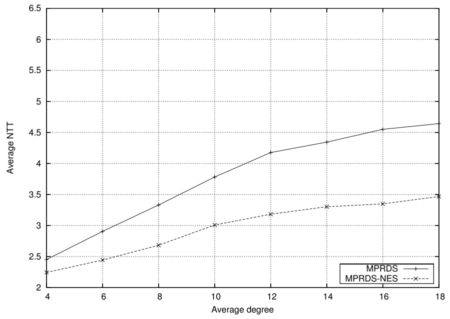
(a) All schemes.

(b) All schemes with NES.



(c) MPR scheme.

(d) DS scheme.



(e) MPR-DS scheme.

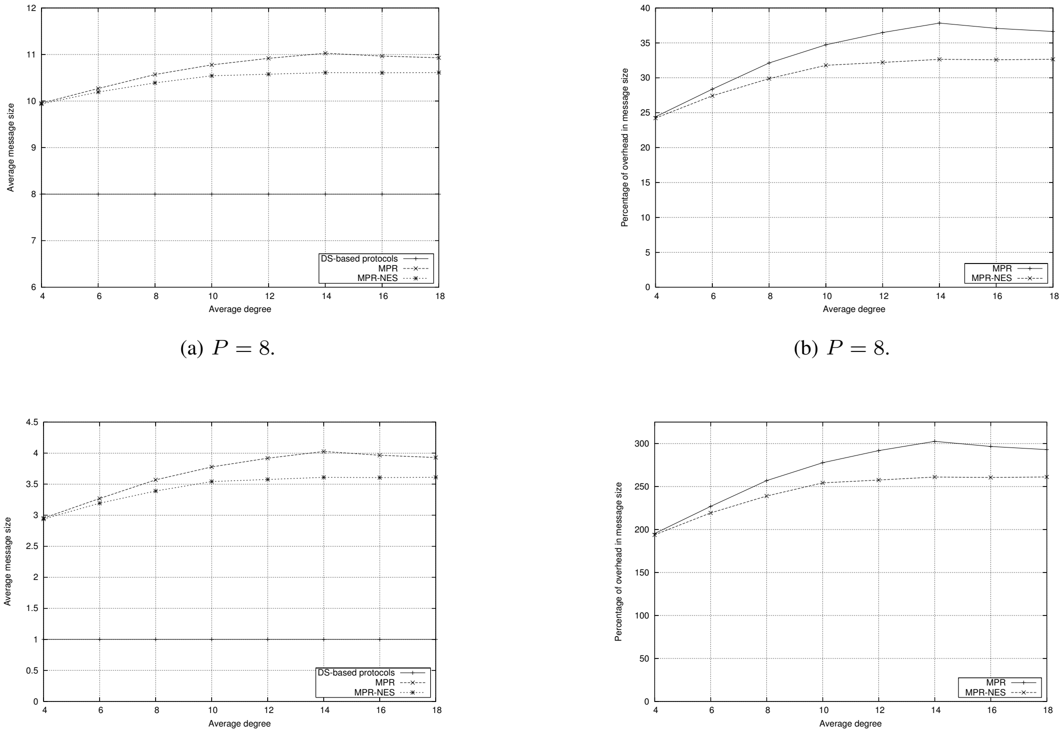
Fig. 6. NTT versus average degree.

the broadcasting protocols by reducing redundant retransmissions.

We now give results concerning the number of times each non-transmitting node receives the message, noted NTN. From Fig. 5, we observe that, in sparse networks, non-transmitting nodes get less redundant messages. While the degree d increases, each node receives more copies of the same message. The neighbor elimination scheme effectively reduces the redundancy in the network.

Fig. 5 presents the measured NTN for all methods under consideration. We see that MPR has a better performance than DS and MPR-DS (each node receiving fewer copies of the same packet), while MPR-DS lies in-between DS and MPR. From 5(b), we observe that after adding the neighbor elimination scheme, the three methods tend to have similar performances. The neighbor elimination scheme reduces NTN, thus reducing the traffic in the network. This improvement is more obvious for DS and MPR-DS protocols (refer to 5(d) and 5(e)). In these two methods, on average, NTN has been reduced by 0.5 to 1 in dense networks (when $d = 8$). But, MPR-NES still has slightly better performance than DS-NES and MPR-DS-NES overall.

We now give results about the number of times each transmitting node receives the message, noted NTT. An observation similar to NTN can be obtained for NTT from Fig. 6. That is, there is less redundancy in sparse networks than dense networks. Recall that with the average degree d increases, fewer nodes retransmit the message. However, the



(a) $P = 8$.

(b) $P = 8$.

(c) $P = 1$.

(d) $P = 1$.

Fig. 7. Average message size and overhead in message size for MPR scheme.

number of times each node, transmitting or non-transmitting, receives the same message increases. This can be explained by the increased coverage of each transmission. According to our observations, it appears that the transmitting nodes receive more copies of the same message than non-transmitting nodes. Once again, we notice that the neighbor elimination scheme improves DS and MPR-DS more than on MPR. In fig. 6, MPR exhibits the best performance on NTT. DS has the most redundancy on transmitting nodes. With the help of neighbor elimination scheme, MPR-DS-NES outperforms MPR-NES and DS-NES for most d values, as indicated in 6(b).

We finally consider the overhead brought by MPR scheme in the size of broadcast messages by including ids of relays in these messages. The other schemes, based on CDS, do not need to forward additional information within the broadcast packet. Let the unit packet size be equal to the size of the id of one neighbor in the forwarding list. Let p be the size of broadcast message in such units. Each MPR message is of different length, which is $p + s$, s being the number of neighbors in forwarding list, while dominating set approaches need p size for each message. We give in Fig. 7 the comparison between the different schemes for $p = 1$ and $p = 8$. We first measured the average size of each message being transmitted, and the percentage of overhead in the size of the transmitted message. We can observe that the overhead brought by the inclusion of ids of relays can be rather huge if the original size is small. For $p = 8$ in 7(a) and 7(b), the overhead ranges from 25% to 40% for densities between 4 and 18, while for $p = 1$ in 7(c) and 7(d), it ranges between 200% and 300%, compared to dominating set based approaches.

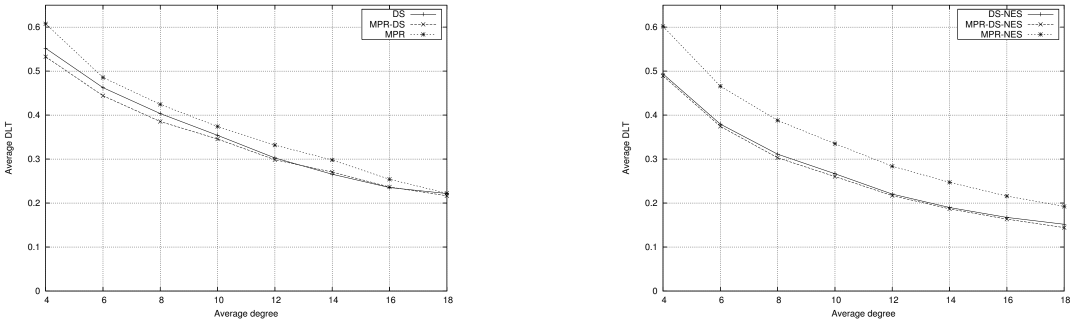
To complete the study of message overhead, we then measured the message dilation, as the ratio of overall message sizes transmitted by given protocol with respect to the overall message size used in blind flooding solution. The latter is np, where n is the number of nodes in the network. We thus give in Fig. 8 the value of this ratio for the values $p = 1$ and $p = 8$. It confirms that for small value of p, the overhead brought by the inclusion of MPR relays is rather huge, while the two schemes based on CDS are very near from each other.

We can infer that CDS-based schemes are superior to MPR scheme when p is small, because the significant overhead (and consequently the number of collisions) in MPR, while the difference will become negligible for higher values of p, that is, when broadcasting large files.

An interesting observation is that the notable improvement on MPR, by adding the neighbor elimination scheme, starts at $d = 10$, as illustrated in Fig. 3(c), 5(c) and 6(c). This happens because in sparse networks more relaying nodes need to rebroadcast to reach isolated neighbors.

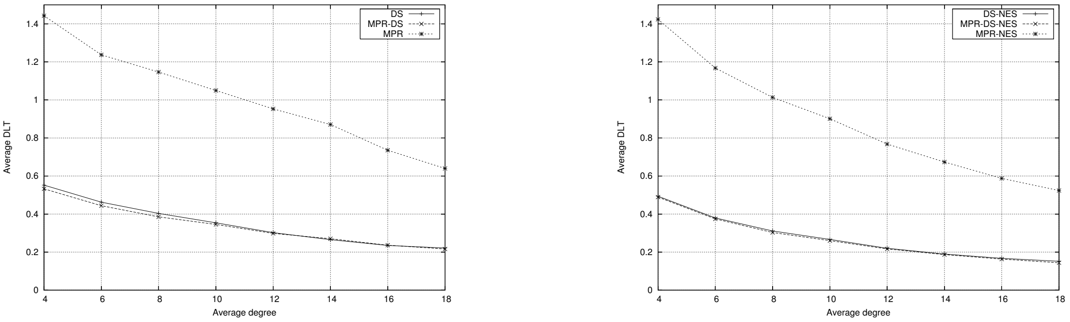
V. CONCLUSION

From the variety of simulation studied, we can draw a number of conclusions. The neighbor elimination scheme (NES) can enhance the performance of all the protocols as an added



(a) $P = 8$ without NES.

(b) $P = 8$ with NES.



(c) $P = 1$ without NES.

(d) $P = 1$ with NES.

Fig. 8. Average dilation for the miscellaneous schemes.

feature. In our simulation studies, NES reduces the number of re-broadcasting, as well as the message redundancy on both transmitting and non-transmitting node. NES provides more enhancements to broadcasting protocols in dense network. Especially, the notable improvement on MPR by adding NES starts at $d = 10$. This happens because, in sparse networks, more relaying nodes need to rebroadcast to reach isolated neighbors. Examples are nodes that are the neighbors of a node with degree one. Such nodes are considerably more likely to exist in sparse networks than in dense networks. NES improves DS and MPR-DS based protocols more significantly than MPR based protocol. This reveals that source-independent protocols benefit more from NES than source-dependent protocols.

Among the 6 examined schemes (three basic schemes with and without NES), MPR-NES appears to require the least number of retransmissions, but the advantage over two other NES based schemes is not major. However, this is balanced by the increased size of broadcast messages, which can cause more collisions at MAC layer, and requires more energy. For smaller packet sizes, CDS-based protocols appear superior. MPR-DS-NES protocol performs slightly better than DS-NES protocol. However, MPR-DS-NES requires the third round of HELLO messages, and therefore is inferior in dynamic networks. Therefore, it appears that pure dominating set based approaches are overall winning methods, remaining competitive under all network scenarios, and having huge advantage in dynamic networks or broadcast packets of small size.

DS based protocols provide better coverage for each rebroadcasting due to the fact that nodes with higher degrees always have higher priority to be in the connected dominating set and rebroadcast the packet.

All algorithms depend on the density of the network. In sparse networks, more nodes need to rebroadcast to reach all the nodes in the network. As the density increases, proportionally fewer nodes need to rebroadcast. As the density of the network increases, the number of times each node, transmitting or non-transmitting, receives the same message increases. The transmitting nodes receive more copies of the same message than non-transmitting nodes for all d values.

As future research related to this paper, we want to consider a more realistic environment. Indeed, we evaluated the performance of MPR, DS, MPR-DS based broadcasting protocols and the constructive effect of adding NES scheme. We assumed an ideal MAC. But in real networks, as the network density increases, heavier contention and collision increase the probability of packet loss. Future study could thus evaluate the performance of the broadcasting protocols under contention, collision, and other network conditions.

Another issue in wireless ad hoc and sensor networks is the presence of node mobility and different transmission radii. Maintenance of connected dominating structure in the presence of moving nodes is a nontrivial operation that may involve a significant amount of message traffic. Different transmission ranges of the mobile nodes or hidden terminal problem might cause unidirectional links. The performance evaluation of the broadcasting protocols may provide new insights by considering the influence of these factors.

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