A Bandwidth-Efficient Broadcasting Protocol for Mobile Multi-hop Ad hoc Networks

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Abstract

This paper presents a new broadcasting protocol called Delayed Flooding with Cumulative Neighborhood (DFCN) designed for wireless ad hoc networks. DFCN enables bandwidth-efficient broadcasting in wide area network composed of large number of mobile devices. The protocol was validated trough simulation which proved its efficiency and cost-effectiveness. Comparison with other well known protocols has shown that the proposed protocol outperforms them in such terms as a number of emissions and redundant receptions.

1. Introduction

A multi-hop mobile ad hoc wireless network (MANET) is a collection of two or more devices (referred to as *nodes* hereinafter) equipped with wireless communications and network capability[22]. Such network does not rely on fixed architecture and pre-determined connectivity. Devices in range of one another can communicate directly. Otherwise intermediate nodes should be used to relay packets from source to destination. Devices are generally mobile which means that the topology of such networks may change quickly in an unpredictable way. This property introduces many challenges. It has motivated many works dedicated to network-level techniques, such as routing, MAC-layer, broadcasting, etc [23, 19, 6].

In this article we deal with broadcasting (also called *flooding*) issue. The general principle of broadcasting in MANETs is as following: starting from a source node a message needs to be forwarded to all nodes in the network. The strategy for selecting the nodes that forward the message constitutes the main difference between all broadcasting protocols. Section 2 gives an overview of some different techniques that have been proposed so far.

Optimizing a broadcasting strategy can be considered as a multi-objective problem whose most important ones are: reaching as many nodes as possible, operating as fast as possible and minimizing network use. The importance of the various objectives and the behavior of the algorithm should depend on the requirements of a particular application. In our paper we focus on minimizing the network use. The broadcasting algorithm described here aims at minimizing the number of emissions (reflecting the network throughput) and at maximizing the coverage. In this context, the application fields of broadcasting range from network-layer broadcasting to application-level diffusion. At the system-level, an example of such application is time synchronization. At the user level, an example is customer-to-customer advertisement systems: people who want to sell some goods broadcast a small ad describing what is for sale and featuring the contact information of the seller.

We model the coverage (ratio of the nodes to be reached) as a constraint to be satisfied. This way the initial multi-objective problem is reduced to a simple-objective one which consists in minimizing the number of message emissions and in satisfying a given set of constraints, including the coverage.

Many broadcasting protocols actually consist of strategies for the determination of dominant sets [21]. These techniques make the implicit assumptions that the mobility (if some) is low and that the network is non-partitioned (meaning that all nodes are reachable through multi-hop connections). Some other protocols [18], proposed more recently, feature more dynamic approaches (such as self-pruning [23]), in which the mobility is central issue. The protocol presented in our paper belongs to the latter category. More precisely, we consider realistic networks such as mall and Metropolitan Ad hoc Network [5]. Such networks have two important properties:

- the node density in the network may vary greatly. A very sparse network is as realistic as a very dense one, as illustrated in Figure 1 and 2. The difficulty of dealing with such variations of density is that the protocol needs to be efficient when the network is made of several disjoint parts as well as when it is highly connected.

- a network may be composed of thousands nodes roaming all across a city.

In such network, the broadcasting process cannot propagate data to all nodes: only a subset of the nodes can be reached at a particular time.

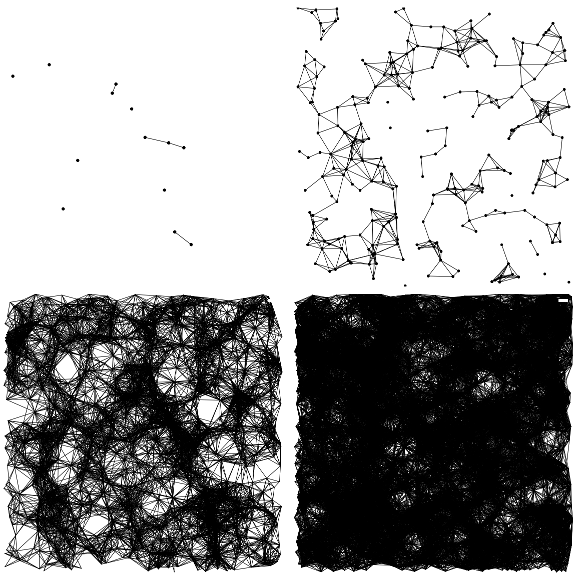

Figure 1. Broadcasting in a low density network (top-left figure, $50 nodes/km^2$) is difficult because the protocol needs to make a very good use of the mobility to achieve a good coverage. When the density increase (top-left figure, $1000 nodes/km^2$), the connectivity gets better, but the network may be partitioned. When the density is highly connected (bottom left and right figures, respectively $5.000 and 10.000 node/km^2$), the broadcasting protocol must be bandwidth-efficient in order to minimize the risk of packet collisions.

The remainder of this paper is organized as follows. Section 2, presents related work. Next, section 3 introduces a new broadcasting protocol - Delayed Flooding with Cumulative Neighborhood (DFCN). In section 4, we describe methodology we use in our simulations to evaluate the results. Then in section 5 we present the results, analysis and

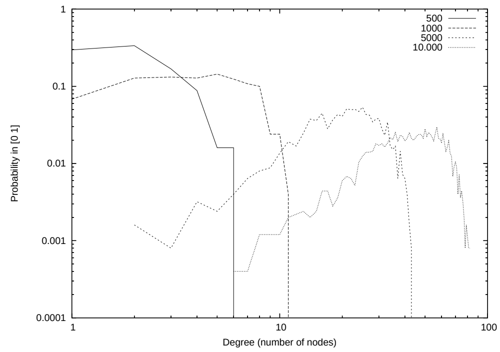

Figure 2. The evolution of the average degree distribution when the density grows.

we compare performance of DFCN to other broadcast algorithms.

2. Related works

Williams, Camp [23] and later Stojmenovic, Wu [21] have proposed the two most frequently referenced analysis of the broadcasting algorithms. We will use two algorithm classifications proposed by those authors.

2.1. Williams and Camp's classification

Williams and Camp [23] classify broadcasting protocols according to the network knowledge that the nodes need to have in order to execute them. They define four categories: simple flooding, probability-based methods, area-based methods and neighbor-knowledge-based methods. This categorization is based on the way protocols select re-broadcasting nodes.

In Simple Flooding [13], also called *blind flooding* each node forwards received messages exactly once. Simple Flooding does not make any attempt to reduce the number of re-broadcasting nodes and does not require any knowledge. This strategy is not suitable for environments with high density regions because. It would generate too much network traffic and sometimes could even lead to network congestion. This problem is referred to as the broadcast storm problem [13].

In probability-based methods [13], each node estimates a potential contribution to the broadcasting process. If this contribution is lower than a given threshold the message is not forwarded [24]. These strategies reduce the problems inherent to flooding but do not solve them. This scheme does not require any network information.

When information about nodes location is available, the decision of re-broadcasting a given packet can be taken according to the additional geographical area covered by a potential emission. Area-based and location-based [13] methods define that if the surface or distance of this area is lower than a given threshold, the message is not re-emitted. Network information can be obtained by GPS or evaluated by triangulation or by measuring the power of the radio signals.

Finally, neighbor-knowledge-based methods (SBA, Flooding With Self-Pruning (FSWP), AHBP, Multi-point Relaying, etc) require the knowledge of the *n*-hop neighborhood (FWSP uses 1-hop neighbors, SBA, Multipoint Relaying and AHBP uses 2-hops neighbors). They constitute the last class of broadcasting strategies. This class can be divided in two subclasses: *neighbor-designating* and *self-pruning* methods. On the one hand, the nodes running protocols belonging to the *neighbor-designating* subclass (AHBP, Multipoint Relaying) operate by designing their neighbors that will be in charge of relaying the message. On the other hand, the nodes running protocols belonging to the *self-pruning* subclass (SBA, FWSP) decide by themselves whether to rebroadcast or not.

Using Williams and Camp's classification, DFCN belongs to the self-pruning neighbor-knowledge-based class.

Protocol	*Scope*	*Deter.*	*Reliable*	*Mobility*
DFCN	1-hop	yes	no	yes
Simple flooding	-	yes	yes	no
Location-based	1-hop	yes	no	no
Probabilistic	-	no	no	no
FWSP	1-hop	yes	yes	no
SBA	2-hop	yes	yes	no
Multipoint relaying	2-hop	yes	yes	no
AHBP-EX	2-hop	yes	yes	yes

Figure 3. The table summarizes the properties of the broadcasting protocols mentionned in the paper. It provides, correspondingly, the name of the protocol, the amount of topology information it requires, whether it uses a deterministic approach or not, whether its is reliable or not, and if it takes into consideration the mobility of nodes.

2.2. Stojmenovic and Wu's classification

Stojmenovic and Wu [21] propose new classifications for broadcasting protocols. In their proposal protocols can be classified according to their algorithmic nature (determinism, reliability) or the information required by their execution (network information, "hello" messages content, broadcast messages content).

A broadcasting algorithm is said to be deterministic if it behaves predictably. If it runs on a particular input, it will always produce the same output. Most broadcasting protocols are deterministic.

An algorithm is assumed to be reliable if it ensures that all nodes in the network will be covered. Probabilistic schemes and area-based methods (see section 2.1) are usually unreliable as they rely on randomness and heuristics, respectively. Note that the concept of *reliability* does not make sense if the network is partitioned. In such case reaching all the nodes is not possible to achieve.

Another classification was proposed by Wu and Lou [25]. It is based upon the amount of state information required for performing broadcasting. More precisely, they categorized protocols on whether they rely on a *global*, *quasi-global*, *local* or *quasi-local* knowledge of the network. *Global* and *quasi-global* broadcasting algorithms are also called *centralized* protocols. Centralized protocols are listed in [15]. Their main drawback is that they are not scalable. They are hence unusable in the MANET. Localized protocols are those which need a *local* (or *quasi-local*) view of the network. Example of the protocols belonging to this class are 1 and 2-hops neighborhood-knowledge protocols.

The network state information (node's identifier, location, degree), and network topology information are interchanged between nodes. Such information is carried by either "hello" messages (which are specifically meant to represent topology information) or broadcast messages. The amount of data embedded in those messages has a serious impact on the network throughput. Protocols can then be classified according to the amount of data is carried either in the "hello" or broadcast messages [21].

Using Stojmenovic and Wu's classification DFCN is a deterministic algorithm. It does not consist in a new approach for calculating dominating sets. Instead it defines heuristics based on local network information. Only 1-hop information is required, which permits DFCN to achieve very good level of scalability. The "hello" messages interchanged by the nodes do not carry any additional information. Only broadcast messages must embed the list of node's neighbors.

3. Delayed Flooding with Cumulative Neighbourhood

In this section we present the Delayed Flooding With Cumulative Neighborhood protocol. First we describe our assumptions on which DFCN relies. Next we provide a detailed description of the protocol.

This is an enhanced version of the protocol presented in [8].

3.1. Requirements

For being able to run the DFCN protocol, the 4 following assumptions must be met:

1. Like many other neighbor-knowledge-based broadcasting protocols (FWSP, SBA, etc) and as mentioned in the previous section, DFCN requires the knowledge of 1-hop neighborhood. One way of obtaining this information is using “hello” packets. We denote the set of neighbors of the node s by $N(s)$.

2. Each message m embeds in its header the set of IDs of the 1-hop neighbors of its most recent sender. We refer to this set as $T(m)$.

3. Each node maintains local information about all messages received. Each instance of such information consists of three items:
   - the ID of the message received;
   - the set of IDs of the nodes that are known to have received the message, referred to as $K(m)$;
   - the decision of whether the message should be forwarded or not, referred to as $a(m)$.

4. DFCN requires the use of a random delay before possibly re-emitting a broadcast message m. We call it Random Assessment Delay (RAD). Its goal is to prevent packet collisions. More precisely, when a node s emits a message m, all the nodes in $N(s)$ receive it at the same time. It is then likely that all of them forward m simultaneously. This simultaneity entails network collisions. The RAD aims at randomly delaying the retransmission of m. As every node in $N(s)$ waits for the expiration of a different RAD before forwarding m, the risk of collisions is reduced. The RAD for a message m is referred to as $r(m)$.

3.2. An event-driven protocol

3.2.1 On the benefit of forwarding

When a node receives a message, the forward decision may depend on different parameters (RAD, neighborhood...). We introduce the notion of benefit as a new parameter allowing the adaptation of the broadcasting service to the customer application.

As previously mentioned in the ”DFCN requirements” (section 3.1, item A), a node s maintains for a message m a list $K(m)$ which contains the IDs of the nodes that are known to have already received m. The list $K(m)$ is managed in this way: When s sends a m to its neighbors, it know that all of them will receive (unless some collisions occur) m. If ever the same situation happened (if s had the same neighborhood), then m would not been forwarded again, as all the nodes around are already known to have received it. When a node n receives a message m from one of its neighbors b, it also add all the neighbords b in $K(m)$, as all of them have received m as well.

The benefit is defined as the ratio between the number of neighbors of s which do not belong to $K(m)$, and the number of neighbors of s: benefit $= \frac{|N(s)-K(m)|}{|N(s)|}$. The smaller is the benefit, the less DFCN will be restricted in emitting messages, hence the greatest throughput it will generate.

The behavior of DFCN is driven by three events. These events are:

- the reception of a message referred to as *reactive* behavior

- the expiration of the RAD of some messages

- the arrival of a new neighbor referred to as *proactive* behavior.

When one of these three events occur, DFCN reacts by behaving in a specific manner, as described in sections 3.2.2, 3.2.3 and 3.2.4.

3.2.2 Message reception event

(see algorithm 1) If a message m is received for the first time, $K(m)$ is equal to $T(m)$ and a RAD is then assigned to m. Otherwise the set $T(m)$ and id of the sender node are added to $K(m)$.

Algorithm 1: The section of the algorithm executed upon message reception.

Data: m: the incoming broadcast message
Data: s: the node which have sent m

```
if m is received for the first time then
    K(m) ← T(m)
    rad(m) ← random ∈ [0, maxRAD]
else
    K(m) ← K(m) ∪ T(m) ∪ {s}
end
```

3.2.3 RAD expiration event

(see algorithm 2) When the RAD of a message expires, its hosting node computes the ratio of neighbors that did not yet receive it. If the ratio is greater than the threshold $minBenefit$, the message is forwarded, otherwise it is dropped. If the message is emitted, then $N(s)$ is added to $K(m)$.

Algorithm 2: the decision function defines if a given message is worthwhile to be forwarded or not.

Data: the broadcast message m, candidate to immediate emission.
Data: s: the node that receives m

$benefit \leftarrow \frac{|N(s)-K(m)|}{|N(s)|}$
$a(m) \leftarrow benefit \geq minBenefit$
if $a(m)$ **then**
  $K(m) \leftarrow K(m) \cup N(s)$
end

3.2.4 New neighbor event

(see algorithm 3) Each time a node s gets a new neighbor, the RAD for all messages is set to zero. Messages are hence immediately candidate to emission (see section 3.2.3). If $N(s)$ is greater than the threshold $densityThreshold$, this behavior is disabled.

Data: s: the node which has a new neighbor.

Algorithm 3: The algorithm executed upon message reception. $M(s)$ is the set of messages received—and not yet expired—by the node s.

if $|N(s)| < densityThreshold$ **then**
  foreach $m \in M(s)$ **do**
    $rad(m) \leftarrow 0$
  end
end

6 4. Description of the experiments

The results presented in this section 5 have been produced using *madhoc* [7] simulation tool. Madhoc is a mobile ad hoc network simulator currently developed in University of Luxembourg. It is an application-level network simulator dedicated to the simulation of mobile ad hoc networks. Our main motivation for using *madhoc* is its ability to simulate high number of nodes and its graphical facilities which proved a great help for protocol development and experimentation.

4.1. Node mobility

The nodes move according to the random waypoint [3, 1] mobility model. As described in [1], the random waypoint mobility model defines that each node chooses randomly a destination in the simulation area. The node moves towards this destination with a randomly chosen velocity. When the node reaches its destination, it remains static for a predefined duration and then starts moving again according to the same rule.

In order to reduce the "harmful" behavior inherent to the random waypoint mobility model [26], each simulation process is initialized using the stationary distribution pattern [12].

The simulated area is a square whose edge is 500m. The velocity of nodes is randomly chosen between 3 and $6km.h^{-1}$. The pause lasts 5 seconds.

4.2. PHY/MAC

We assume that the establishment of a connection (discovery of the neighborhood using, hello packets and initialization of the connection) requires 250ms.

The coverage radius (maximum distance from the source from which the signal can be sensed and demodulated) used for the simulations, can varies between 30 and 60 meters. The *maximum bandwidth* (theoretically obtained when the signal is not attenuated and when the link is free of interferences) is 11Mbps. These characteristics correspond to the IEEE 802.11b specifications.

Communications are established according to the rules defined by the CSMA (Carrier Sense Collision Avoidance) MAC layer. CSMA is clearly the smallest common set of the specific MAC layers used by existing wireless networking technologies (IEEE 802.11a/b/g).

4.3. Radio wave propagation

Radio wave propagation depends on the natural environment of the nodes. In open space the propagation is omnidirectional and the covered area is a circle. Some works aiming at modeling the propagation of radio waves use techniques like advanced statistical models or ray-tracing [2]. For simplicity most of the works in the area of broadcasting consider the open space path loss as the radio wave propagation model. According to open space path loss model radio signal gets attenuated as the distance grows.

4.4. Parameters of the protocol

As explained in section 3.2, DFCN relies on the *benefit* and *densityThreshold* thresholds. We have experimentally found out that 0.4 and 4, respectively, are good values for these threshold. The following benchmarks relies on these values.

4.5. Benchmarking process

The simulation process consists of the selection of some random nodes being the starting point of the broadcasting process. In order to prevent the broadcasting process from starting from a isolated node (from which it would have no chance to complete) the number of neighbors of the initial node must be greater than the average number of neighbors in the whole network.

The broadcasting process is said to be:

- **completed** if it could satisfy the coverage constraint. Coverage satisfaction ensures the validity of the broadcasting process. More presicely, if the coverage cannot reach the constrained value, then the broadcasting process is considered to have failed.

- **failed** if the broadcast message expires before the broadcasting process could satisfy the coverage constraint. The lifetime of broadcasting messages depends upon the application. Packet routing layers need quite short lifetimes while high-level applications, like advertising application, may want the message to be alive several hours. In our simulations we set the message lifetime to 1 minute. Upon the expiration of its lifetime the message can no longer be transmitted. Thus broadcasting process is terminated.

In order to evaluate the performance of the DFCN protocol we compare it to other competing protocols. As mentioned in section 2, numerous broadcasting protocols have been proposed. But not all of them are relevant competitors to DFCN. More precisely, centralized (global and quasi-global) broadcasting protocols cannot be applied in the context we defined in section 1. Protocols relying on location information like [20] [13] cannot be used as references because we assumed that such information is not available. Similarly, some broadcasting protocols use mechanisms that enable node to adjust power of the transmitter and receiver of its communication interface [4]. As we do not assume availability of such mechanisms, we do not compare such protocols to DFCN.

We compare DFCN to the standard and most efficient fully localized protocols. We consider the following ones:

- **Simple Flooding** [14], also known as *blind flooding* which is a good reference protocol being the most obvious solution for broadcasting. Simple Flooding defines that each node forwards received messages exactly once. This algorithm is reactive-only.

- **Flooding With Self-Pruning (FWSP)** [10] which implements a neighborhood-aware strategy based on 1-hop knowledge. Each broadcast message includes the list of IDs of the neighbors of the sender node. FWSP-enabled nodes upon reception of a broadcasted message retrieve the set of IDs embedded in the message and subtracts it to the set of IDs of its own neighbors. If the resulting set is empty, the message is dropped, otherwise it is forwarded. This algorithm is reactive-only.

- **SBA** [17] implements neighborhood-aware strategy based on 2-hops knowledge. SBA uses the same strategy as Flooding with Self-Pruning protocol. It requires the knowledge of 2-hop neighborhood. Each SBA broadcast message that includes a list of IDs of the 2-hop neighbors of the sender node. The strategy carried out by SBA-enabled nodes is as following: upon reception of a broadcasted message, the node retrieves the set of IDs embedded in the message and subtracts it to the set of IDs of its own neighbors. If the resulting set is empty, the message is dropped, otherwise it is forwarded. SBA also defines a technique which consists in re-adjusting the RAD according to the degree of the node concerned and the maximum degree of its neighbors. The SBA strategy is reactive-only.

- **Multipoint Relaying** [9] relies on the knowledge of 2-hops neighborhood. Multipoint Relaying's messages contains the set of nodes that must act as relays. Multipoint Relaying then works this way: Upon message reception, the node finds out if its ID is contained in the message-embedded set of relays. If yes, it constructs the smallest set of 1-hop relays that cover all the 2-hop neighbors. In turn, it embeds this set in the broadcast message itself before sending it around. The construction of the set of the forwarding nodes is done according to the greedy algorithm described in [11]. The Multipoint Relaying protocol is reactive-only.

- **AHBP-EX** [16] is an extension of the AHBP [16] protocol. It aims at supporting high mobility networks. Its strategy is simple: upon detection of a new neighbor, the node consistently applies the AHBP strategy consisting of designing 1-hops neighbors as relays and emits the message. AHBP-EX is both reactive and proactive.

5. Results

In this section we describes the results of our simulations.

The results presented below are obtained by varying the density in $[0, 10.000]$ nodes by square kilometer. Since the simulation area is $250,000m^2$ $(500 \times 500m)$, the number of nodes varies from 0 to 2,500. In order to achieve some decent statistical confidence, the various measures were obtained by averaging the measures out of 20 distinct simulations.

The evaluation of the performance of broadcasting protocols is typically based on the ratio of rebroadcasting nodes. Unfortunately this measure misses relevancy when applied to proactive protocols. It happens because one single node may send several times the same message. This is why in this paper we consider the number of emissions to be a better way of evaluating the qualities of broadcasting protocols. We also take into consideration the number of redundant receptions of the same message and the duration of the broadcasting process (makespan).

The following subsections describe the performance of DFCN according to four measurements which are:

5.0.1 Application domain

the protocols that do not feature any proactive management of the mobility (Simple flooding, SBA, Multipoint Relaying, etc) are unusable in the environment where the density is lower than 1,000 nodes by square kilometer.

Based on reaction to neighborhood changes AHBP-EX and DFCN perform well down to $100 nodes/km^2$. Broadcasting in partitioned ad hoc networks relies on the mobility of the nodes. Because there are several partitions in the network, the only way for the broadcast message to jump from one partition to another is to find temporary paths heading to other partitions or to be carried by nodes moving to other partitions. This process may last a while, since the temporary paths appear erratically and the speed of the nodes is limited.

5.0.2 Number of emissions

the number of emissions is one of the most relevant measure because it has a direct impact on the network bandwidth use. This value has to be minimized. Figure 4 shows the average number of emissions in case when only one node initiates the broadcasting. A situation when 10% of the nodes initiate broadcast simultaneously is shown on Figure 5. In both cases it can be seen that DFCN emits by far less than its biggest competitor, Multipoint Relaying.

5.0.3 Number of redundant receptions

the number of redundant receptions directly depicts the waste of resources (bandwidth, energy, etc). It has to be minimized. Figure 6 shows that DFCN uses about 3 times less resources than its competing protocols.

5.0.4 Makespan

is a time required to complete the broadcasting process.

Figure 7 shows that DFCN is clearly not the fastest broadcasting protocol. This result comes from its selective strategy. Because DFCN carries out less emissions, the broadcasting process needs more time to complete. It is a

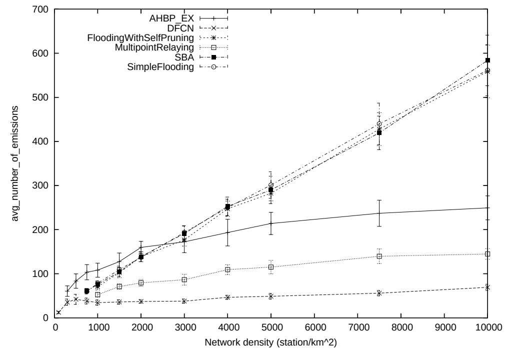

Figure 4. The number of emissions carried out by each broadcasting protocol. Only one single node initiates a broadcasting process

tradeoff (enlightened in several studies on broadcasting protocols for ad hoc networks): the more greedy a broadcasting protocol is, the faster it is.

6. Conclusion

Ad hoc networking is a promising but challenging emerging technology. Research tackles many aspects of this topic like broadcasting, routing, distributed computing etc. In this paper we have introduced a new broadcasting algorithm called DFCN. We have proved trough simulation its efficiency and compared it with another well known protocols. The results have shown that the proposed protocol outperforms these protocols in such terms as a number of emissions and redundant receptions. It is only slightly slower than its competitors. This is a natural consequence of its selective strategy which results in reduced number of emissions. DFCN proves a bandwidth-efficient broadcasting over mobile ad hoc networks. Thanks to its mobility and density-aware strategy DFCN operates well either in high-density and low-density networks. Additionally, it does not consume much more bandwidth as the density increases.

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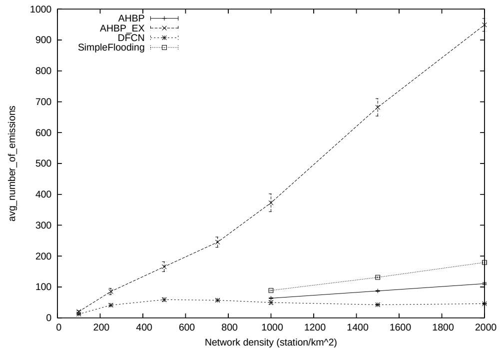

Figure 5. The number of emissions carried out when 10% of the nodes initiate a broadcasting process. Because of the computational limitations of the worknodes used for the simulation, we could not use densities greater than $2,000 nodes/km^2$.

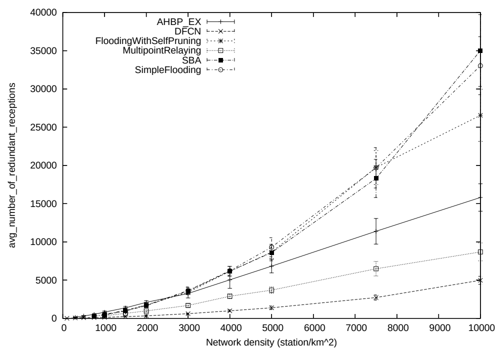

Figure 6. The number of redundant receptions generated by each broadcasting protocol.

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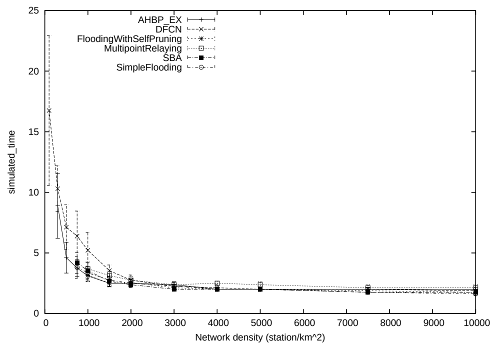

Figure 7. The execution time (makespan) of each tested broadcasting protocol. The lower the better.

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