Broadcasting in Ad Hoc Networks with Smart Antennas

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***Abstract*: Smart antennas have the advantage over traditional omnidirectional antennas of being able to orientate radio signals into the concerned directions in either transmission mode or in reception mode. Since the omnidirectional antenna use in broadcasting over the whole network is the source of an excessive redundancy of broadcast packet receptions within each node, we suggest using smart antennas to improve the medium usage in the case of broadcasting. We propose to adapt a current broadcast protocol to smart antenna applications and present two smart antenna broadcast approaches. We also present a comparative performance study between omnidirectional and smart antennas when broadcasting. We show that we can improve battery power utilization and bandwidth use with smart antennas.**

1. Introduction

Broadcasting a packet in the network consists in delivering this packet to all the nodes in the network. The most obvious broadcasting technique is flooding. With this mechanism, the broadcast packet source sends its packet to all of its neighbors, and each node receiving this packet will retransmit it, if it receives it for the first time. All nodes of the network thus have to retransmit the broadcast packet if no collisions occurred. In lower density networks, the flooding technique works well but in networks with higher density the participation of all nodes in the broadcast packet retransmission does not provide a good solution. Indeed, the increase in the number of nodes having to retransmit the broadcast packet causes many collisions that influence the reachability performances dramatically. For this reason, several proposed broadcast approaches focused on realizing the trade off between the increase in the number of nodes having to retransmit the broadcast packets to increase reachabilities and the decrease in this number to minimize potential collisions.

Another problem of broadcasting is that there are no means to avoid two neighbors from receiving the same broadcast packet and then retransmit it at the same time. The handshaking mechanism proposed in IEEE 802.11 to resolve the hidden node problem cannot be used in the case of broadcasting. To overcome this problem, past works introduced the use of jitter and RAD (*Random Assessment Delay*).

The use of jitter (random delay) consists in ensuring that the broadcast packet is transmitted from the network layer to the MAC (Medium Access Control) layer with a sufficiently large random delay to allow some nodes to access the medium before other nodes do. These last nodes will detect that the medium is busy.

RAD is the tracking of the number of times a broadcast packet is being received during a giving period of time. This period is randomly chosen between 0 and *Tmax s*. This delay helps in deciding whether retransmit the broadcast packet or not, and whether to add the jitter effect, *i.e.*, avoiding certain collisions.

Broadcasts in ad hoc networks assume that the underlying antennas are omnidirectional. Under this assumption, the retransmission of a packet within a node to cover a set of its neighbors that have not yet received the broadcast packet will disturb the neighbors that have already received the broadcast packet. We are proposing to improve broadcasting on the base of the possibility that smart antennas can restrict the radio propagation to the zone covering only the concerned nodes. This will save certain nodes from receiving the same broadcast packet many times over. Consequently, this will save on the energy needed for reception and increase bandwidth utilization since we do not only save nodes from unnecessarily receiving packets but we also free certain zones of the radio medium.

The next section introduces directional and smart antennas. The rest of this paper is organized as follows. Section 3. describes previous studies on broadcast protocols. In section 4. we introduce new algorithms to carry out broadcasting based on smart antennas. The performance evaluation of our protocols is presented in section 5.. Section 6. concludes this paper with a summary of our study.

2. Directional and smart antennas

An omnidirectional antenna is an antenna that transmits and receives equally in all directions. Its most significant disadvantage consists in the fact that the destinations receive their packets with a signal radio level presenting a low percentage of the energy transmitted in the environment. The natural broadcasting characteristic of an omnidirectional antenna limits both the medium use efficiency and the bandwidth reutilization efficiency. For these reasons, directional antennas were designed to fix the radio propagation directions. However, directional antennas do not eliminate the most significant disadvantage of omnidirectional antennas, i.e. interferences. The next step in designing antennas therefore has to be the deployment of antennas that can minimize these interferences. These antennas are called smart antennas. A smart antenna is an antenna composed of many antenna elements that are arranged in a linear, circular or planar configuration. The number of these antennas, N_s is a characteristic of the smart antenna. Currently, most smart antennas are deployed on base stations, but their implementation in laptops or cellular mobile phones is also feasible [1]. Their role is to increase the radio signal quality by optimizing radio propagation and to increase medium capacity by increasing bandwidth reutilization. Their smartness resides in the combination of the signals received within the smart antenna elements. This combination is ensured by the `DSP` (*Digital Signal Processing*). Mainly, this combination is based on the multi-path signal diversity [6].

There are two kinds of smart antennas: switched beam antennas and adaptive array antennas. A switched beam antenna generates a multiplicity of juxtaposed beams, the outputs of which can be switched to either a single or to many receivers. The role of the DSP in the switched beam antennas is limited to detecting the higher radio signal level and consequently to choosing a specific beam for transmission or reception. The DSP also has to switch from one beam to another when the users are moving within the network. Note that in this kind of smart antennas, the beams are fixed and predetermined.

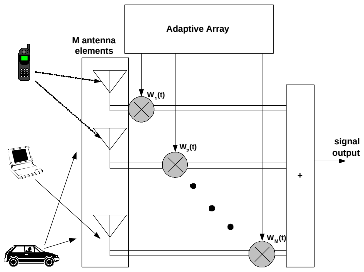

Figure 1: Smart antennas.

In an adaptive array antenna, which is more complex and advanced than a switched beam antenna, the beam structure is adapted to the surrounding signals by steering the beams toward the bona fide signals while canceling the reception within the interference beams, as for example described in the Applebaum and Widrow algorithms [7]. We show in figure 1 a model example of a smart antenna where $W_i(t)$ represents the weighting factor associated with the signal received within the antenna element i at the time t.

To resume the difference between switched beam antennas and adaptive array antennas, the switched beam antennas focus their smartness on detecting the higher radio signal level whereas the adaptive array antennas benefit from all the information received within all the smart antenna elements and use it to optimize the signal output via a weighting system that adjusts the reception level within each smart antenna element.

3. Related work

The proposed broadcast techniques in the literature can be categorized into four families [15]: simple flooding [2, 5], probabilistic broadcast [14], location based broadcast [14] and neighbor information broadcast [3, 4, 8, 9, 10, 11, 13].

As mentioned before, flooding represents a simple mechanism that can be deployed in low density or highly mobile networks.

The probabilistic broadcast is similar to flooding except that nodes have to retransmit the broadcast packet with a predetermined probability. In fact, the nodes share some neighborhoods and there is no need for all the nodes to participate in the broadcast packet retransmission. Randomly choosing the nodes that have to retransmit can improve the bandwidth use without influencing the reachability. A probabilistic broadcast technique based on counters is proposed in [14]. In this technique, the counter deployed by each node in the network makes it possible to count the number of times that a broadcast packet is received by this node during a `RAD`. If this number does not exceed a specific threshold after the expiration of the `RAD`, the broadcast packet is retransmitted. Otherwise, the broadcast packet is simply thrown out.

In the case of location based broadcast techniques, a node x retransmits the broadcast packet received from a node y only if the distance between x and y exceeds a specific threshold. Another approach based on `GPS` considers the coverage (in terms of nodes that can potentially receive the broadcast packet) that will be added by a potential retransmission. Retransmission then only occurs if this coverage exceeds a specific threshold.

The information on the neighborhood also makes it possible to minimize the number of nodes participating in the broadcast packet retransmission. [3] uses the information on the one hop neighborhood. Node A, receiving a broadcast packet from node B compares its neighbors to those of B. It retransmits the broadcast packet only if there are new neighbors that will be covered, *i.e.*, and that will receive the broadcast packet. Other broadcast protocols are based on the the 2 hop neighborhood information. [3, 8, 9, 10, 11, 13] propose similar techniques. The protocol used in [9] is similar to the one proposed in [3]. The difference is that in [3] the neighborhood information is sent within HELLO packets whereas in [9] the neighborhood information is enclosed within the broadcast packet.

In [11] and [3] HELLO control packets are used to make it possible for each node to be informed about the 2 hop neighborhood. If node A wishes to retransmit a packet it can compute the set of nodes among its 1 hop neighbors that can reach all of the 2 hop neighbors. When A retransmits the broadcast packet to its neighbors, only the nodes belonging to the computed set have to retransmit it since the other nodes will not reach new neighbors. The difference between the protocols proposed in [11] and [3] consists in the way the nodes are informed if they have to retransmit the broadcast packet or not, and also in the algorithms used to compute the set of nodes having to retransmit the broadcast packet. In [3] the computed set is enclosed within the broadcast packet, whereas in [11], the computed set is enclosed in the HELLO packets that are used for the OLSR routing protocol. The proposed protocol in [10] differs from the one proposed in [11] mainly in the fact that the computing of the set of the nodes having to retransmit the broadcast packet is done at each broadcast transmission and not at the frequency of the HELLO packets. Moreover, the computation of the set covering the 2 hop neighborhood takes into account the information on the last node retransmitting the broadcast packet to minimize the size of this set. In [8] the minimization of the size of the set covering the 2 hop neighborhood considers a certain priority for nodes belonging to this set. A priority system is also used in [13] where the priority is proportional to the number of neighbors.

The study carried out in [15] showed that the probabilistic and location broadcast protocols are not scalable in terms of the number of broadcast packet retransmissions. The neighborhood based broadcast techniques perform better by minimizing the number of nodes participating to the broadcast packet retransmission. The most significant disadvantage of these protocols is that they are sensitive to the mobility that does not guarantee the exactitude of the information on the neighborhood.

In one of the first studies on the improvement of smart antennas' broadcast performance, we have kept the use of the information on 2-hop neighbors to do broadcasting since it has been shown in [15] that broadcasting based on this information is more efficient than the other broadcast protocols.

4. Broadcasting with smart antennas

4.1. Assumption

Each node is provided with the angle table that contains the transmission angles of all neighbors. We keep the function of HELLO packets to provide the 2-hop neighbor information to each node. Compared to omnidirectional antennas, the difference is that we enhance the 2-hop neighbor information. With smart antennas, a node cannot only know about its neighbor identities but also know about the transmission angles toward these neighbors. Indeed, each node is informed about the transmission angles to communicate with its neighbors, and also the transmission angles used by these neighbors to communicate with its 2-hop neighbors. Each node therefore includes the identities of its neighbors in the HELLO packet and the transmission angles relative to these neighbors. In the following, we propose two broadcast approaches based on smart antennas.

4.2. A first broadcasting approach

We suggest to adapt the algorithm proposed in [11] for smart antennas. Based on the 2-hop neighbor information, each node selects from its neighbors the set of nodes responsible for retransmitting the broadcast packet. In [11], the MPR selection is based on the maximum coverage criterion. The coverage in this context concerns the nodes that can receive the broadcast packet. A node is elected an MPR if it covers the largest number of nodes when compared to the other candidates. These last are its neighbors and their coverage is calculated on the base of omnidirectional antennas. In our first approach, the number of candidates is multiplied by the number of antenna elements of the underlying smart antenna. If Δ represents the number of neighbors of a node x, then the number of candidates to be an MPR of x is equal to $N_s\Delta$. In fact, we do not choose a node as an MPR to retransmit into all directions but we choose a node as an MPR to retransmit into specific directions. Our algorithm is formulated in the following.

Let x be a node that wishes to calculate $MPR(x)$ which is the set of its MPRs. The set $N(x)$ represents its neighbors and the set $N_2(x)$ represents its 2-hop neighbors that contains no nodes of $N(x)$. $Coverage(x, y, \alpha)$ represents the number of nodes covered by a neighbor y of x within the angle α. (y, α) represents a candidate to be an MPR of x. The algorithm 1 represents our proposed algorithm to calculate the set of MPRs adapted to smart antennas.

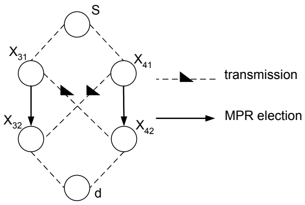

Figure 2: Broadcasting with smart antennas: scenario 1

Retransmission rule. Similarly to the native MPR broadcast technique, each node receiving a broadcast packet for the first time from a node of which it is an MPR within some specific angles has to retransmit this packet within these angles. If a packet is received more than once, it is neglected. However, we add another retransmission rule to our first broadcast approach to guarantee that our algorithm will ensure that all the nodes in the network will receive the broadcast packet. With the new rule, each node that is an MPR of the node from which it receives the broadcast packet has to retransmit within the specific angles calculated by the algorithm 1 and also within the angles that cover its own MPRs. This is to ensure that cases similar to the one presented in figure 2 are taken into account. In this figure, S is the source of the broadcast packet. A dashed line points to a link within a specific angle. In this case S chooses X_{31} and X_{41} as MPRs in the respective directions of X_{42} and X_{32}. X_{31} and X_{41} respectively chooses X_{32} and X_{42} as MPRs to reach *d*. In this case, if none of them retransmits within the angles to reach their MPRs also, node d will not receive the broadcast packet.

4.3. A second broadcasting approach

We propose a second broadcast approach which corresponds to a slight modification of the algorithm [11]. In this approach, the MPR election is kept the same as in [11]. We change only the retransmission rule. Each node receiving a packet from a node for which it is an MPR will not retransmit to all its neighbors. In fact, we assign a set of transmission angles, which have to be used in the retransmission, to each node y which is an MPR of a node x. In other terms, as in the algorithm 1, each node is elected to transmit in specific angles and the only difference is that the election of MPRs is ensured

Algorithm 1: `MPR` election

```
foreach $\alpha_i$ of the $N_s$ angles do
    foreach $y$ of $N(x)$ do
        Compute $Coverage(x, y, \alpha_i)$;
Select as MPRs the $(y, \alpha_i)$ which are the only nodes to provide reachability to a node in $N_2(x)$;
while $N_2(x)$ is not entirely covered by the elected MPRs do
    foreach $\alpha_i$ of the $N_s$ angles do
        foreach $y$ of $N(x)$ where $(y, \alpha_i)$ is not a MPR do
            Compute $Coverage(x, y, \alpha_i)$;
    Select as an MPR the $(y, \alpha_i)$ such as $Coverage(x, y, \alpha_i)$ is maximum;
```

before the election of the specific angles.

Retransmission rule. With this approach, our aim is to not use the rule with which a node y, receiving a broadcast packet from a node x, has to retransmit the packet within all angles α where (y, α) is an MPR of x. Remember that with the first approach, each MPR node has to retransmit within the angles for which it is an MPR and also within the angles that make it possible for it to reach its own MPRs.

"Order" definition. Let Δ and Δ_2 respectively be the set of neighbors and the $2-$hop neighbors of a source S. Let us denote X_{i1} a node of Δ and X_{i2} a node of Δ_2. S chooses its MPR based on the maximum coverage criterion. This means that there is a selection order. We say that X_{i1} is of an order superior to X_{j1} if it is chosen by S before this last one chooses X_{j1}. We say also that X_{j1} is of an order inferior to X_{i1}.

Assume that d is a node located at a 3 hops distance from the broadcast packet source S. Two cases are present: there is a unique path to reach d (via X_{22} for example) or d is a common neighbor to nodes that are at a 2 hops distance from S. In the first case, d is necessarily a neighbor at a 2 hops distance from one or many nodes X_{1i}. X_{22} certainly is an MPR for these X_{i1} to reach d. Plus, X_{22} is reached since it is a neighbor at a 2 hops distance from S.

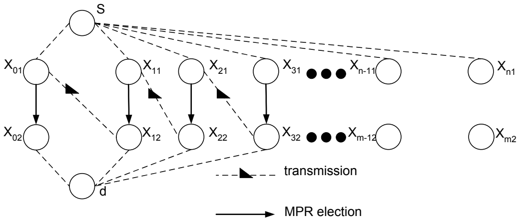

Figure 3: Broadcasting with smart antennas: scenario 2

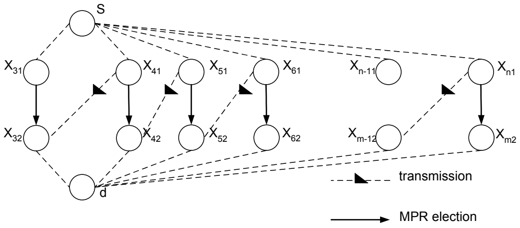

Figure 4: Broadcasting with smart antennas: scenario 3

In the second case, assume that d is a common neighbor to some X_{i2}. Assume that X_{32} receives the broadcast packet from a node X of which it is not an MPR to reach d. Two scenarios are possible in this case. (1) X can be of an order that is superior to the one of X_{32} (for example X_{32} from X_{21} in figure 3) or (2) it is of an order inferior to the one of X_{32} (for example X_{32} from X_{41} in figure 4).

(1) Since d is a neighbor at a 2 hops distance from X_{21} then X_{22} exists which is the MPR of X_{21} to reach d. If X_{22} also does not receive the broadcast packet from X_{21} of which it is an MPR for d but from a node X_{11}, an MPR of X_{11} must equally exist to reach d.

(2) Since d is a neighbor at a 2 hops distance from X_{41} then X_{42} exists which is the MPR of X_{41} to reach d. If X_{42} also does not receive the broadcast packet from X_{41} of which it is an MPR for d but from a node X_{51}, an MPR of X_{51} must equally exist to reach d.

In both cases presented above, and as illustrated in the figures 3 and 4, if a neighbor of d receives the broadcast packet from a node Y_1 that is not an MPR of the packet source X, a node Y_2 exists that can reach d by its MPR. Y_2 is of an order superior (figure 3) or inferior (figure 4) to the one of Y_1.

However, we should remark here that the scenario illustrated in figure 5 in which d cannot be reached, is possible with our broadcast algorithm. Indeed, in this figure X_{32} and X_{42} receive the broadcast packet from X_{41} and X_{31} respectively. They will not retransmit the packet since the respective MPRs of X_{31} and X_{41} are X_{42} and X_{32}. The election of MPRs in our approach requires that there is a coverage order that has to be applied to X_{31} and X_{41}. Let us take the example in which X_{31} is of an order superior to the one of X_{41}. X_{31} uses transmission angles to reach X_{32} but this last receives the broadcast packet from X_{41} before X_{31}. Plus, X_{41} uses the transmission angles to reach X_{32} and other nodes but not X_{42} since this last is covered by X_{31}. Therefore, we propose to add another rule to this approach. Each node that is an MPR of the node from which it receives the broadcast packet, has to retransmit within the specific angles calculated by the MPR computing algorithm and also within the angles that cover its own MPRs.

We thus conclude, that adapting the MPR broadcast technique to smart antennas is not categorical. In both approaches proposed above, we have to add rules to

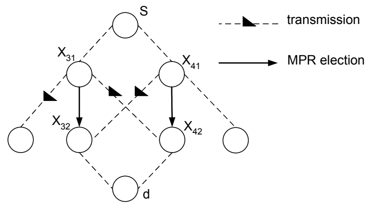

Figure 5: Broadcasting with smart antennas: scenario 4

Main lobe gain	Beamwidth	Side lobe gain
$0dB$	60°	$-7.4dB$
$0dB$	40°	$-7.6dB$

Table 1: Antenna pattern parameters used in the simulations

guarantee that we can reach all nodes in the network.

5. Performance evaluation

5.1. Antenna patterns

In the simulations we assume that switched beam antennas are used within all the nodes. We adopt the antenna model and beam steering introduced by Ramanathan [12]. The antenna patterns consist of a main lobe of a gain g_m and a beamwidth θ_m and a sidelobe of a gain g_s and a beamwidth $(2\pi - \theta_m)$. Table 1 illustrates the patterns used in our simulation. The number of smart antenna elements is set to 24. These values make it possible to cover the omnidirectional neighborhood (360°) and to multiply the number of candidate transmission angles. Please refer to [12] for more details about the antenna pattern model and beam steering.

5.2. Simulation environment

We simulated different broadcast flows, from 5 to 10 CBR flows. Each flow is characterized by a packet of a size equal to 512 bytes transmitted every 100 milliseconds. Each broadcast traffic source continues its broadcast during 10 seconds which corresponds to the simulation time. 20 seeds are used for each result presented next. We run simulations in networks with sizes 25 and 49 nodes.

We measured the reachability, the number of collisions per node, the number of transmissions in the network for each broadcast packet and the number of times a broadcast packet is received within a node. The reachability is represented by the ratio between the number of broadcast packets and the number of effective delivered packets.

Remark. In this paper, we do not consider the cost incurred by the transmission of control packets for the MPR election.

We have simulated four broadcast approaches. In the figures, ”Flooding broadcast” points to the flooding approach, ”omni MPR broadcast” points to the MPR broadcast approach based on omnidirectional antennas, ”smart broadcast algorithm 1” points to the first broadcast approach based on smart antennas and ”smart broadcast algorithm 2” points to the second approach based on smart antennas.

5.3. Simulation results

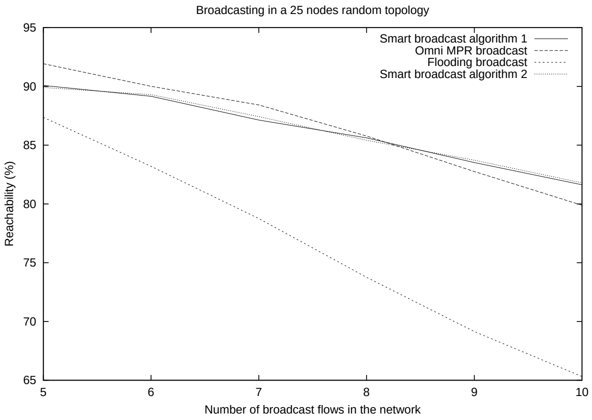

Figure 6: The reachability in different broadcast approaches

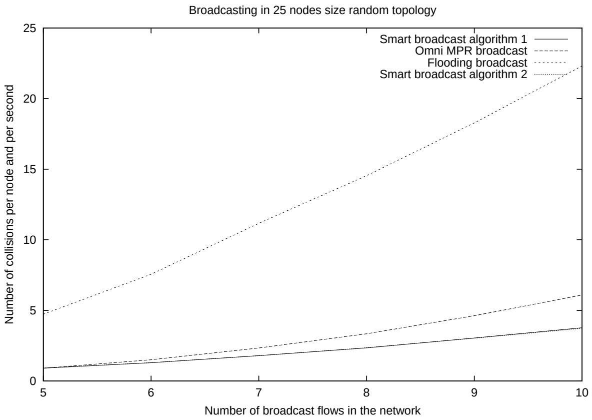

Figure 7: Number of collisions per node and per second in different broadcast approaches

Figure 6 represents the reachability as the function of the number of broadcast flows in the network within a network of 25 node size. We can remark that the use of smart antennas shows the same high reachabilities as the use of omnidirectional antennas when applying the MPR technique for broadcasting. Note also that both proposed broadcast algorithms in this paper show the same reachabilities results despite the fact that the second approach is theoretically better than the first approach. In the details we can also see that smart antennas present slightly better reachability than omnidirectional antennas when we increase the number of broadcast flows and slightly lower reachabilities when reversed. This is due to the negative effects of increasing retransmission redundancy (remember that with omnidirectional antennas we have more redundancy than with smart antennas) when the number of broadcast flows increases. Indeed, this increases the number of collisions in the network as can

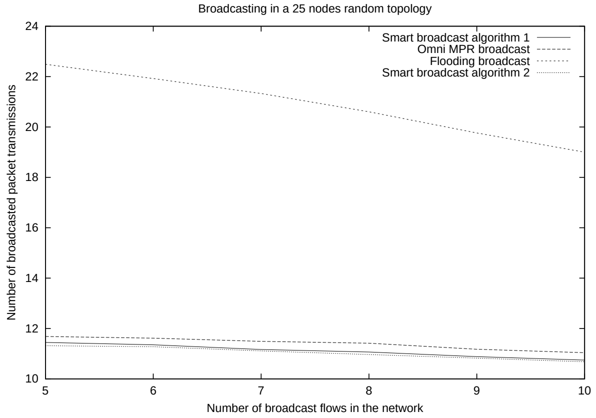

Figure 8: The number of broadcast packet transmissions in different broadcast approaches

be noticed in figure 7. We have to note here that the redundancy used with omnidirectional antennas does not correspond to a larger number of MPRs but rather to a larger number of nodes covered by an MPR. This is illustrated in figure 8 presenting the number of transmissions in the four simulated approaches. Note that both MPR based approaches show the same number of transmissions.

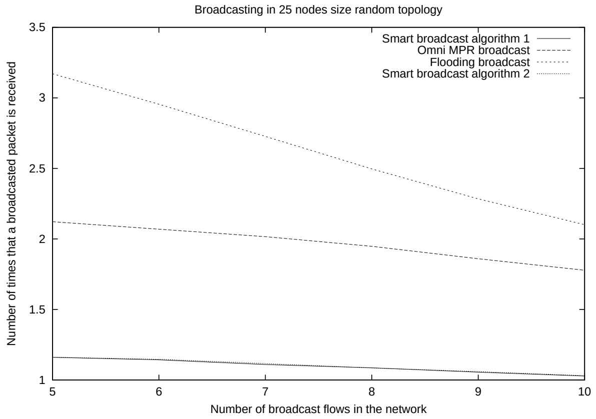

Figure 9: The number of times a broadcast packet is received in different broadcast approaches

We now consider another performance metric, that is the number of times a broadcast packet is received within a node in the network. The corresponding simulation result is presented in figure 9. With smart antennas we can observe that this number is almost equal to 1 whereas with omnidirectional antennas, a node receives the broadcast packet an average of 2 times. Smart antennas thus have the advantage to save battery power used for unnecessary broadcast packet reception, and also the advantage to free the medium when the transmission is into specific directions.

6. Conclusion

Based on our study of the performance of ad hoc networks with smart antennas, we arrive in this paper at the conclusion that these smart antennas improve broadcast protocol performances in ad hoc networks when compared to omnidirectional antennas.

Our study on broadcast protocols is based on the fact that the broadcast characteristic of the radio medium is the source of redundant broadcast packet reception observed in broadcasting protocols. In this context we propose in this paper the optimization of a current broadcasting technique based on the 2 hop distance neighbor information. The idea of our approach is to orientate the broadcast packet retransmission to only concerned directions. We show that adapting an omnidirectional broadcast protocol to smart antennas is not obvious. Simulation results show the capability of smart antennas to save nodes in the network from receiving the same broadcast packet many times over while keeping the same reachability as omnidirectional antennas. This ensures a better utilization of the power battery and the radio medium.

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