A Location-aware Routing Scheme for Wireless Mesh Networks using Directional Antennas

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Abstract: - This paper addresses the problem of neighbor discovery and route computation in wireless mesh networks where the wireless routers are equipped with directional antennas. Here we take advantage of the directional antennas capabilities to estimate the position of nearby nodes located in the first-hop neighborhood. The algorithm developed spreads the node's position information through the network using an efficient flooding mechanism and based on this information each node within the network can calculate the power and direction required to reach nodes on the second or third hop using a directional beam instead of an omnidirectional beam.

Key-Words: - wireless mesh networks, routing protocols, directional antennas, neighbor discovery

1 Introduction
A wireless mesh network (WMN) is a data network that implements the paradigm of multihop relaying to deliver data packets using wireless links. These networks have attracted much attention in the research community due to its potential to become a key technology for the development of wireless broadband access in scenarios where a fast deployment, low-cost network infrastructure is required. Most of the nodes that are part of these networks are static or have a reduced mobility thus the routing protocols are designed to increase the network throughput and reduce the end-to-end delay instead of deal with node mobility. Moreover, directional antennas can focus electromagnetic energy in a specific direction and have been considered as a complementary technology that is capable of improve the performance of WMNs because they minimize co-channel interference, enhance coverage range and provide spatial reuse.

The majority of the researches previously undertaken have analyzed the impact of directional antennas in the WMNs in terms of medium access control, power consumption and network throughput. For example, researchers in [1-3] addressed the problem of medium access control when using beam forming antennas, they proposed solutions that aim to exploit the multiple non-interfering channels by modifying the original 802.11 MAC while the work in [4] uses the same concept but the proposed solution does not require any modification on the 802.11 MAC neither new hardware.

Algorithms designed to control the energy irradiated during transmissions is another topic of growing interest. The authors in [5] have proposed a solution that uses the minimum power required for transmitting using directional antennas. Another paper [6] suggest to use directional antennas in combination with routing and scheduling algorithms for coordinating transmissions and find the shortest cost paths in order to be energy efficient. Improving network throughput motivated researchers in [7] to develop a directional antenna based routing protocol that uses direction information to route packets.

However, exploit the features of directional antennas in the network layer have recently attracted the attention of researchers. The work in [7] proposed a directional OLSR protocol that exploits the spatial separation of directional antennas in order to improve the throughput of WMNs using as a metric hop-count, remaining path bandwidth or measurement based metrics such as ETX[8]. In[9] the authors formulated a routing tree algorithm for smart antenna use in wireless mesh networks, the results shown that this solution provides a throughput improvement in the network. It is observed that most of the previous work done in routing protocols has been focused on investigate
the impact of directional antennas in network throughput or network connectivity, rather than finding a more efficient route. This is the major motivation in our work.

The rest of this paper is organized as follows: Section 2 states the problem that we are going to address, Section 3 presents the antenna model used in this work, in Sections 4 and 5 we present our neighbour discovery and routing mechanisms, in Section 6 we present and analyze the simulation results and finally in Section 7 we present the conclusions and establish future work.

2 Problem Formulation

2.1 Neighbor Discovery Mechanism

In a WMN, after nodes are deployed they need to discover their neighbors. Knowledge of its neighbors is essential for almost all routing protocols, medium-access control protocols and several other topology-control algorithms. In an ideal situation nodes should discovery their neighbors as soon as possible in order to reduce the energy consumption and also to allow other protocols (topology control protocol, routing protocol) to quickly start their execution [10]. Results in [11] showed that neighbor sensing can have a large impact on the performance of a routing protocol, especially in terms of packet loss and overhead. The amount of packet lost depends on both the data rate and the frequency of the discovery messages.

In the literature, we found previous work related to neighbor discovery in wireless mesh networks, most of the authors classified the neighbor discovery algorithms in Omnidirectional neighbor discovery and Directional neighbor discovery. In the first approach, all the nodes are equipped with omnidirectional antennas therefore irradiate energy in all directions (360°) to discover its one-hop neighbors. The latter assumes that all the nodes are equipped with directional antennas which could irradiate energy directionally or omnidirectionally as required in order to discover its neighbors. The authors in [12, 13] present algorithms for neighbor discovery in wireless networks where nodes have omnidirectional antennas. While the algorithm proposed in [13] can operate in asynchronous mode, synchronization is a requirement for the algorithm described in [12].

Finally, prior work also proposed neighbor discovery algorithms using directional antennas. In [10], the authors develop algorithms considering three strategies: directional transmission and omnidirectional reception (DO), directional transmission and directional reception (DD) and omnidirectional transmission and directional reception (OD). All these strategies first are evaluated considering a direct discovery algorithm, which means that a node discover its neighbors only when it successfully hears a transmission from that neighbor. Then the strategies mentioned before are evaluated considering a gossip-based discovery algorithm in which nodes "gossip" about each other's location information to speed up discovery. The gossip-based algorithm allow a node to discover its neighbors indirectly and also allows a node to discover multiple neighbors in one step. The results of this works showed that those differences help nodes to discover their neighbors significantly faster than with a direct-discovery algorithm. The main drawbacks with gossip-based algorithms proposed here are: First, this work consider only static wireless mesh networks and second: The authors assume that each node gets its location using a location device such as GPS and as was showed in the results of this work, if the number of nodes with GPS decreases the performance of the discovery algorithm also degrades.

In [14] the authors present a novel neighbor discovery algorithm with directional antennas considering the mobility of the nodes and improving the power consumption. For the first issue the frequency of the neighbor discovery is self-adapted according to the dynamics of the network. Secondly, to improve the power efficiency and reduce overhead, the protocol has the ability to limit neighbor discovery attempts in directions where no new neighbors are likely to be found. This work does not take in consideration multi-hop system and only consider discover one-hop neighbors.

2.1 Route computation supported in node position information

Since the first development of routing protocol for wireless networks, researches have shown their interest to support the routing decision based on the position of a node in order to increase the packet delivery ratio and reduce the end-to end delay. On the literature there are several implementations in both reactive and proactive routing protocols.

In [15] the authors propose a reactive routing protocol, Location Aided Routing (LAR) protocol which uses the position information obtained by a GPS sensor to limit the search for a route to the so-called request zone, determined based on the expected location of the destination node at the time
of route discovery. Simulation results indicate that using location information results in significantly lower routing overhead, as compared to an algorithm that does not use location information. Drawbacks of this approach are the need for GPS and the reactive nature of the protocol which increases the setup delay of a route.

In [16] the authors propose an algorithm to determine the estimated position of a node based in the information provided by smart antennas instead of employment of the GPS system. The routing protocol proposed is called Location Enhanced On-Demand (LEOD). The analytical and simulation results showed a better performance compared with other reactive routing protocol such as Ad-hoc On Demand Distance Vector (AODV) protocol [17]. However the drawback with this solution is the reactive nature of the protocol -because is based on AODV- thus the route setup time is greater than proactive routing protocols which may be not suitable when real-time applications are considered in a high node density scenario.

Recently in [18] the authors describe 2-way random neighbor discovery algorithms based on algorithms proposed in [10] two of which may still use omnidirectional antennas in certain stages of the algorithm and the other two uses directional antennas all the time. The drawback with this work is that does not consider the gossip based approach and for synchronization purposes assumes that the nodes are equipped with GPS sensors.

3 Antenna Model

In this work, we assume that each node has a multi-element antenna containing N elements, each antenna element has a coverage of $\frac{k\pi}{N}$ radians, the direction of the main lobe of each antenna element is considered as the main direction of the element, and the sidelobes are considered as despicable. Fig. 1 shows the directional antenna model used in this work. The antenna system is similar to the previously used in [15] and can operate in two modes: directional and omnidirectional but only one mode can be used at the same time. The omnidirectional pattern is formed by setting the antenna gain of each element at the same value thus the irradiated pattern resulting is a quite similar to an omnidirectional pattern. On the other hand the directional pattern is formed by selecting just one antenna element pointing in the desired direction, setting its gain to $g_d$ and placing nulls in all other directions. The latency when passing from one mode to other is despicable. A node stays in omnidirectional mode while it is on idle status to receive the signal from all directions because it is almost impossible to know where the signals may come from. Also omnidirectional mode is used when a node wants to transmit the signal to all directions. Whereas, a directional mode is used when it can know the direction of coming signal and when it transmits the signal directionally. When a signal is received, we assume that the node is capable of determine the angle of arrival and create a registry of all the nodes surrounding with their respective angles of arrival. Finally, we also assume that the transmission power is fixed in both modes, therefore the transmission range in directional mode is longer than in directional mode.

4 Directional Scheme for Routing in Wireless Mesh Networks

4.1 Neighbor Discovery Mechanism

One of the key characteristics of WMN is the self-configuring capability, which means that the network does not need a centralized entity to perform the tasks required to keep the network functioning. Neighbor discovery is one of the self-configuring task that is performed once nodes are deployed, this mechanism allows each node to discover their surrounding neighbors. Then, this information is used by the upper layer protocols such as topology control, medium access control and routing protocol to perform their own tasks.
The mechanism proposed in this paper works in the following way: When a new node is placed in the network or when a node's status changes it performs a node discovery procedure as described in the AODV RFC [16], here we modified the omnidirectional procedure to incorporate directional antennas. First, the node sends HELLO packets in all directions using all the antenna elements in the node as shown in Fig. 2. Then, when the nodes inside the coverage area of the sending node receive the HELLO packet they determine the direction of arrival (DoA) and store the direction for future use as needed. It is possible to discover the direction of the node because the omnidirectional pattern on the receiving nodes is also constructed by setting the gain of each antenna element at the same value, thus the receiving node knows the antenna element in which the signal was received and then calculate the direction of arrival assuming that all the nodes are installed using a common point of reference (common north) as shown in Fig. 3.

The signal strength received at the antenna element in the receiving node is used to estimate the distance between the neighbor nodes. This distance is calculated using a propagation model, in this paper we are going to use the Eq. 1:

$$P_R = \frac{G_R G_T}{4\pi R^2} \times A = \frac{G^2}{(\lambda d)^2} G_T P_T G_R$$  \hspace{1cm} (1)$$

The distance along with the direction of arrival is stored in the node's memory, one registry for each neighbor discovered. Once the receiving node processes the HELLO message, it sets the radio on transmission mode and sends back an ACK in the same direction as received using the same antenna element where the HELLO message was received as showed in **Erreur! Source du renvoi introuvable.** Now the node that sent the initial HELLO discovers the existence of a neighbor node and using the same procedure explained before can determine the direction and distance to the node. This relative location information is used to approximate the position of the destination node using a geometric calculation.

**4.2 Route Discovery procedure**

The objective of our algorithm is to offer an alternative, more efficient route with less number of hops between source and destination compared with the route offered by traditional AODV. The hop reduction is possible due to the use of directional radiation patterns instead of omnidirectional patterns and by sharing the position of the neighbours of neighbors nodes (nodes in the second hop). To perform this procedure is necessary to modify the packet structure of RREQ. Basically, we need to add two sets of data: one for the node $j$ which is the target of the directional link and other for node $i$ which is the intermediate node and potential next hop if the optimization is not possible. The optimized path found by optimization procedure is also included into RREQ. The following fields should be included in the RREQ:

- $(Tx_i)$: Transmit power of node $i$
- $(DoAi)$: Direction of Arrival of node $i$
- $(Tx_j)$: Transmit power of node $j$
- $(DoAj)$: Direction of Arrival of node $j$
- $(OptPath)$: Path which is optimized

Fig. 4 shows the flooding of RREQ with our proposed mechanism. Initially, source node $S$ initiating RREQ saves the direction and power used to reach the next neighbor ($T_5$ and $D_5$) into the $Tx_i$ and $DoAi$ fields, then it generate the RREQ packet. $Tx_j$ and $DoAj$ are set to zero. $OptPath$ is same as AODV route request option header, $\{S\}$. Then node $A$ receives de RREQ and checks if it is the destination, if not; node $A$ rebroadcast the RREQ including the $Tx_j$ and $DoAj$ required to reach the destination.
next hop neighbor. Notice that as node A did not receive any information about previous neighbors in the route, A did not calculate an optimized path. When node B receives the RREQ packet it calculates the link cost of the directional link and if it is under the threshold, the route is optimized and the intermediate node is excluded from the optimized route.

Next, node C receives the RREQ and performs the same procedure described previously, but in this case the directional link is unreachable so the intermediate link is not deleted from the route and the RREQ is broadcasted.

Finally, the RREQ arrives to the destination with two routes available: the traditional AODV route and the optimized route, then the RREP is sent back with the information of both routes so the source node can use the best available.

Fig. 4 Route discovery with directional antennas

5 Performance Evaluation

We use the MATLAB simulation tool to simulate our proposed algorithms and comparing them with AODV which is a commonly used protocol for wireless multihop networks. We simulate our scenarios in a bounded area of 1500x1500 meters, with constant bit rate (CBR) traffic for data communications, transmission range is set to 250m in omnidirectional mode. The power irradiated is fixed in both cases and the gain in omnidirectional mode $G_o$ is 0.0 dBi (no gain) and the maximum gain possible in directional mode is 15.0 dBi. The nodes were placed randomly in three different scenarios and the number of nodes was set up to 15, 25 and 50 nodes.

In all the cases, source and destination nodes were also selected randomly. In Fig. 5 black solid lines represents the traditional route calculated by AODV and dotted line represents the optimized route calculated by our algorithm. Knowledge of node's position in the second hop enables intermediate nodes in a route to reduce the number of hops as seen in Fig. 5(a) and (b).

![Network Layout used in simulation](Fig. 5 Network Layout used in simulation)

(a) 15 nodes network (b) 25 nodes network

The effect of hop reduction can be found in Fig 6(a) and (b), the average end-to-end delay is consistently lower in our directional AODV (D-AODV) compared with traditional AODV. We can also notice in Fig 6(b) that the optimization performed by our D-AODV overcomes AODV even if the distance between source and destination increases. This is because as longer is the path from source to destination there are more hops that can be reduced, and by the fact that the hops are replaced by directional links that are less likely to suffer form interference.

![Average end-to-end delay](Fig. 6 Average end-to-end delay)

(a) 25 nodes network (a) 50 nodes network

Finally, the performance in terms of average end-to-end delay was evaluated for the three scenarios: 15, 25 and 50 nodes. Fig 7 shows that when increasing the number of nodes in the network our proposed algorithm provides a route with less end-to-end delay than the traditional AODV algorithm.
This is because, as the longest route is, the proposed algorithm has the opportunity to reduce more hops and therefore decrease the end-to-end delay.

Fig. 7 Performance comparison between AODV and D-AODV for three different scenarios

6 Conclusion
In this paper we addressed the problem of neighbor discovery and route calculation using directional antennas with the aim of reducing the number of hops between source and destination nodes. The simulation results showed that the proposed solution offers an optimized route with less hops and by consequence with less end-to-end delay. Future work is necessary including more simulations considering partial mobility of nodes and including throughput metrics in the routing decision algorithm.

References:


