Distributed Web-Topology Formation with Directional Antenna in Mesh Environment *

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Abstract

Recent developments on the directional antennas have given a new dimension to revisit the problem of how to design more efficient topology formation and control protocols for a wireless mesh network (WMN). The WMN can be thought as the commercial extension of mobile ad hoc networks, forming a wireless multi-hop backbone network with static nodes such as mesh routers. Topology control is required by all the networks to increase the network performance. In order to improve the overall network performance and robustness, these static nodes in WMNs can be assumed to be equipped with multiple radios using directional antennas. The neighbor discovery part of the topology formation is done by the directional links to increase the network range. Our web-topology scheme forms the topology based on maximum 2+1 degree bounded nodes. The formation of this topology is robust and efficient, and yields better performances than the network without the topology control.

1. Introduction

Recent developments on the directional antennas have given a new dimension to revisit the problem of how to design more efficient topologies and control protocols for a wireless mesh network (WMN) [1, 3]. The WMN can be thought as the commercial extension of mobile ad hoc networks, forming a wireless multi-hop backbone network with static nodes such as mesh routers. In order to improve the overall network performance and robustness, these static nodes in WMNs can be assumed to be equipped with multiple radios using directional antennas [2].

However, to fully leverage the potential benefits of directional antenna based mesh backbone networks, the issue of neighbor discovery and topology formation should be addressed properly. Ref. [1] proposes a TDMA scheme forming a topology with directional communications. Data transmissions in this centralized network surely have shorter path across the network but increases the hop count if the degree of connectivity is low. The main disadvantage of this protocol is that without the power control mechanism, the network could get partitioned while limiting the node degree.

The motivation behind our approach is to bound the node degree while reducing complexity and still maintaining the network connectivity. Our research caps the node degree to three in the backbone network forming the robust topology. Thus formed topology is scalable and communicates with minimum hop counts. The worst case performance comparison is with the topology with minimum degree nodes. The best case would be achieving the same hop count as of the [6]. The directional antenna equipped in mesh routers and gateway has sectors for the directional transmissions. The individual transmission on each sector for neighbor discovery and topology formation certainly has some delay in the topology formation. Mesh routers can tolerate some delay at the topology formation phase. With the efficient algorithm, this delay will not degrade the network throughput.

2 Background and Related Work

Locating and tracking applications, military defense applications and many other types of applications have been the key areas for the directional antenna. Especially with power saving mechanisms, the transmission range is increased for large network connectivity. This will introduce some interference to the neighboring nodes. Many solutions have been put forward for controlling the interferences.

Transmission power control is one of the key solution given in [7]. Adjusting the power of the CTS/DATA/ACK by observing the power of the RTS packet can be done by

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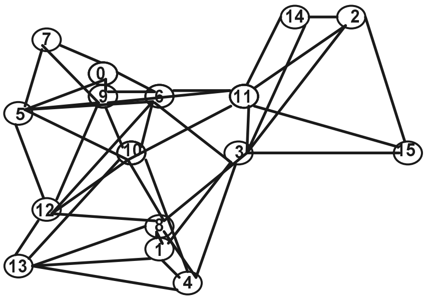


Figure 1. Full connected network with 16 nodes Network

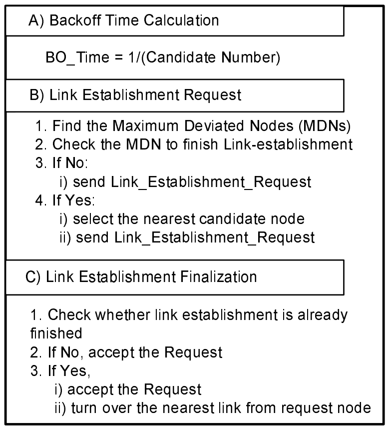


Figure 2. Two-degree link Establishment Algorithm

correlating with each other for the successful communication. This method controls the interference of the communicating nodes compared to the traditional power control transmissions. This should create a scalable robust network with reduced complexity.

Dong et al [6] suggests the initial topology formation using Backlink-based Algorithm (BBA). It forms a tree structure with the two-degree connectivity while maintaining the network connectivity. Some of the nodes construct extra links known as the backlink so that any transmission needed to follow the long routing path for the destination can use this link and reduce the hop count.

Directional communication is prone to the deafness problem due to the lack of the state information of the neighbors. Therefore, a new mechanism of exchanging the state information of the neighbor after RTS/CTS exchanges is introduced [8]. The transmission is done directionally to neighbors which could be potential source nodes in the near future. When a packet arrives, the node will analyze the history of the transmissions it had received so far, and controls the scheduling so that packet collision is avoided and the waiting time for the channel to become idle is reduced. This protocol outperformed the existing directional MAC protocols when the traffic flow is large.

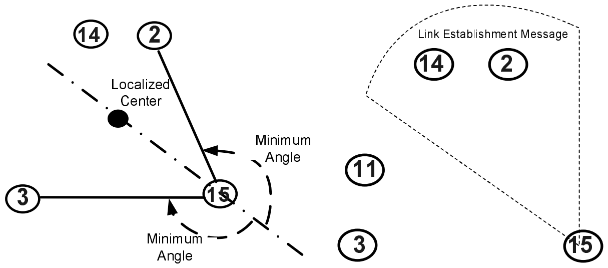
Ref. [9] exploits the MAC scheduling and reservation scheme for effective communication in wireless ad hoc networks using TDMA. The basic advantages lie on the locally gathered information and allocation of the slots dynamically to the different links. With little overhead it also has a power control scheme during the neighbor discovery phase, reservation phase as well as in data transmission phase. The basic advantage here is the full utilization of the directional antenna in all the phases.

3 Proposed Scheme - Distributed Topology - Web-Topology Formation

All the mesh routers and gateways of WMN are assumed to have x directional mesh radios and GPS. For the robust topology, we assume $x = 3$. Minimum k-connected network is considered as being the energy efficient and it can utilize the network resources. Two directional mesh radios are used to form the minimum k-connected network and one radio is remained for the web-topology formation. The beam width of the directional radio is $360°/n$ for n sectors. All n sectors are required to directionally broadcast HELLO messages (including node ID, transmitted antenna sector and location information from GPS) to discover neighbors. On receiving the HELLO message each node maintains its own neighbor table with received information. All the neighbor nodes from this table are termed as a candidate node. A fully connected network topology with 16 nodes is shown in Fig. 1. Clearly, this topology may not be suitable due to the interferences from the ongoing communication. Hence, we propose a novel method for creating so-called "$web - topology$". The proposed scheme is divided into two phases as described below:

3.1 Phase I: Two-degree Link Establishment

All neighbor nodes whose HELLO packets are received are the termed as the candidate nodes for the formation of the two-degree link establishment. All the nodes will go to the backoff state with the equation shown in Fig. 2a. The nodes which finishes the backoff timer and will start to find the maximum deviated nodes (MDNs) as shown in Fig. 3a from the localized central point. MDN is



(a) Angular method to find the maximum deviated nodes

(b) Link request process

Figure 3. Two-degree link establishment phase

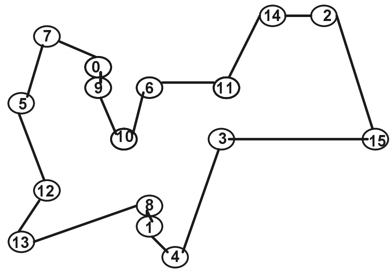


Figure 4. Link Establishment after phase I in randomly network of 16 nodes

found by getting the localized central point of the candidate nodes and find the deviation of the nodes from this angle. If the nodes are not maximally deviated, it will ignore and then go the next node. It will send the $Link\_Establishment\_Request$ to the MDN sector. Node N_{15} sends the $Link\_Establishment\_Request$ message from its directional antenna sector 3 to node N_2 as shown in Fig. 3b. The algorithm for link establishment request is shown in Fig. 2b. Node N_2 replies with the Acknowledgement message if there is no link establishment from other nodes in that sector as shown in Fig. 2c. If the requested node is already having two links to its neighbors then it will shift one link to the requesting node and connect itself also with this node. This maintains the all the links without the need of extra control messages. This ACK message is transmitted by all the sectors to inform the neighbors about the link formation. This will prevent others from forming link at this location.

Simultaneous transmissions are possible between the other nodes within the candidate nodes in different sectors for communication. If any requested node is not able to make the link then it will turn over the nearest link to request node.

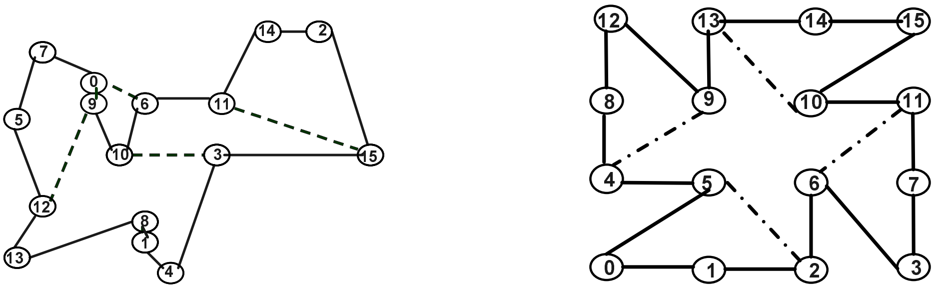
In case of the candidate nodes with the equal distance from the source, then new metric is needed used to choose the appropriate node to establish the link. The node will take the help of the time stamp of link establishment. This will ensure that the recently made link is not broken too often when other link is still available for the process. This situation arises in the grid topology where all the nodes are equally placed in the predefined area. The link establishment with the more than one nodes are possible. This metric helps to efficiently establish the link with the candidate nodes. Topology formation after the first phase is shown in Fig. 4. This topology is minimally connected which is not robust in comparison with Fig. 1. Clearly it requires less directional radios and more hop counts for a packet to reach the destination if any of the intermediate link breaks. In terms of the cost of the directional radio, this topology is the optimum solution with a very minimum maintenance of the network.

This topology is not always good for the all type of traffic. Most of the links are required to have a backup links incase of the link failures. If more links are broken then network is partitioned to two or more networks. Having one more radio can solve the partitioning problem then it is worth for a research. The added radio network and one more link to some of the nodes could make the link robust. This is the reason for us to propose a phase II to make a topology robust with minimum possible radios.

3.2 Phase II: Web-link Formation

In this phase all the nodes may choose one additional link from the remaining candidate nodes which it does not have a two-degree-link formation and is near to this node, and establish the link. The node, N_0, with highest candidate node count will send $Web\_Link\_Establishment$ message to the selected candidate node after waiting for a random backoff timer, if N_0 can have a new connection in the network. The nodes having a large number of candidates will have a liberty to choose the one of the remaining nodes after the first phase, by using backoff time scheduling. The farthest neighbor node from the sender will be responding to this message. On receiving this $Web\_Link\_Establishment$, the receiver will evaluate the following three conditions before sending the ACK message for the link establishment. Conditions for the web_link formation: i)There is no link in the same sector as request, ii) it doesn't have a third link and iii) request node is not two hop neighbor.

The ACK message is not sent if any condition is met. This ACK message is also sent in all direction so that all the 1hop nodes is informed about the web-link formation. All the other receiving node will now wait for their turn to send the $Web\_Link\_Establishment$ message after the expiry of their backoff timing.



(a) Link Establishment after phase II

(b) Full Link established 16 nodes grid network

Figure 5. Random scenario selected for the simulation with 6 sector directional antenna

Our approach is based on distributed algorithm with a local synchronization among the nodes by broadcasting a control packet in the network. The local synchronization is the information exchange between the neighbors about the completion of the link formation. Without all nodes completing the phase I, it is difficult to start the phase II as it is based on previous phase. In the distributive algorithm, it is difficult find the end of the phase I, so node in the localized neighbor with the largest backoff time will broadcast the control packet after forming the links. This will allow the nodes to start the phase II. This broadcast of the control packet may experience congestion due to control packets from all the nodes. The probability of having more nodes in the neighbors for the control packet transmission is very less. Only one of the nodes in a neighborhood broadcasts. In above network have four nodes capable of phase II as shown in Fig. 5a.

Using the distributed system over the centralized system depends upon the type of application. The distributive system is definitely good for some reason but also poses serious problems of complexity. So if the application cannot bear the highly complex system then the distributed system is not recommended. Whereas delay is low in the case of the distributed system where each of the nodes could take the minor decisions for the improvement. In our case each nods has a decision power to choose the nodes for the link. Within this process we can have a problem of optimization where distributive system is not so good at. Still reviewing all the above pros and cons, our system is doing well with the distributed fashion.

The topology formation on the 16 nodes grid topology is shown in Fig. 5b. In this figure, the all the nodes are placed in grid topology. The phase I link formation is explained in section 3.1, it follows the righthand rule to form the link if there are more than 1 nodes with the same distance. But web-link formation is not bounded with the rule so it can have the different web-link formation. In Fig. 5b, one instance can form web-link by four nodes but the ideal case would be forming the web-link minimum resources. Just by using two nodes for forming the web-link. Node N_{10} forming link with Node N_5 and Node N_9 forming link with Node N_6 by saving four radio resources to form the links. Our future work will be concentrating on making the more efficient web-link formation with the minimum resources utilization.

Web-topology is a distributed topology formation scheme with a maximum of 2+1 node degree. From Fig. 5 it is visible that the hop count is decreased than topology with two degree links.

4 Performance Evaluation

We now present the results based on the performance evaluation based on Qualnet simulation version 4.5 [12].

4.1 Simulation Environment

We have considered n static wireless nodes in a grid and random topology placed in 1000x1000m^2. All the nodes are equipped with the 3 directional wireless radios based on IEEE 802.11b specifications. The wireless radio are strictly operating on the directional mode for both the transmission and reception of the packets. The transmission range of the directional antenna is considered uniform. All the nodes are connected with the fixed power source so that the energy is depleted in the middle of the transmission so that the whole of the network is connected all the time. All the nodes which are having both the links will have point-to-point communication. The mesh portals need to have a direct communication with the other mesh portals as have higher data traffic. They are basically considered as a backbone nodes of the networks.

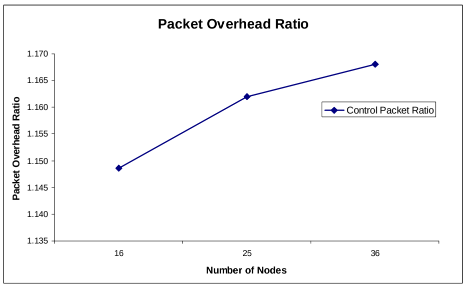


Figure 6. Packet overhead ratio for the topology formation

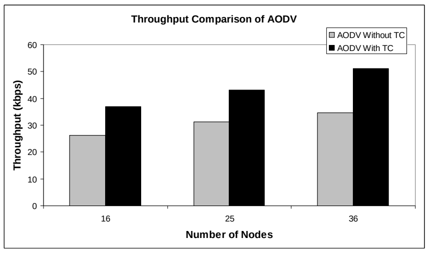


Figure 7. Throughput comparison with AODV routing protocol by applying web-topology scheme

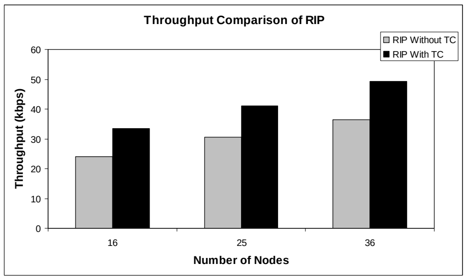


Figure 8. Throughput comparison with RIP routing protocol by applying web-topology formation

4.2 Simulation Results

Fig. 6 shows the packet overhead ratio which is required for the topology formation. In distributed web-topology with directional transmission requires $Link\_Establishment\_Request$, $Web\_Topology\_Request$ and $ACKmessages$. The ratio is taken with respect to the control packets required for the neighbor discovery with the omnidirectional transmission range. The figure shows that the number of overheads required for our protocol is not exceeding 20% of the control packets required by the omnidirectional communication. The advantage of spending these extra packets clearly visible with the transmission range of the communication. With the same transmission power as the omnidirectional communication, directional transmission range is larger and can reach to the distant nodes with the same power. Only one of the antenna sectors are active in communication at any given time and rest of the antenna sectors are in the receiving state. This will help the nodes to schedule the transmissions if more than one node has data packets to transmit via any given nodes. The scheduling can overcome the problem of deafness which is more prevalent in these kinds of directional communications.

Figures 7 and 8 show the throughput analysis of the distributed web-topology mechanism with and without Topology control (TC). CBR traffic is used for our evaluation as it has a constant traffic to the network. The CBR packets are generated in the range of few kilobytes to 1Mbps at maximum. We used 2 basic routing protocol, the Ad Hoc On-demand Distant Vector (AODV) [10] and Routing Information Protocol (RIP) [11] to compare our web-topology formation scheme. We first simulated both routing protocols on the simple omnidirectional transmission neighbor discovery with directional data transmission by modifying their codes for the directional transmissions. Then we run our algorithm with directional neighbor dicovery to form the web-topology. The information from this topology is used in the modified AODV and RIP protocol and throughput is recorded. The data collected from multiple simulations for both the simulations is compiled. Fig. 7 and 8 show that the routing protocol without the topology control is not giving the high throughput as compared to the topology informed routing protocol. Fig. 7 shows the increased throughput for the AODV with web-topology formation. With the extra information and links provided in the 2-degree bounded network, it is easy to get the channel without actually getting the interference from the nearby transmissions. There is about 40% increment in the throughput with our topology control scheme in AODV.

The directional link can support multiple transmissions with in the same regions by different nodes. With the normal directional transmission, nodes need to negotiate with the other nodes for the channel. This might take a long time due to the ongoing communication in the neighbors. This waiting time is one of the main factors of reduced throughput. The other reason for the reduced throughput is in the deafness of the nodes. Only one directional is active in case of the node transmitting the directional data. Any nodes within the range having data to transmit should will send the control packets to negotiate the transmission but it is not possible to do. The nodes need to come to the omnidirectional mode to receive the control packets. Our scheme has a modified version of the antenna used. We basically use the directional transmission but with all the sectors in the state of receiving. Since they are independent antenna elements at the each nodes, they can be used for listening to the channel for any messages for the nodes. If there is any messages, then the node will schedule the transmissions so all the data to the nodes are entertained. This gives an increase in the performance as shown in Figures 7 and 8. Though having only two active links with all the nodes and one extra link to some of the nodes only, we can have better management of the data giving the increased performance.

Fig. 8 also shows the similar figures for RIP protocol where the protocol has the information about the routing but not the dedicated routing path as given from our algorithm. In RIP we also got the similar results where the throughput is higher than the simple RIP protocol for directional antenna. This gives the clear edge of utilizing the directional transmission for the neighbor discovery where the little amount of control overhead can discover distant nodes and form a topology within very short span of time. Also with the topology information, the throughput of the network is increased and the congestion due to the ongoing transmission from the neighbors is also reduced.

5 Conclusion

Our web-topology formation algorithm is distributed and has maximum three degree of connectivity. This low degree connectivity is the key factor of easy network maintenance. As shown by the performance web-topology scheme is performed better than stand alone routing protocols. Our scheme is scalable and it can perform well in the large network size. The simulation result shows the increased performance as it have more nodes with the extra links for efficient packet routing. The simulation result showed that the AODV and RIP protocol with the topology formation performed better in terms of throughput. The network packet overhead is bit higher than of the normal transmission, but the aggregated performance of the system is still increased.

Our work is mainly with the static nodes but we will be working on the mobile nodes as well. This will increase the overall topology formation. The topology in the mobile nodes is prone to the link failures. Our future work will be focusing on maintaining the network connectivity with the mobile nodes and form efficient topology with minimum resource utilization.

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