Relation between Interference and Neighbor Attachment Policies in Ad-hoc and Sensor Networks

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Abstract

Neighbor attachment is the process of establishing links between nodes that on the physical layer are visible to each other. In ad-hoc and sensor networks many strategies can be followed to connect to adjacent nodes. A simple scenario would be to consider all nodes within the transmission range of a node as its neighbors. More sophisticated scenarios can establish neighborhood relations with a limited number of carefully selected nodes. Different neighbor attachment policies result into different network topologies at the link-layer. In any topology a packet sent from a node to one of its neighbors will experience interference, which is caused by simultaneous communications between other nodes in the network. Obviously, high levels of interference would severely disrupt communications and reduce overall network capacity. In this paper we examine how neighbor attachment policies can change the amount of interference experienced by network nodes. We will also show that Carrier-to-Interference ratio (C/I) is directly affected by neighbor attachment policies. Our study enables us to identify neighbor attachment directives that can reduce interference, or optimize C/I in large multi-hop ad-hoc and sensor networks.

1. Introduction

Neighbor attachment in ad-hoc and sensor networks directly affects the link-layer network topology. By adjusting some controllable parameters, such as transmission power and antenna direction, different topologies can be formed. A properly designed topology can reduce power consumption, remove low quality links, and improve routing efficiency in a multi-hop network. Especially innovative physical layer techniques, like antenna beam-steering and beam-forming, introduce new possibilities for neighbor attachment. For example, by using high-gain directional antennas, more neighbors can be detected in a specific direction, while at the same time interference with nodes outside the main antenna lobes are reduced.

The state-of-the-art literature related to topology control focuses mainly on life-time extension, hop-count reduction, or performance optimization (e.g. [1]), without taking into account effects of neighbor attachment on the amount of interference experienced in the network. In this paper we attempt to fill this knowledge gap by comparing four widely used neighbor attachment policies based on their interference imprint. The motivation for our work is the fact that interference has a direct impact on the capacity of a network. Consequently, our study paves the way to identify the suitability of each neighbor attachment policy to support different application types in ad-hoc and sensor networks.

The structure of this paper is as follows. In Section 2 we provide an overview of related work in this research domain. In Section 3 we describe the neighbor attachment policies considered in this paper and show how they affect the network topology. Our findings related to the amount of interference and resulted Carrier-to-Interference (*C/I*) ratios for different network topologies are presented and discussed in Section 4. In Section 5, we summarize a few major conclusions.

2. Related work

Several papers have already studied interference in ad-hoc and sensor networks. Here we provide a helicopter view of main approaches in these papers, and position our own research in relation to them. In [2] authors have looked at the impact of interference on the connectivity properties of a dense network with random deployment of nodes. This line of work is pushed forward in [3] where authors discuss the effect of interference on the link quality and connectivity of large networks. Although much attention is given to the connectivity problem in ad-hoc networks, effects of interference on capacity are only discussed by approximation. Also, in the calculation of interference in [3], the dependency of interference on the location of nodes inside the network is not considered. In [7] authors represent an approach to preserve network connectivity based on the principle of maintaining the number of physical neighbors of every node equal to or slightly below a specific threshold value. They show that interference remains bounded under this approach. Here we show that interference always remains bounded in ad-hoc networks regardless of the node degree. This finding matches with previously found results in [4]. In [5], authors give algorithms to construct a network topology for wireless ad-hoc networks such that the link interference in the resulted topology is either minimized or approximately minimized. Having the same objective of minimizing interference, many works (e.g. [6]) have suggested construction of topologies that require low transmit power. However, we show here that minimizing interference on the link level is not the sufficient condition to guarantee maximum Carrier-to-Interference ratio (*C/I*), and consequently maximum capacity.

In summary, topology control policies published so far do not take into account in a realistic manner the amount of interference experienced in the network. Due to the impact of interference on channel capacity, without proper interference estimation, the capacity calculation methods provided in the literature lack accuracy as well.

3. Neighbor attachment policies

The neighbor attachment policies considered in this paper are described briefly here.

Policy 1: Nodes are equipped with omni-directional antennas. Any node considers all other nodes within its maximum transmission range (its coverage area) as its neighbors.

Policy 2: Nodes are equipped with directional antennas [8] with beam-width α. Each node sweeps its surroundings sector by sector, and establishes neighboring relations with all nodes that are discovered in this way. Considering additional gain of the directional antennas in comparison to omni-directional antennas, this policy generally results into more discovered neighbors (at farther distances) than the first policy.

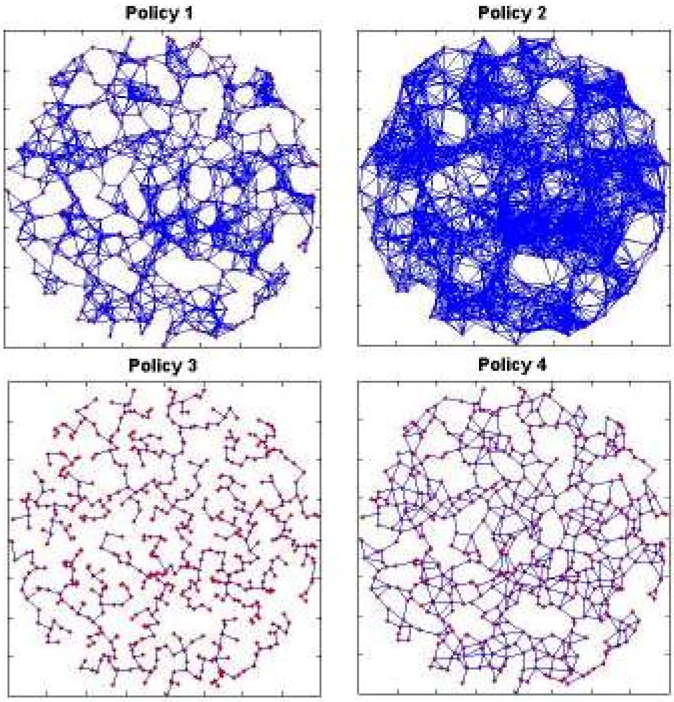

Figure 1. Example of link-layer network topology for the considered neighbor attachment policies, with 600 nodes uniformly distributed over a circular area of normalized radius 8. Here η=*4.0 and α=60* degrees (for policies 2 and 4).

Policy 3: Nodes are equipped with omni-directional antennas. All nodes run a local algorithm to construct a Minimum Spanning Tree (MST) [9]. Each node only links its adjacent nodes on the MST as its neighbors.

Policy 4: This policy uses omni-directional antennas, together with an angular parameter α to select neighbors [10]. Neighbor selection consists of two phases. In the first phase each node, e.g. node *u*, increases its transmission power gradually to find closest neighbors one-by-one. New neighbors are added until there is at least one neighbor in any cone of angle α centered at node *u*, or the maximum transmission power has been reached. Phase one may produce a considerably higher number of neighbors than strictly needed for network connectivity. Therefore, in the second phase of neighbor selection some links are pruned. Assume node *u* has two neighbors *v* and *w*. Node *w* will be removed from the neighbor list of node *u* if the power needed to send a packet from *u* to *w* directly is more than the power needed to send the packet from *u* to *w* via *v*.

For connection between nodes we assume a simple pathloss propagation model in which received signal power at distance *d* is proportional to $d^{-\eta}$, where η is the pathloss exponent[1]. This assumption results into a circular coverage area of radius *R* around each node with an omni-directional antenna. Let *P* be the power received at distance *R*. In other words, *P* is the minimum required power for correct reception of signals. For convenience in notation and

[1] The value of η depends on the environment. In free space η=2. In densely built areas η can be as high as 6. The exact value of η is usually determined by measurements.

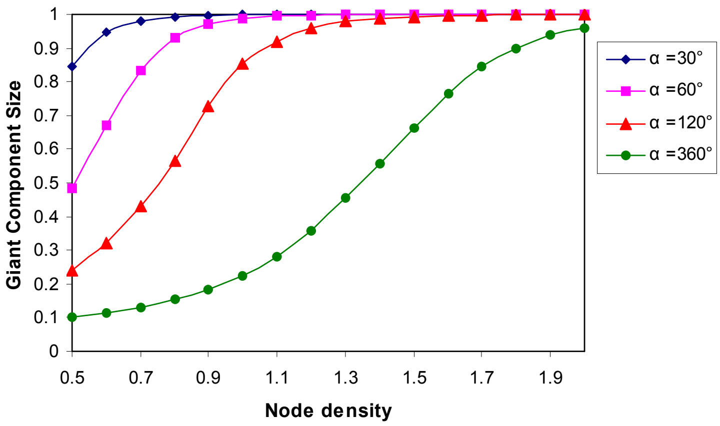

Figure 2. Growth of the giant component size, as function of node density, for different antenna beam-widths. Each point in this figure is the mean value taken over 1500 independent simulations when the corresponding numbers of nodes are uniformly distributed over a circular area of normalized radius 8.

ease of interpretation, we normalize in this paper all distances to R and all powers to P. Figure 1 shows an example of the network topologies obtained for each of the neighbor attachment policies described above in a network consisting of 600 nodes uniformly distributed over a circular area of normalized radius 8. This figure clearly shows the impact of neighbor attachment policies on the resulting network topologies. The number of links and the average number of neighbors per node (called mean degree) are strongly affected by attachment policies. In Section 4 we will see how these variations affect the experienced interference in the network.

The use of directional antennas is becoming more widespread in telecommunication systems. Here we spend a few words to describe the impact of using directional antennas on the network topology and network connectivity characteristics. This brief description will help to interpret results provided in Section 4. In comparison to omni-directional antennas, directional antennas can provide higher gain in a certain direction. As the antenna beam-width reduces, the directional antenna gain usually increases. This increased gain would mean that nodes at farther distances could become neighbors. Consequently, this effect can increase the link density, the mean degree and improve network connectivity. Figure 2 shows an example of the influence of antenna beam-width on network connectivity. In this figure we have used the giant component size [11] as an indicator for connectivity in the network. The largest connected cluster in a network of nodes spread over a certain geographical area is called the giant component. Giant component size is the fraction of nodes in the network that, in single-hop or multi-hop fashion, are connected to each other. Obviously, when the giant component size is 1, the entire network is connected. Figure 2 is obtained through simulations and shows how full connectivity can be reached at lower node densities when directional antennas with narrow beam-widths are used.

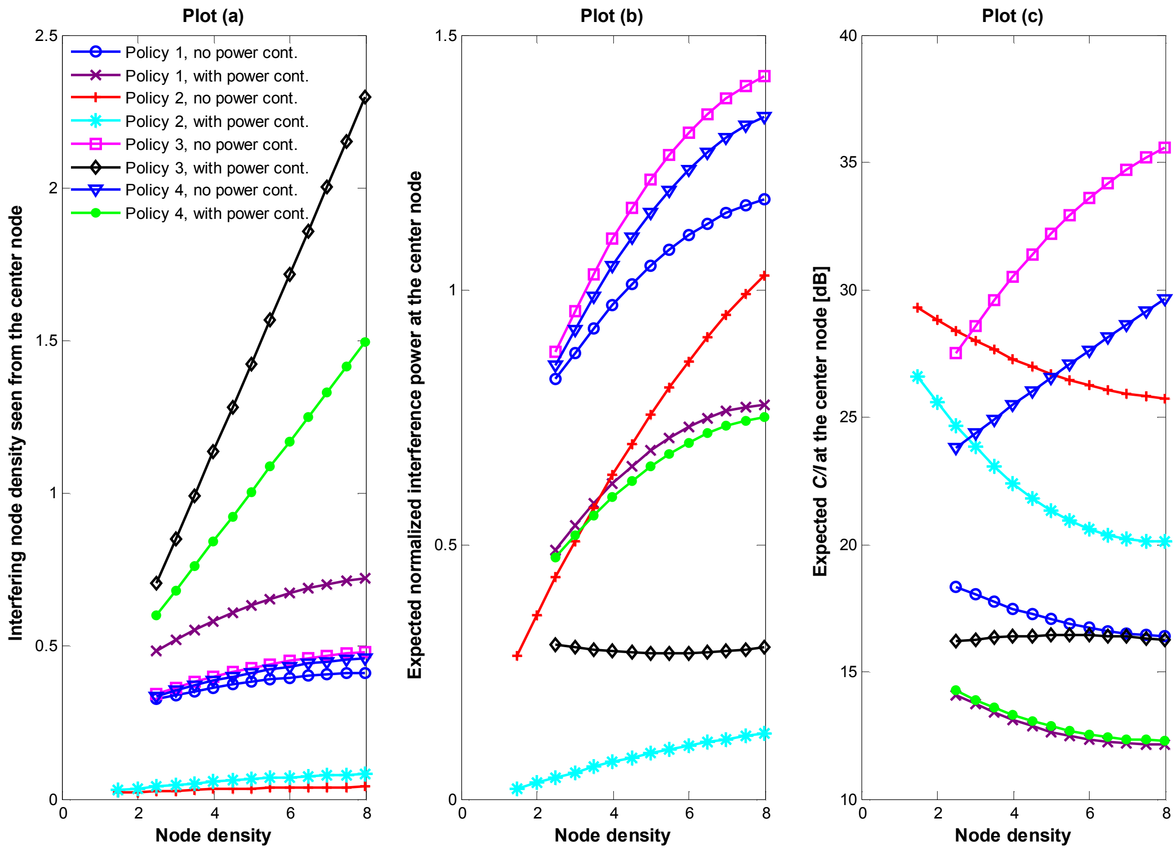

Figure 3. Interfering node density, normalized interference power, and *C/I* as function of the node density for a node in the center of a circular area of normalized radius 8. Each point is the expected value taken over 1500 independent simulations of the corresponding configuration. Assumed is: CSMA/CA with reservation at the MAC layer, η=4.0, α=60 degrees for policies 2 and 4, and 10.4 dB processing gain in plot (c).

4. Impact on interference

In this section we present our results regarding the amount of interference caused by deploying each neighbor attachment policy in a large network of randomly but uniformly distributed nodes.

The topology imposed by the neighbor attachment policy will be used to send packets along the shortest path in multi-hop fashion between any two nodes in the network. The question addressed here is whether any of the considered neighbor attachment policies has significant advantage or disadvantage in terms of experienced interference in the network. We have investigated this point with power control as well as without power control. In the former case, each packet is transmitted with the minimum required power to be received correctly by the intended neighboring node. In the latter case, all packets are transmitted with maximum power.

Figure 3 summarizes a part of our results; showing interfering node density, expected interference power and expected Carrier to Interference ratio (*C/I*) for each neighbor attachment policy. All results presented in the subplots of Figure 3 correspond to networks formed by uniformly but randomly distributed nodes over a large circular area of normalized radius 8. The node densities vary from 1 to 8, which correspond roughly to networks of 200 to 1600 nodes. Each point presented in this figure is found by taking the expected value over 1500 different network configurations.

The interference situation does not need to be the same for all nodes in the network. In Figure 3 we concentrate on a receiving node in the center of the area. The center node can be expected to experience the highest amount of interference in the network. In the calculation of interference we have assumed CSMA/CA with reservation at the MAC layer. Further we have assumed that all nodes always have data to be transmitted to any other node. Subplot (a) in Figure 3 shows the density of *source-destination pairs*[2] that can be formed in the entire network based on the above mentioned assumptions. In other words, this subplot shows the interfering node density seen from the center node. In subplot (b) we have computed the aggregate interference power at the center node, assuming the pathloss propagation model with $\eta=4.0$. The interference power here is normalized to *P*, the minimum required power for correct reception of radio signals. Subplot (c) shows the expected *C/I* for the center node, when this node is receiving a packet from one of its direct neighbors chosen in random. In calculation of *C/I* we have assumed a processing gain of 11 (10.4 dB).

Based on Figure 3, we can make several interesting observations:

- For all policies without power control, the interfering node density tends to level-off towards an upper limit independent from the node density. This is due to the working of the MAC protocol. Whenever a transmission link is established between a source node, and a neighboring destination node, the MAC protocol will prohibit a portion of nearby nodes in the network from simultaneous transmission. This portion is directly related to the size of the coverage radius of a node, which is a fixed value in case of no power control. When the density of nodes increases, more nodes will fall within the prohibited transmission areas. As a result, the density of interfering nodes is not expected to increase linearly with increasing node density.
- For all policies with power control, the density of interfering nodes tends to increase linearly with increasing node density. This is again related to the working of the MAC protocol. In contrast to the case when no power control is used, the size of the prohibited transmission area for each source-destination pair tends to decrease at high node densities; allowing room for higher density of interfering nodes.
- High density of interfering nodes does not necessarily mean high interference power. For example, policy 3 with power control results into the highest interfering node density, while it produces relatively low interference power (see subplots (a) and (b)).

[2] A source-destination pair is formed when on the MAC layer two neighboring nodes are permitted to communicate directly with each other.

- All scenarios produce less interference when power control is used. Also using directional antenna reduces interference. However, a low value of interference does not always mean a high value for *C/I*, or the best network capacity. For example, policy 3 without power control provides the best *C/I* for high node densities, while it is suffering from the highest amount of interference power in comparisons to other policies. We know that in policies 3 and 4 nodes attach only to their closest neighbors. Obviously, the expected distances to the closest neighbors reduce by increasing node density. A consequence of this fact is the increase of the wanted signal power relative to the interference power when no power control is used. This explains the improvement of *C/I* for the related cases in subplot (c) of Figure 3.
- For policies 1 and 2, with or without power control, the amount of interference increase, and *C/I* decrease by increasing node density.
- From all policies, policy 2 without power control provides the best *C/I* at low node densities. At high node densities policy 3 without power control offers the best *C/I*. Therefore, if maximization of *C/I* at the physical layer is desired, not using power control is preferable.

5. Conclusions

In this paper we have investigated a number of commonly used neighbor attachment policies based on their interference behavior. Our approach has provided valuable new insights into capabilities and limitations of multi-hop point-to-point networks. We have shown that, by choosing a suitable antenna beam-width, directional antennas can reduce the amount of interference in the network. Further, we have shown that although power control or directional antennas can reduce the amount of interference, they do not necessarily produce the best Carrier-to-Interference ratio (*C/I*). Given the direct link between high *C/I* and high capacity, we can conclude that neighbor attachment policies that focus on interference reduction may fail to realize any capacity improvement in ad-hoc and sensor networks.

The value of *C/I* is just one of the parameters that affect the capacity of the entire network. Our plan is to extend this work in near future to find the relation between network capacity and neighbor attachment policies in more detail.

Acknowledgement

This work was supported by IOP GenCom SiGi Spot project IGC.0503 in The Netherlands.

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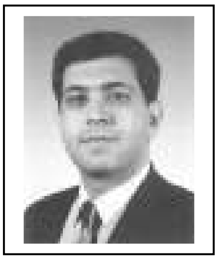

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