Determination of Critical Transmission Range in Ad-Hoc Networks

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Abstract

Ad-hoc networks are wireless mobile networks that do not rely on preexisting infrastructure. In such networks, multi-hop routing is used to achieve large degree of network connectivity and each node in the network acts as a router for its neighbors. The range of the radio transceivers is chosen as a trade-off between full network connectivity, the reuse of the available spectrum, and power consumption. This paper presents an algorithm to calculate the minimum transmission range of the transceivers that is required to achieve, with some probability, full network connectivity. Furthermore, we also study the effect of mobility on this value.

1. Introduction

As the transmission range of the transceivers in an ad-hoc network is typically significantly smaller than the span of such networks, multi-hop routing is commonly used to achieve high degree of network connectivity. To implement multi-hop routing, any network node also acts as a router for other nodes. However, due to mobility, the wireless links are frequently broken and new links are frequently reestablished. Such dynamic network topology presents a significant challenge for the network routing algorithms. Proposals of several routing algorithms, such as DSR [6], AODV [13], ZRP[4,5], and TORA[12], have been recently published in the technical literature. In these algorithms, the routing task is performed using either a proactive or a reactive scheme, or a combination of the two, as it is done in the hybrid ZRP protocol.

Ad-hoc networks can be represented as a connected graph $G(v,e)$, with a set of vertices v and a set of edges e. Each vertex of the set v represents a network node and each edge of the set e represents a wireless link. The total number of nodes is $n=|v|$. Direct connectivity between two nodes is possible only when two nodes are geographically close enough, as a transmission needs to be received at least some minimum signal level to ensure some quality of service (e.g., Bit Error Rate). In a mobile network, where relative distances between nodes change all the time depending on the propagation conditions, links are broken and new links are established continuously.

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In this paper, we present a method to calculate the minimum value of the transceivers' transmission range, which we term here the *critical transmission* range*,* that allows maintaining full network connectivity (i.e., so there is no network partitioning). This issue has also been considered using a statistical approach in [3].

We have also studied how this value changes subject to nodal mobility. In particular, we have examined how the nodal motion pattern affects to the critical transmission range. Furthermore, we have analyzed how the connectivity value is affected when the transmission range is lower than the critical range and we have compared how the level of network connectivity changes, subject to the choice of the mobility model. The goal was to examine how much variation in the transmission range and in node connectivity one can expect as a function of the mobility models used in the study.

This paper is structured as follows: In section 2, we describe the connectivity model that we have used in our study of the critical transmission range. In section 3, we introduce the critical transmission range concept and the approach to its calculation. Sections 4 and 5 present the mobility models and the connectivity parameters used in this study, respectively. Section 6 discusses some simulation results and their implications. Finally, section 7 concludes this work.

2. Wireless Transmission Range

The optimal reception range of a wireless transceiver cannot be represented by a fixed number. Rather, the factors that condition this value change constantly in any practical wireless environment. Different fading mechanisms, some of which are frequency-dependent, have been extensively studied and the resulting propagation models that can be used for modeling have been developed for different network operational conditions, such as terrain shape, atmospheric conditions, and man-made obstacles. Another issue that determines the reception range is the transmission power: The larger the transmitted power is, the longer is the reception range. However, large transmission power can significantly increase the power drainage and reduce the battery lifetime. Another important issue is the antenna configuration; i.e., not only the transmitter power is important, but how this power is spatially distributed is important as well.

At a first sight, one could claim that the longer the transmission range is the better. However, this is not always so. Although longer transmission range reduces the number of hops that a packet needs to transverse in an ad-hoc network, it also increases the number of nodes that locally compete on the shared channel, effectively increasing the access delay and reducing the network capacity. Also, short transmission range allows better frequency reuse and longer battery lifetime.

Conversely, the network throughput can be improved by shortening the transmission range, because more simultaneous transmissions can co-exist at the same time in different areas of the network. The problem is that for too short a transmission range, the chances of a network being partitioned increase. Of course, as network partitioning prevents some nodes from communicating with their destinations, such a condition should be avoided as much as possible.

We assume that any node transmission can be successfully heard at any other node whose geographical separation from the transmitting node is less than certain distance, where distances are calculated as Euclidean distances. We also assume a flat two-dimensional space without any propagation obstacles that could block or reflect signals in any way. Thus, if a,b are network nodes and their locations are x_a and x_b, respectively, we say that a and b can communicate directly if the distance between a and b is less than the transmission range (l); i.e., node a can receive from b if $|x_a-x_b|<l$.

Although the above model of nodal connectivity is very simple, use of this mode in our work does not reduce the generality of our algorithm. Rather, this simple model will allow us to concentrate on the evaluation of the critical transmission range and not be burdened by a complex calculation of the network connectivity. When using a more complex propagation model, the condition on Euclidean distance being greater than some value needs simply to be substituted by a similar condition that would indicate that the received power is above some critical value.

3. Problem formulation

Our model of an ad-hoc network consists of a set of nodes distributed throughout a certain area. As the nodes move, the particular location of any node changes in time, as do the connectivity between the nodes.

Thus, each node's set of neighbors, defined as nodes within the transmission range of the node in question, will continuously change. To simulate these changing neighbor-relations, it is common to assume some mobility model that represents the motion of the network nodes. Such a model emulate how nodes move in a certain communication environment (i.e. cell phone users in a city, mobile robots in a factory, etc). Thus, the topology of an ad-hoc network can be viewed as a sequence of snapshots, which represent the location of the mobiles, temporally separated by some periodic time interval. Of course, as the actual mobility patterns are not well specified, such mobility models are hypothetical in nature. Nevertheless, as shown in this paper, in many cases the results are not sensitive to the choice of a particular mobility pattern.

Our basic goal in this work is to obtain the transmission range of the wireless transceiver, such that no network partitioning occurs. However, due to the random nature of the problem, it is difficult to provide a single value. Rather, using the network snapshots, we are able to calculate some statistics of this critical transmission range. Of course, the problem is that one cannot simply construct a graph of the network, as the existence of links between nodes depends on the parameter that we are evaluating, namely the critical transmission range. In other words, the usual procedure of building a graph by including an edge between node i and node j if $|x_i-x_j|<l$ is not possible here, because the value l, the transmission range, is unknown.

A closer look at network links can lead to a simple but useful classification of links into two groups: links that are needed in order to maintain a fully connected network and other links which could be removed without partitioning the network. The first type is essential to maintain full connectivity (we term these links *essential links)*, while the latter is redundant.

In order to identify the essential links, we introduce the concept of a *direct neighbor.* Given two network nodes a and b., we say they are direct neighbors[1] if there is no another node c that is closer to a than b is and, at the same time, is closer to b than a is. That is, a and b are direct neighbors if and only if:

$$\neg\exists c \,\big|\; |x_a - x_c| < |x_a - x_b| \wedge |x_b - x_c| < |x_a - x_b| \qquad \textbf{(1)}$$

The geometric interpretation of (1) is that, if the intersection of the circle centered at x_a with the radius $|x_a-x_b|$ with the circle centered at x_b with the same radius of $|x_a-x_b|$ is empty, then a and b are direct neighbors. However, if another node exists such that it is closer to both a and b than the distance between a and $b,$ then this node could be used for relaying transmission between a and b. In such a case, the direct link between a and b could be discarded without losing full network connectivity.

Specifically we are looking for the *critical* transmission *range* that we define as:

$$min(l) \in R^+ \,\big|\; Conn(G(v,e^*)) = 1 \qquad \textbf{(2)}$$

where

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[1] We can say that node c is in between nodes a and b.

$$e^* = \{(i,j) \in v^2 \mid |x_i - x_j| \le l\} \quad \textbf{(3)}$$

The function *Conn(G)* measures the connectivity in the graph. When the transmission range is not large enough, that is, when the transmission range is under the critical transmission range, the network gets partitioned. Instead of having only one set of connected nodes constituting one graph, we end up with two or more sub-networks, each one clustering a subset of nodes.

In order to be able to compare different partitioned networks we need a quantitative measurement of connectivity. We define *connectivity* as the ratio of the connected network nodes pairs, divided by the maximum number of such possible connections. Thus, the value of *connectivity* varies between 0 and 1.

If the network has n nodes, then the maximum number of connections is $n(n-1)$ (i.e., when the network is in the fully connected state). At any given instant, the may be k separate clusters within the network, and n_i represents the number of nodes in the cluster number i. The *connectivity* is expressed as:

$$Conn(G) = \frac{E[\#neighbors]}{n(n-1)} = \frac{\sum_{i=1}^{k} n_i(n_i - 1)}{n(n-1)} \quad \textbf{(4)}$$

If the network is fully connected, then $k=1$, $n_1=n$, and we get maximum connectivity; i.e., C=1. Conversely, for small transmission range, every single node is forming a cluster of size one; so $k=n$ and the connectivity reduces to zero. But if the network is split in two equal size clusters, the connectivity value is a bit less than C=½, with the value of $C=½$ when $n \to \infty$.

We name as *critical* link the one, which determines the critical transmission range. We say that the link between nodes i and j is the critical link (CL) if:

$$CL = (i,j) \in e^* \mid |x_i - x_j| = l \quad \textbf{(5)}$$

So the critical link is the one that, if removed, partitioning of the network will occur.

Theorem: The critical link is a link between two direct neighbors.

Prove: From (1), (2) and (5) we have that l is the minimum (positive) value that guarantees full connectivity. Let us assume that this critical link, between nodes i and j, is not a direct neighbor link, then:

$$\exists c \mid |x_i - x_c| < |x_i - x_j| \wedge |x_j - x_c| < |x_i - x_j|$$

But, if such node c exists, then we can remove the i to j link without changing the network connectivity:

$$l' = max(|x_i - x_c|, |x_j - x_c|),$$

where $l' < l$, which contradicts the assumption that the link i to j is the critical link.

The intuitive idea is that direct neighbors are able to communicate directly, without any other node's intervention (because this is the shortest path available between them). In our reasoning, we have conscientiously omitted the fact that any transmission will be practically restricted in power, which cannot be exceeded due to hardware limitations.

In the Figure 1, we can see that links (a,b), (b,c) and (c,d) correspond to pairs of direct neighbors. However, the link (b,d) link is not between two direct neighbors, since node c can act as a relay between them.

We create a graph by linking the direct neighbors. We refer to this graph as the *direct neighbors set:*

$$G^d = \left\{ G(v, e^d) \;\middle|\; \forall m \in e^* \;\middle|\; m \text{ is a Direct Neighbor} \right\} \qquad \textbf{(6)}$$

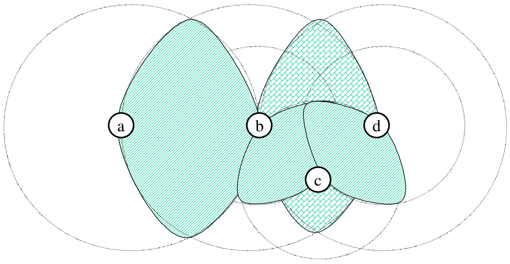

Figure 1. Sample network.

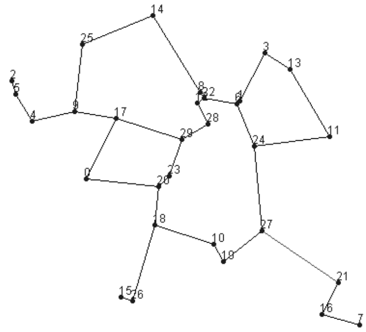

Figure 2. Sample direct neighbors graph.

It would appear that the solution to finding the critical distance is now to find the maximum length link in the Direct Neighbor Graph (DNG). However, if the (DNG) contains loops, then network connectivity could be still maintained by removing some of the links that create a loop. In particular, it might be the case that the maximum-length link can be removed, leading to shorter critical link. Thus, to find the “true” maximal link, we need to remove links from our graph, as to eliminate all the loops. Of course, we should remove the links in the order of their length.

Theorem: The edges of the DNG are a subset of e^*

Prove: This is trivial that because of the construction of the set e^d from e^*, $e^d \subseteq e^*$.

In the Figure 2 we show an example of a DNG graph, where the longest link is from node 27 to 21. Note that in this case as there is no loop in the graph, the longest link is also the critical link.

Trees are graphs that do not contain loops. A Minimum Spanning Tree (MST) of a graph is a spanning tree that covers all the network nodes and whose some of the link values is minimal. Here, we assume that a link value is its distance. A MST of a graph is another graph:

$$MST = G\left(v, e^t\right) \left| \begin{array}{l} Conn\ (G) = 1 \\ min \left(\sum_{(i,j) \in e^t} \left| x_i - x_j \right| \right) \end{array} \right. \qquad \textbf{(7)}$$

Where e^t is a set of edges that, on one hand, provides full connectivity (i.e., covers all the network nodes) and, on the other hand, also represents the minimum sum of the graph edge lengths. The algorithm to compute this set is described below. We use the minimum spanning tree of the DNG as a way to remove the unnecessary links[2] from it. The longest edge of the resulting MST is the critical link, and its length is the critical transmission range. Two algorithms are well known for the MST calculation:

- ❖ Kruskal [8] algorithm starts with a list of links, sorted by cost, adding one link at a time to the constructed MST, if the newly added link does not create a loop in the current MST. Otherwise, the link is skipped. The algorithm terminates when all nodes are present in the being constructed MST.

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[2] To obtain the minimum value of the tree, in essence, the MST algorithm removes the longest link of each loop.

❖ Prim [15] algorithm starts with one node in the constructed MST, chosen at random. It builds the MST by adding new links, one at a time. The new link is selected as the shortest link from the current version of the MST and the nodes not currently in the MST. The algorithm terminates when all nodes are present in the being constructed MST.

Theorem: e^t is a subset of the direct neighbor set e^d

Prove: The definition of a direct neighbor is when the node is closer to the node in question than any other node. From the construction of the MST by the Prim algorithm, one can observe that each new link chosen is the shortest possible connecting one node from inside the current tree with other node from the outside. However, because the algorithm selects the shortest links, these are also the direct neighbor links.

Of course, it is not necessary to first create the DNG and then use the MST algorithm. One can use directly the MST algorithm, starting from a "fully connected" graph; i.e., a graph in which all the nodes are connected to all the other network nodes. In other words, the method is to obtain the MST of the $G(v,v^2)$ without calculating first the direct neighbor graph. This way, the number of calculations can be reduced and simulation time shortened.

Once we have the algorithm to calculate the critical transmission range, we can apply it to a static network. However, as we pointed out in the introduction, ad-hoc network nodes move all the time. Thus a static determination of the critical range is not very useful. We have experimented with a number of mobility models to evaluate the effect of the different parameters on the value of the critical transmission range. Of course, it is also of interest to determine how connectivity is affected by choosing a smaller value than the critical range.

4. *Mobility models*

Mobility models attempt to represent the motion of network nodes and are used to evaluate the effect of the nodal movement on the performance of algorithms and protocols. Similarly, traffic models are used to represent the pattern of traffic generation by the network nodes. To properly study the behavior of a network (and an ad-hoc network, in particular) both types of models are necessary.

As is the case with traffic models, there are two basic types of mobility models: traces and synthetic ones. Traces are observed motion patterns recorded from real life use of the system (i.e., a mobile phone carrier could provide the motion pattern of users in a certain area). In principle, traces can more accurately describe the behavior of a practical system, especially when the number of samples in the trace is big enough. However, the use of traces has also problems. In a new system, traces may not be available yet. Besides, traces of current systems may also be difficult to obtain due to several factors like customer privacy issues and confidentiality of data. Thus, sometimes another type of modeling is needed. Synthetic models try to present a realistic motion behavior by computer generating data using a certain algorithm. Several approaches have been studied in this area [9].

In our past work, we have developed several mobility models trying to emulate some possible mobiles' behavior when the mobile nodes are robots [16]. Our models were based on three different types of behavior: a column of nodes, a grid of nodes, and a set of nodes pursuing some mobile target point. The basic idea in these models was that any node has a reference location, but by introducing a certain randomness in the model, nodes can move a random offset around their locations. However, because of the importance of inter-nodal distance, the above models appear to be too restricted and we looked for other, more general, mobility models.

Mobility models are usually a mixture of more than one behavior: such as moving from one point to another following a straight line, in addition to introducing some level of randomness, such as choosing the next target point at random. Totally random models have also been used, like the most know Brownian motion model, which has only a random behavior component. Brownian model is based on the motion of atoms in a solution, which exhibit an erratic behavior.

We have conducted our simulations using several models: "random waypoint" [6], Random Gauss-Markov [9], and a random node spreading model. All our experiments have been conducted on a limited motion area of 500 by 500 space units. To eliminate boundary effects, nodes that hit a boundary emerge from the opposite site of the area; i.e., the coverage area wraps around. The random waypoint model is based on three mechanisms:

1. Nodes select a target location at random.
2. Nodes proceed on a straight line from their current location towards the target location at a certain speed, fixed or randomly chosen.
3. When arriving at the target location, a node waits for a certain amount of time and repeats the process again.

Random Gauss-Markov model is designed to adapt to different level of randomness by using one tuning parameter. Nodes maintain a certain speed and direction that are randomly changed. The model has a parameter to control the memory effect of the previous values of direction and speed. The following equation shows how the new value for node speed is chosen from a linear combination of the previous velocity vector v_{n-1} , an asymptotic mean μ, and a Gaussian process x_n with zero mean.

$$v_n = \alpha v_{n-1} + (1-\alpha)\mu + \sqrt{(1-\alpha^2)}\, x_{n-1} \qquad \mathbf{(8)}$$

The parameter α acts as a "knob" allowing regulation of the motion from fully deterministic fixed motion (zero randomness) to totally random, identical to the Brownian motion (zero memory effect). This model is especially interesting because it can represent different behaviors through a single parameter.

One characteristic that holds for all realistic mobility models is that nodes cannot vanish on one location and reappear in other distant location. This is due that the fact that nodes have a limited motion range (i.e., limited acceleration) so they cannot reach more than a certain area from its current location in a finite time. Our third model assumes exactly this type of motion, a sort of Star-Trek "tele-transportation." We believe that this unrealistic model is useful in checking the most limiting conditions of the variations in inter-nodal distances.

5. Network Throughput

One of the possible advantages of ad-hoc networking when using a single common channel for all the nodes is that, due to their geographical spreading nodes, several transmissions can take place at the same time. We are interested in showing how big this number of concurrent transmission can be, if the proper transmission range is chosen. We also want to show how the transmission range affects the network throughput.

In order to evaluate the network throughput, the Media Access Control (MAC) scheme needs to be implemented. For our study here, we used the Dual Busy Tone Multiple Access (DBTMA) scheme proposed in [2]. This scheme is based on the use of two busy tones that "mark" the transmission and the receiving area, effectively preventing other nodes from initiating a transmission that might collide in a transmission already in progress. DBTMA also uses the RTS/CTS dialog (as is done in the MACA[7] and the MACAW [1] schemes) before starting a data transmission to assist in setting up the two busy tones. Through the use of the RTS/CTS dialogue and the two busy tones the hidden/exposed terminal problems are efficiently addressed by the scheme.

6. *Simulation Results*

All the simulations have been conducted using Java language programs and the Simjava library [11]. We have studied the evolution of the critical link using different mobility models. To achieve this we have deployed a certain number of nodes —from 2 to 100— inside our working area of 500 by 500 space units. Our program calculated the critical transmission range, stored it in a file then rearranged all the network nodes using the selected motion model and repeating the process.

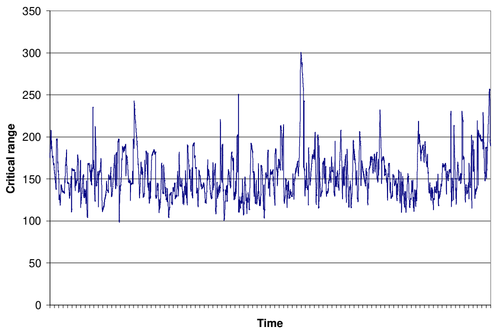

Figure 3. Time evolution of the critical transmission range length in one Gauss-Markov mobility model

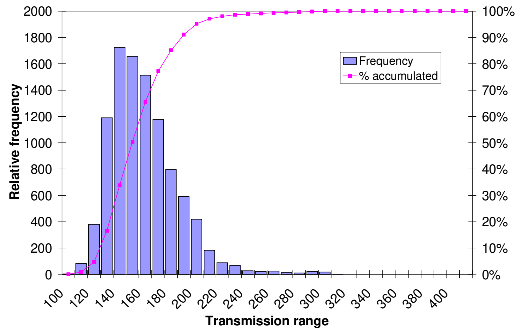

Figure 4. Frequency histogram and accumulated percentage of Random Gauss-Markov model with 25 nodes

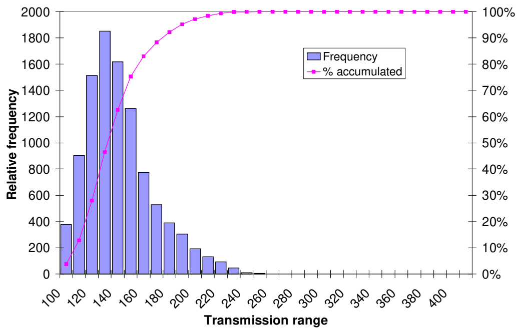

Figure 5. Frequency histogram and percentage of Random waypoint model with 25 nodes

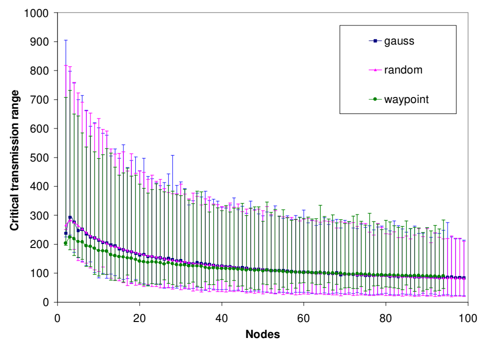

Figure 6. Comparison between values obtained with different mobility models

Figure 3 shows the time evolution of the critical transmission range in an example run of our simulations. Although it is bounded, the collected data show highly random behavior and a Fourier analysis reveals no periodic patterns hidden in these values. Critical range seems to have chaos characteristics, so time evolution does not provide much information about the process.

Our next step was to perform a statistical analysis, in particular, to obtain the cumulative distribution function of the critical transmission range. To do this we have plotted the relative frequency of the critical transmission range values that we have obtained from the simulations. Comparing Figure 5 and Figure 4 one can observe that there isn't too much difference between the two, except for the different mean values. These two figures are using a 25-node network but a different mobility model. What we can see is that the random waypoint mobility model provides a lower mean value for the critical transmission range. This means that better connectivity can be obtained with this model than with the random Gaus-Markov model. However this is only true for transmission range values shorter than approximately 250 space units or greater, because for these values both models are providing 100% connectivity and therefore no difference is observed.

In Figure 6 we are presenting a condensed summary for the three mobility models, showing the minimum, maximum and mean values of the critical transmission range. It is interesting to point out the initially higher values that start to decrease later for networks with more than three nodes. A *log(n)/n* function can be fitted to these experimental results; while minimum and maximum values can be likely approximated by negative exponential functions. (However, these values exhibit some level of noise, due to the randomness of the motion).

One important observation is that the data in the histograms can provide us a guide in selecting the transmission range for and ad-hoc network. This value is the relative frequency of occurrence of the different link lengths. Choosing the maximum value we can ensure full network connectivity. When choosing a lower value, the graph can provide us with a statistical indication on the percentage of network connectivity. Assuming that the process is ergodic, this is also an indication on the percentage of time that our network remains fully connected. This is an important parameter because it provides input to the radio design process. Another observation from the Figure 6 is the intuitive conclusion that the more nodes a network has, the shorter is the critical transmission range. Furthermore, the critical transmission range seems not to be much dependent on the specific mobility model used. This is an important point, because it suggests that results obtained with different mobility models could be sensibly compared.

For throughput calculation we have also used a 500 space units by 500 space units lattice with 25 nodes generating offered load of 10 (Erlangs). We have simulated the DBTMA MAC algorithm with different transmission. As can be seen in Figure 7 the throughput ranges approximately from one to three. So it is clear that a careful selection of the transmission range has a profound impact on the network throughput. Although not in the graph, for transmission range longer than 500 space units the network experiences constant throughput of 0.93. For transmission range of less than 150 space units, the network gets partitioned with high probability, so the results in this range are not of much interest.

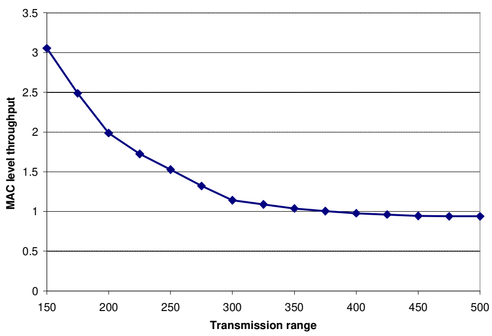

Figure 7. The effect of the transmission range on the network throughput

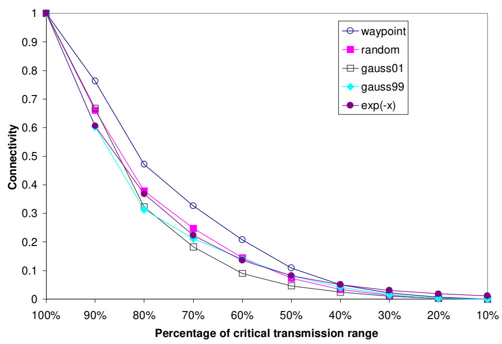

Figure 8. Connectivity versus transmission range

We have developed a modified version of the Prim algorithm, so that we can evaluate the number and size of each cluster when the network is partitioned. The starting point is the same as in the Prim algorithm; we select a node and look for the closest neighbor adding it to the set of already connected nodes. We continue this process of adding the nodes to the set of already connected nodes. However, if the distance of the to-be-added node to the cluster is more than the critical transmission range, we store the current set (cluster) size, and start with the next node building a new cluster tree. The algorithm terminates when all the nodes appear in the clusters.

We then use the equation (1) to evaluate the connectivity. To evaluate connectivity, we have performed another type of simulation: We start by obtaining the critical transmission range for the model. Then we evaluate connectivity for selected fractions of the critical value, ranging from 90% to 10%. This evaluation is performed by using one of the mobility models considered before. Next figure summarizes our results.

Of course, for values equal or greater the critical transmission range, the maximum connectivity $C=1$, because the network remains fully connected. As the maximum transmission range is smaller and smaller fraction of the critical transmission range, there is more and more partitions in the network and the total connectivity diminishes. A negative exponential can be fitted easily to any of the curves. The figure does not indicate strong dependence on the mobility model (we used a 25-node network for this calculation). The biggest difference is (again) with the random waypoint mobility model, which provides somewhat higher level of connectivity than the other models, but the difference is still not a significant one.

7. Conclusions

We have demonstrated a method to compute the critical transmission range for a wireless network, given that the locations of the mobile nodes are known. Our results suggest that there is not a strong dependence on the mobility models we have tested. We have calculated the minimum value for the transmission range that maintains full connectivity in the network. We assume that all network nodes use the same transmission range. Smarter power control algorithms could, indeed, reduce this value for some of the network nodes, without penalty to network connectivity. We have also shown how network throughput is dependent on the transmission range by simulating a MAC in a mobility scenario.

Although we have implemented our algorithms as centralized, a distributed version of our protocol is possible. Such an approach would make it more suitable for a practical implementation of a scheme based on the determination of the critical transmission range to, on one hand, ensure high network connectivity and, on the other hand, limit the transmission power of the nodes.

When we know the critical link, we can use this transmission range value to choose the proper wireless transmission range in our transceivers. We can also use this information to know which is the impact to choose transceivers with a shorter range (how much time —on average— we will have our network partitioned).

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