Improving communication in wireless networks via mobility

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Abstract— **The modeling of mobility for a collection of wireless devices operating over a large area is a formidable task as it involves many degrees of freedom such as network topology, local densities and speed and so, much of the work in this area focuses on imposing assumptions on mobility which make the models somewhat artificial. On the other hand, a detailed model of mobility in the context of radio propagation represents a significant challenge. Therefore, the authors adapt a cellular automaton model to reduce the mobility problem to its simplest form whilst maintaining the essential features. A simulation model including the main attributes of radio propagation is developed. It is used to understand the relationship between communication, interference and mobility in the context of ad-hoc networks. The authors demonstrate how mobility can enhance communication across a range of network densities and also explore the impact of cell coverage design across a range of network densities.**

Keywords: cellular automata, mobility and simulation

I. Introduction

In the context of radio communication, there is a tradeoff between a large number of nodes and their ability to communicate. With a large number of nodes, one can always find a node pair and hence send the information on one hop to the next node. However, it can also be a disadvantage in that, when a particular node broadcasts, it causes interference at all nodes in its vicinity. Thus, while the presence of a large number of links guarantees network connectivity, it brings with it the possibility of increased interference, which in its worst form might lead to a breakdown in communication. This is a major cause for concern in such networks.

II. BACKGROUND

The modeling of mobility for a collection of wireless devices operating over a large area is a difficult task as it involves many degrees of freedom such as network topology, local densities and speed. Consequently, much of the work in this area focuses on imposing assumptions on mobility which make the models somewhat artificial. Building on the idea that nodes are randomly located, i.e. independently and uniformly distributed across a disk in a plane, the limitations on radio communication between a pair of nodes has been studied using two approaches. The first approach assumes that the distribution of nodes is fixed (static mobility), [1], while the second approach allows the nodes to move around in a completely random manner or according to known mobility patterns (random mobility), [2,3,4]. There are also models which are a hybrid of these two approaches, [5]. In our preliminary study, [6], we discussed the merits of each of these approaches and compared them with our model.

There are also a number of additional models which consider the connectivity properties of wireless network, for example,[7,8]. These models assume random mobility patterns and develop connected graphs based on two nodes being able to communicate within a given radius.

However, the mobility models which have been employed in these studies are deficient because (a) they do not model delay explicitly and (b) they do not take into account the idea of "restricted mobility" which can occur when one node is occupying a site to which another node would like to proceed. In practice, one would wait until the site became unoccupied, or seek an alternative route. This behavior can be a cause for spontaneous congestion which arises, when nodes become blocked due to the presence of other nodes. This is a starting point for our work.

In our preliminary study, [6], we proposed a simple, albeit crude, cellular automaton model, [9], to study the key aspects of mobility (both free and restricted), communication and wireless interference. Some simplifying assumptions were made, yet the model revealed some qualitative features of wireless communication which would not have otherwise been accessible.

In this paper, we provide a brief overview of the model described in [6], and elaborate on the changes that have been made to the wireless propagation model. In the preliminary study, the underlying assumption was that two nodes communicated a fixed amount of data only if the signal between them was stronger than the thermal noise of the nodes within their "neighborhood" (See Section III). If this was not the case (due to interference from neighboring nodes) then no communication took place. This crude "ON-OFF" mechanism has been replaced with a more realistic model of wireless communication which is described in the next section.

III. THE CELLULAR AUTOMATON MODEL

The simulation mechanism is divided into a number of stages: mobility and communication/transmission. During the mobility phase, the system determines the location of each node in the system and using a simple set of rules, the nodes move to their next position in the grid. A number of assumptions were made including (a) two nodes cannot occupy the same location at the same time; (b) the simultaneous movement of two nodes from different directions cannot overlap, (i.e. if two nodes converge on a site at the same time, only one is selected at random with equal probability.

Following this, the set of allowable connections is determined based on the states of nodes within given neighborhoods. These connections are found based on the fundamental properties of radio communication between a pair of nodes which will be dealt with in the section describing the communication phase.

In the final stage information is transferred between nodes and the relevant statistics are gathered.

The extensions to the original model aim to incorporate more realistic features of wireless propagation. These are described in the next section as part of a brief overview of the simulation model.

A. Structure of the Environment

The geography consists of a square grid with M sites. Each site can be referenced using the *(i,j)* position in the grid. The grid is populated with N nodes with independent mobility processes.

Each site can be occupied by a single node. The neighborhood of a site is a central theme of this model. The "von Neumann" neighborhood of a site is shown in Fig. 1(a). An extended neighborhood, called the "Moores" neighborhood, includes the diagonal positions. This is shown in 1(b). An extended Moores neighborhood can be defined to cover a large area, for example 1(c) shows an extended neighborhood of dimension 2, and one can visualize neighborhoods of higher dimensions. We define the central node in each neighborhood as the focal node of the neighborhood. The focal node for various neighborhood definitions is shown in *Figure 1 (a)-(c)* and is colored in black.

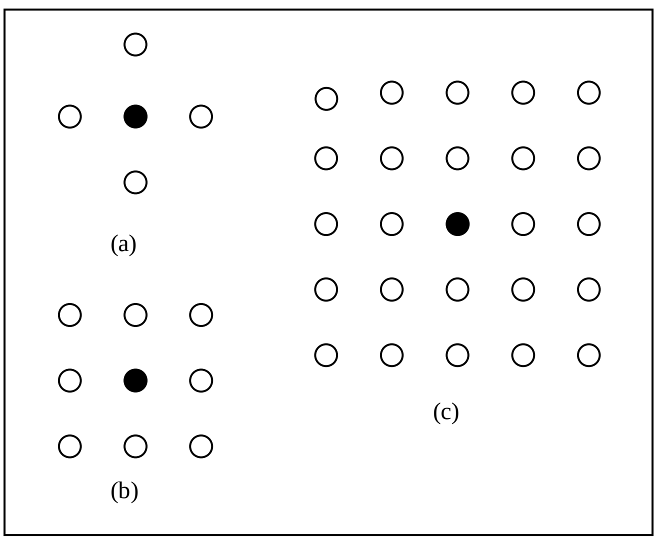


Figure 1. Definitions for Von-Neumann and Moores Neighborhoods

In the model, neighborhoods can be referenced in three contexts: mobility, communication and interference. The mobility neighborhood defines the set of available moves for a node. The communication neighborhood is the set of nodes that can communicate with a focal node. The interference neighborhood includes those nodes contributing to interference at the receiver node. These neighborhoods may not always be the same, for example, one can define a Von Neumann neighborhood for mobility, a Moores neighborhood of dimension one for communication and a Moores neighborhood of dimension two for interference.

In our model, for the sake of simplicity, we have initially assumed a "Von Neumann" neighborhood for mobility and a Moore's neighborhood of dimension one for transmission, and interference. Other combinations are explored later in this paper.

B. Mobility in the Model

We consider an ad-hoc network with N nodes distributed across a lattice L. The lattice is divided into overlapping neighborhoods of a certain size.

We assume that time is discretized, such that at each unit of time, each node moves randomly and independently in one of four directions (for a von-Neumann neighborhood) or it can remain fixed, with certain probability p_{stay}. Motion in the grid is determined by neighborhood type, size and the probability of staying in place, p_{stay}. This probability represents the rate at which terminals move around. For a von-Neumann neighborhood, the probability of moving in one of (N,S,E,W) directions is given by

$$p_{d,move} = (1 - p_{stay})/4 \qquad (1a)$$

where *d* represents the direction in which the node moves. For a Moore's neighborhood this probability is given as

$$p_{d,move} = (1 - p_{stay})/8 \qquad (1b)$$

Using a uniform random number generator, if the generated number is greater than the probability of staying in place, then the node will move. If a node wishes to move to a site that is currently occupied, then the node will remain in its current place. Figure 2a-b, summarizes the mobility characteristics of the grid providing a before and after snapshot of movement in a time slice.

C. Communication/Transmission

After all the nodes have moved, we consider the communication properties of the new grid as follows. For each node in the grid we first identify the communication neighborhood and then calculate for each neighbor in the communication neighborhood, the received SNR for this, i.e. the number of possible interferences. Figure 3 shows this idea graphically for a Von-Neumann neighborhood. Node A, the focal node, can communicate with any of the four surrounding nodes within its neighborhood (shown as striped). The received signal strength at node B can be found by examining the contribution to the interference from each of node B's neighboring nodes (referred to as other nodes and shown in light grey). If the SNR at the neighbor is greater than randomly generated threshold, then a connection may be established with node A.

In the preliminary model, a simple ON-OFF function was used to determine if a connection was allowed. Thus, for each node, if the received SNR was greater than a pre-determined threshold β, then a connection was possible. This is somewhat crude, since in practice, some data can be transmitted even with low to moderate levels of SNR. Also, the threshold does not have to be constant across all nodes. To encapsulate this, idea we have introduced a mathematical function f(γ) which is a continuous, increasing S-shaped function of γ, with $f(0)=2^{-M}$ and $f(\infty)=1$,[10]. This function is attractive since it also embodies details of the transmission system in that it represents the probability that a packet arrives without errors at the CRC decoder. The dependent variable γ, is the received SNR.

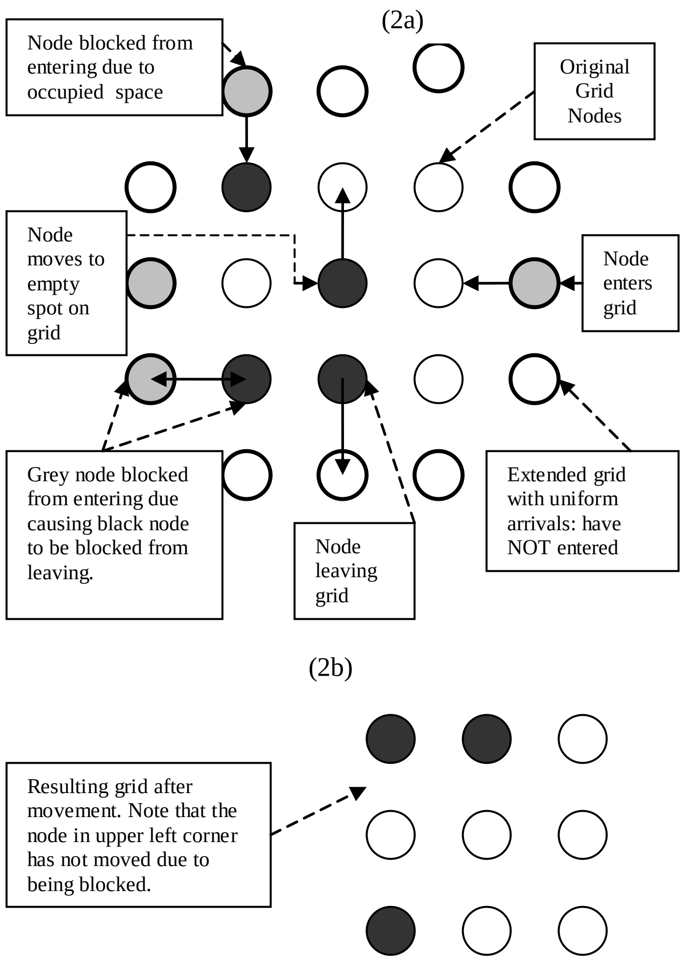


Figure 2: Arrivals, Departures and Movement within the grid: 2b shows the resulting grid after movement in 2a.

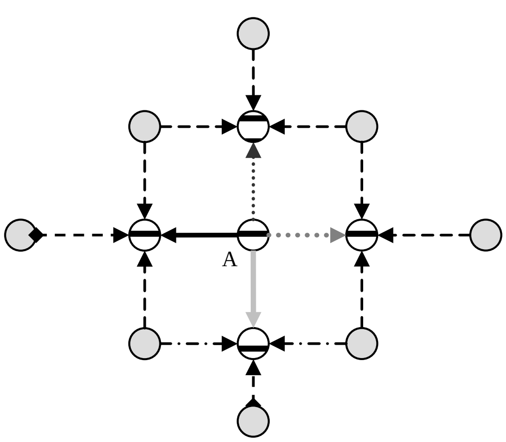


Figure 3. Calculating SNR requirements using a Von-Neumann Neighborhood for Mobility, Transmission and Interference. A similar diagramatic representation can be defined for a Moore's transmission and communication neighborhood.

We have used a random variable *p* which is a probability value between 0 and 1 and compare this with $f(\gamma)$. A transmission can take place providing $f(\gamma)>(1-p)$, otherwise the transmission will fail.

At each time-slot t, depending on its location, neighborhood, number of occupied neighbors, and battery level, each node i, will adjust its emitting power $P_i(t)$ within a given range [0,P]. Initially, we make the simplifying assumption that $P_i(t)=P_{max}=0.5$ for all i, i.e. every node emits a maximal power which corresponds to the worst power assignment for interfering communications. The received signal strength at node B is calculated via

$$P_{rec} = \frac{cP_{\max}}{d^{\alpha}}$$

Where α is the path loss exponent, and *d* represents geographical distance, for example the distance between any two adjacent nodes along the horizontal or vertical direction is set to be one, and other dimensions can be readily found using the positions of the nodes on the lattice. The multiplicative constant *c* is related to the real world required to normalize some parametric values. Initially it was set to 1.

The SNR is found via

$$SNR = \frac{GP_{rec,center}}{(P_{rec,other} + AWGN)}$$

Where G is the processing gain and AGWN is given by $\sigma^2=5\times10^{-15}$ and is a system constant.

Based on the SNR calculations, if the total number of available connections (K) for the center node (A) exceeds k, the total number of allowable connections (K>k), then only k connections are established as active, these being the strongest ones. Likewise, if K<k, then only K connections are maintained as active. Initially we have set k=1 but we plan to manipulate this value when investigating the broadcasting properties of the network.

Having established the communication profile for the network, the model gathers a number of statistics including the number of occupied sites and the network density: the number of connections divided by the number of nodes in the grid.

IV. Simulation Results

The simulation experiments described in this section were run on a 20x20 grid network. The following parameters were used in producing these results: processing gain = 10, path loss exponent 3.6, number of allowable connections k=1, P_{max} =0.5 for all nodes, average poisson demand per entry node varied between 120 and 250. A Moore's neighborhood of size one was used as a baseline for the experiment, for mobility, interference and communication. The probability of remaining fixed varied depending on the experiment. The simulations were run over 400 cycles. We calculate the total network normalized throughput which is based on the SNR being transmitted vs. network density.

The patterns which have emerged resemble an S-shaped curve whose shape varies depending on the parameters of the simulations. Figure 4 compares the normalized network throughput with the network density for a number of different mobility patterns. One can observe that regardless of mobility, when the network density is close to zero, no connections are possible and hence network throughput is near zero, but as the density increases, there is an approximately linear increase in the throughput level. But once the network reaches a "critical mass", the network throughput begins to tail off asymptotically and no throughput is achieved for network densities above 70%. This result is similar to [2].

The effect of mobility is noticeable by examining the individual figures labeled 4(a)-(d). For example, in Figure 4a we observe the impact of p_{stay}=0.1 (high mobility) vs p_{stay}=0.9 (low mobility). With very low mobility (p_{stay}=0.9), the normalized network throughput does not exceed 800 units and communication breaks down once the network is at 50% saturation whereas with high mobility (p_{stay}=0.1), network throughput increases by 25% to 1000 units and communication is possible up till 70% saturation, a 40% increase. The impact of mobility is shown in the remaining figures (b)-(d), in which one can see that increasing pstay up to 40%, (thereby reducing mobility)

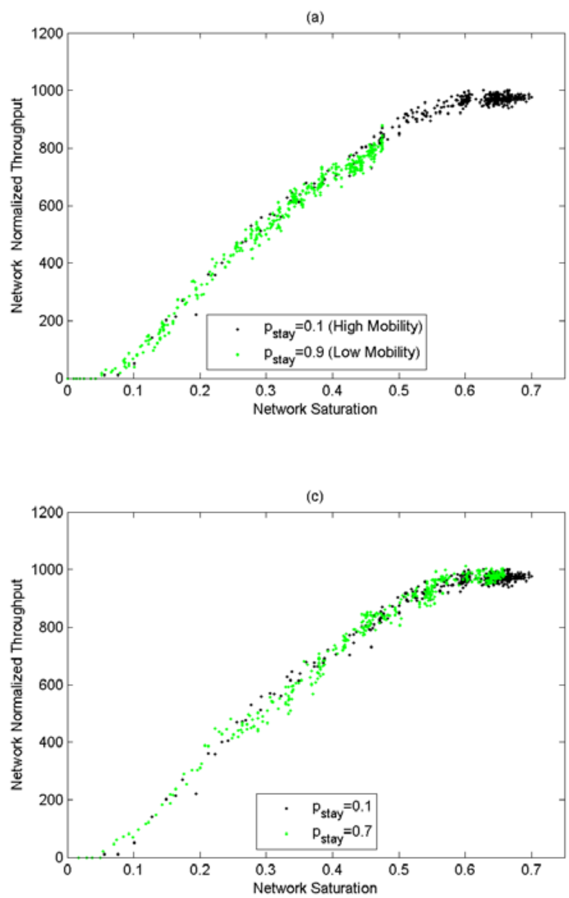


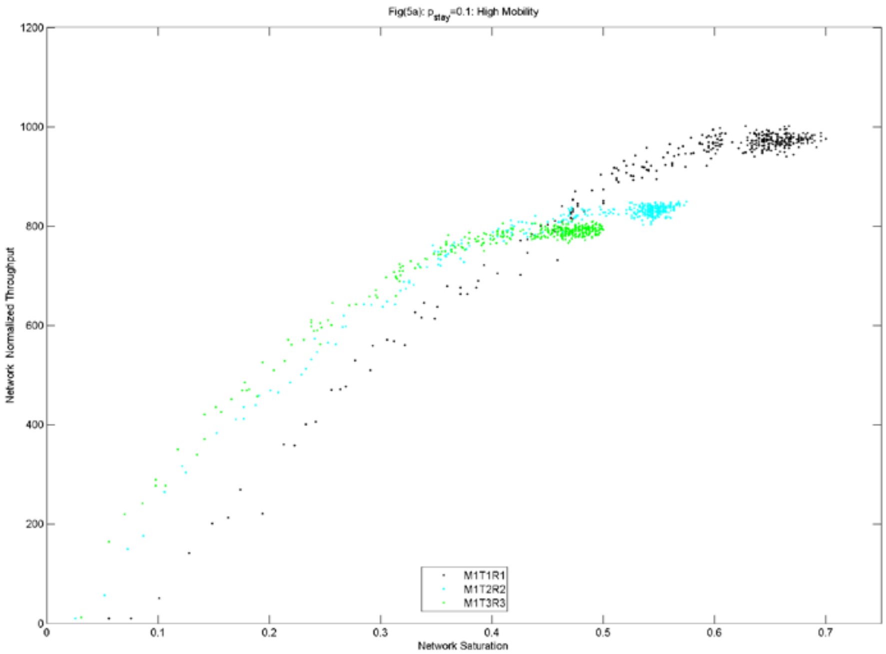
Figure 4a: Mobility and Communication.

We also looked at the impact of neighborhood size on network throughput capability. The Moore's neighborhood was assumed throughout this analysis, since it appears more applicable in the wireless context. We used the following notation to describe neighborhood size with M=mobility, T=Tx and R=Rx. The dimension of the neighborhood was described using a single digit. Thus, a Moore's neighborhood of dimension one for mobility, transmission and receiving was denoted as M1T1R1, with other configurations defined in a similar way.

We compared the M1T1R1 design to M1T2R2 and M1T3R3, in which the mobility neighborhood remained the same, but the transmission and communication neighborhoods were extended over larger areas. This produced the effect of larger coverage areas. These designs were investigated for mobility levels, p_{stay}=0.7 and p_{stay}=0.1.

In Figure 5a-b, one can observe that at low levels of network density, throughput is highest when the transmission/communication neighborhood size is large (M1T3R3), but as the network density increases, the neighborhood size for transmission and communication should be tailored accordingly. As the network approaches its "critical mass" of 70% it is preferable to limit this neighborhood size to the M1T1R1 design which is superior This result points towards a need for elastic design of coverage areas. The affect of mobility is less noticeable at high density levels as expected, comparing the graphs of 5a and 5b, at lower levels the points appear to be more sparse. to the other two designs in that the network still maintains a high level of throughput, which is not the case for the other two designs. In fact, M1T2R2 fails to work beyond a network density of 60% and likewise, M1T3R3 fails at 50%.

Thus, for high levels of network density, the use of small coverage areas is preferred in order to maximize the network's throughput, whereas with lower levels of network density, larger coverage areas are to be preferred. This suggests that mobility may enhance communication when the network is operating below saturation. However, as the network becomes saturated, nodes cannot move around and the impact of mobility is reduced.



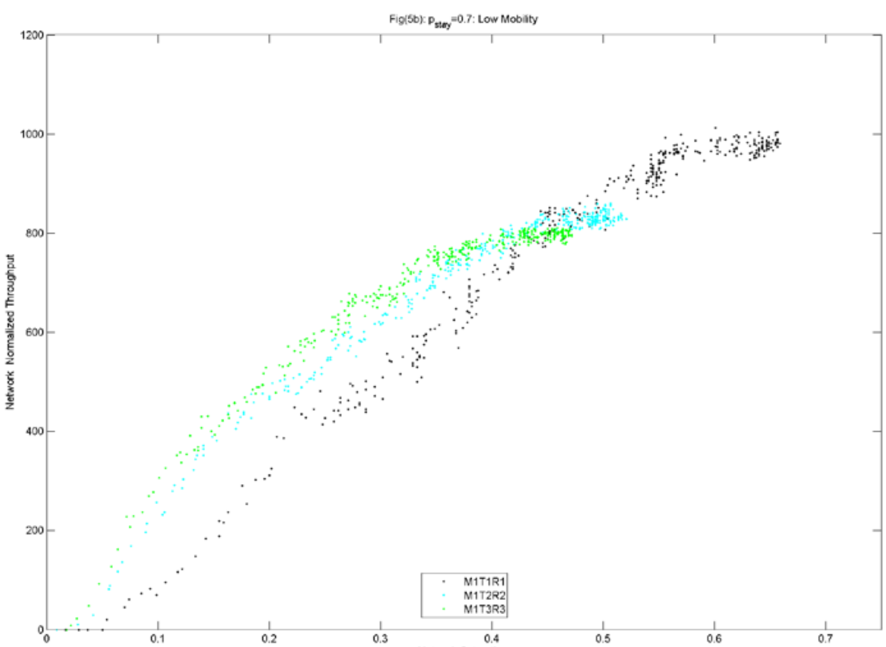


Figure 5a-b: The impact of neighborhood design on the throughput capabilty

V. CONCLUSIONS and FURTHER WORK

This paper describes a generic wireless network whose topology and radio properties emerge as a result of an underlying cellular automaton model. The benefit of the approach is that its simplicity enables us to discover a number of qualitative features of communication in wireless networks which might not have been accessible in other ways.

The relationship between network density and throughput follows a logistic growth pattern in which, initially, there is a positive linear association between throughput and network density, but once the network achieves a critical density, network throughput achieves a maximum level and ultimately tails off asymptotically, until the network becomes saturated, communication failures spread throughout the network resulting in no throughput at all.

Mobility does improve communication across all levels of network density, but this affect is more noticeable at higher levels of network density. With higher mobility, the capacity of the network increases and the network can support larger levels of saturation. This means that mobility delays the onset of communication breakdown and improves network capacity.

With regard to transmission and communication neighborhood size, at lower levels of network density it is beneficial to partition the network into larger neighborhoods (to achieve greater throughput), but once the network is approaching saturation, smaller neighborhoods are preferred in order to boost network throughput and avoid communication breakdown.

With the increase in popularity of Wi-Fi networks, we would like to use these insights to recommend a network design which would optimize throughput under dynamic traffic conditions using (a) elastic coverage areas and (b) mobility to delay the onset of communication breakdown in which too many nodes converge in a particular area and no communication is possible. We also plan to investigate the “broadcast” properties of such networks.

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