Application of Cellular Automata to Modeling Mobility and Radio Communication in Wireless Networks

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Abstract— **In this preliminary study, we first show how a simple Cellular Automata (CA) model can be tailored to the context of radio communication. We then use the model to examine the tradeoff between mobility and radio communication. Within this context, one can view the presence of link *(i,j)* as an advantage in that it enables node *i* to send a packet on one hop to node *j*. However, it can also be a disadvantage in that, when node *i* broadcasts it causes interference at *j*. Thus, while the presence of a large number of links guarantees network connectivity, it brings with it the possibility of increased interference, which reduces the capacity of the network. Our analysis examines how in certain cases, mobility may add to the efficiency of practical networks, whereas in other situations, mobility may become a liability.**

Keywords: cellular automata, mobility and simulation

I. Introduction

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. 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 while the second approach allows the nodes to move around in a completely random manner or according to known mobility patterns. We will refer to the first method as static mobility and to the second as random mobility. There are also models which are a hybrid of these two approaches.

A classic example of static mobility can be seen in [1], which demonstrates how the throughput per source-destination pair deteriorates as the number of nodes per unit area increases.

By contrast, the authors in [2] use random mobility to show that under certain conditions, mobility can significantly increase the per-user throughput. The underlying assumption is that each node has data to send to one other node. The mobility model shows that they will eventually be close enough to communicate. However, delay is not modeled explicitly. Likewise, the authors in [3],[4] propose different mobility patterns on users but their model does not deal with traffic "blocking" behavior or with the channel conditions.

The WINLAB infostations work [5] is an example of a hybrid approach, in which some of the nodes are fixed (infostations) and others move around randomly. The mobility model does address the spatial location of a node (by imposing a grid structure) but, like [2], no limit is imposed on the number of nodes that can simultaneously occupy a single site. In this model, there are numerous nodes, each needing the same information consisting of many separate items. They will only give something if they can get something else that they need. Eventually everyone will get everything. The infostations structure help a lot in making it happen.

The studies are important because they highlight (from different angles) that mobility is a critical factor and should be taken into account to improve wireless network performance. 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 the starting point for our research.

We are aware that a detailed model of mobility in the context of radio propagation represents a significant challenge. Consequently, we propose a simple model which can reduce the mobility problem to its simplest form whilst maintaining the essential features.

II. The Cellular Automata Model

Instead of trying to understand the system from "above" using complex equations, we propose to simulate the system by the interaction of devices following simple rules. This will allow the complexity to emerge and is the idea behind the Cellular Automata (CA) approach, [6],[7].

Cellular Automaton (CA) models are increasingly used in simulations of complex physical systems such as models of self-reproduction in biology, diffusion models in chemistry, in geography to simulate urban sprawl, and most famously in the "Game of Life" in which it was demonstrated that cellular

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automata are capable of producing dynamic patterns and structures. In some of these systems, the CA model provides general qualitative features of the system, while in other cases useful quantitative information can be obtained. The CA approach involves looking at interactions at a local level in order to see whether any global properties emerge. This approach has been used by one of the authors to study qualitative features of traffic jams in urban areas [8], [9] and in this paper these ideas are applied to understand the mechanism of radio communication in wireless networks.

In this model the mobility problem in the wireless network is reduced to its simplest form while the essential features are maintained. These features include (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); and (c) some fundamental properties of radio communication between a pair of nodes.

No attempt is made to draw a more direct analogy between the model and mobility patterns of wireless devices in a real environment.

In wireless networks, the presence of link *(i,j)* can be an advantage in that it enables node *i* to send a packet on one hop to node j. However, it can also be a disadvantage in that, when node i broadcasts it causes interference at *j*. Thus, while the presence of a large number of links guarantees network connectivity, it brings with it the possibility of increased interference, which reduces the capacity of the network. We would like to examine this tradeoff in the context of simple mobility and radio communication behavior to discover the qualitative features of the system with respect to mobility and radio communication.

The benefit of the CA approach is that it can capture the dynamics of the interactions between devices at a local level, without the need for a global description of the entire network. This means that there is no need to impose a network structure (ad-hoc or fixed) – rather allow the structure to emerge as a result of the interactions and user-requirements.

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. We assume that time is discretized, such that at each unit of time, each node moves randomly and independently in one of four directions or it can remain fixed, with certain probability p_{stay}. This probability represents the rate at which terminals move around. Thus, the probability of moving in one of (N,S,E,W) directions is given by

$p_{move} = (1-p_{stay})/4$. One can extend the number of directions, but for simplicity we limit this study to four directions.

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.

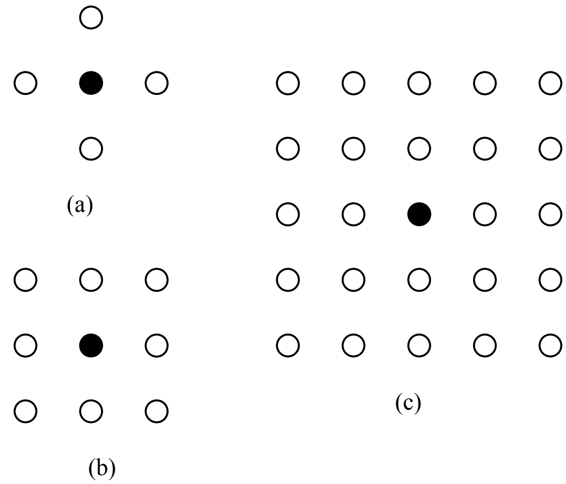

Figure 1. Definitions for Von-Neumann and Moores Neighborhoods

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. Later we plan to explore other combinations of neighborhood.

B. The Transmission 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. 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 $P_i(t)=P$ for all i, i.e. every node emits a maximal power which corresponds to the worst power assignment for interfering communications.

The power of the signal emitted by node *i*, and received by node *j* is $P_i(t)g(x_i(t)-x_j(t))$, where $x_i(t)$ and $x_j(t)$ are the positions of node *i* and node *j* on the lattice at time *t*, respectively and $g(\widetilde{x})$ is the channel gain function in the wireless medium, with $\widetilde{x} = |x_i(t)-x_j(t)|$.

We assume that node *i* can transmit data to node *j* if the signal received by *j* is strong enough, compared to the thermal noise and interference. Formally this can be written as

$$\frac{P_i(t)g(x_i(t)-x_j(t))}{\sigma^2+\sum_{\substack{k\neq i,j\\ k\in\Im}} P_k(t)g(x_k(t)-x_j(t))}\geq\beta \qquad (1)$$

where σ^2 is the power of the thermal background noise and β is the signal to noise ratio required for successful decoding. For simplicity, we initially assume no noise, i.e. $\sigma^2=0$. Note that the denominator includes interference from nodes within the neighborhood of the receiving node (See Figure 2). In this preliminary study the channel gain function *g* is distance-based and *P=1* for all users. Thus we only consider the number of nodes located within neighborhood of receiving node *j* from which an SINR is found.

If condition (1) holds, then, node *i* transmits data to node *j* at rate R packets/sec. The measure of network performance is the total capacity which is calculated as the total number of active connections in the network multiplied by R.

From condition (1) we can build a graph that summarizes the available links between nodes. In this model, we use uni-directional links. Thus, components are assumed to be connected if there exists a link between them. We will consider the situation where connectivity is defined only when a link exists between two nodes in both directions (bi-directional) in a separate study.

C. Communication

If node *i* wants to communicate with node *j*, which is in the same neighborhood then the interference from other nodes in this neighborhood needs to be calculated. Consequently, we examine the power and channel gain conditions of each node within the interference neighborhood of the receiving node in order to calculate the signal-to-interference ratio for node *i* to node j. Figure 2 shows which nodes are included when calculating the SINR from the focal node A to nodes in its neighborhood (for example node B). For diagrammatic simplicity, the "Von-Neumann" neighborhood definition has been used for mobility, transmission and interference. In this example, there are four possible connections, (colored in grey and black (solid and dotted) lines). The SINR is calculated for each connection, and establishes the connection providing that the SINR criterion is met. If there is a limit on the number of connections allowed for each receiving node (say only one connection is allowed), the best available connection is selected from the list.

The SINR criterion is currently based on a step-function: either a transmission can take place, or else it cannot (ON-OFF model). We plan to extend this criterion to cover other aspects of wireless communication such as random channel fading, cooperative coding and diversity, [10].

III. Simulation Model and Results

The mechanism is divided into three stages: mobility, communication and transmission. During the mobility phase, the system determines the location of each node in the system using a set of simple rules. Following this, the set of allowable connections is determined based on the states of nodes within given neighborhoods. This is called the communication phase. The final stage is the transmission stage in which the information is transferred between nodes and the relevant statistics are gathered.

Our simulation experiment used a 10x10 grid with fixed Poisson demand (μ=40) and different SINR thresholds β=0 and β>0. The simulation is run for 150 cycles for various mobility levels ($p=p_{stay}=0.1,\ldots,0.9$). The results in Figures 3-5

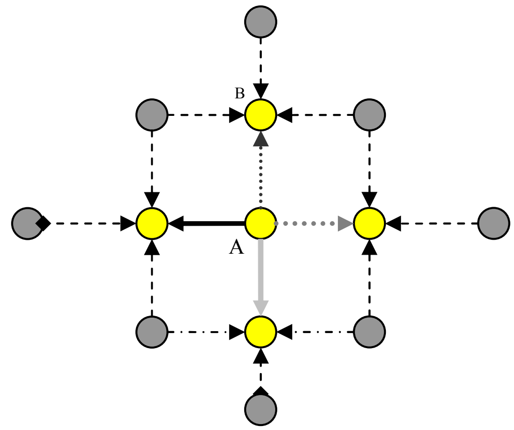

Figure 2. Calculating SINR requirements using a Von-Neumann Neighborhood for Mobility, Transmission and Interference

display the correlation between the number of active connections and the percentage of occupied nodes over the entire simulation period.

We considered three cases β=0, β=1 and β=2 to examine the effect of nearby nodes on the signal strength between node *i* and node *j*. We use β=0 where a connection is always possible between two nodes in a given neighborhood (regardless of other nodes in the neighborhood). With β>0, the effect of other nodes (see Figure 2) within neighborhood of the transmitting pair is dealt with explicitly: a connection is only possible if the signal strength between node i and node j is greater than the SINR threshold, β.

We found that the number of active connections ranges from a high of 80 when β=0 and decreases to 30 with β=1 and a high of 15 when β=2. This is expected, since with each increase in the SINR threshold, it becomes harder to create connections when there are other nodes nearby impairing the signal strength between i and j.

In Figure 3 (β=0) the number of connections is highest as the network approaches saturation and communication is significantly lower and sometimes non-existent at lower levels of network density. Moreover, the relationship between network density and the number of active connections appears to be exponential in nature. The effect of mobility is not immediately apparent with similar patterns for the different levels of $p=p_{stay}$. (Note that we use *p* and p_{stay} interchangeably). However, at low levels of mobility (p=0.9) connections are always possible across the network density spectrum (sparse graph). But at higher levels of mobility, there are more active connections as the network approaches saturation (denser graph), supporting the hypothesis in [2] that mobility increases per-user throughput.

The main difference between Figures 4, 5 and Figure 3 is that many more connections are possible at lower levels of network density (when compared with Figure 3) fewer connections form as the network approaches saturation and very few connections are possible as the network density increases beyond 80%. This trend was noticeable even at

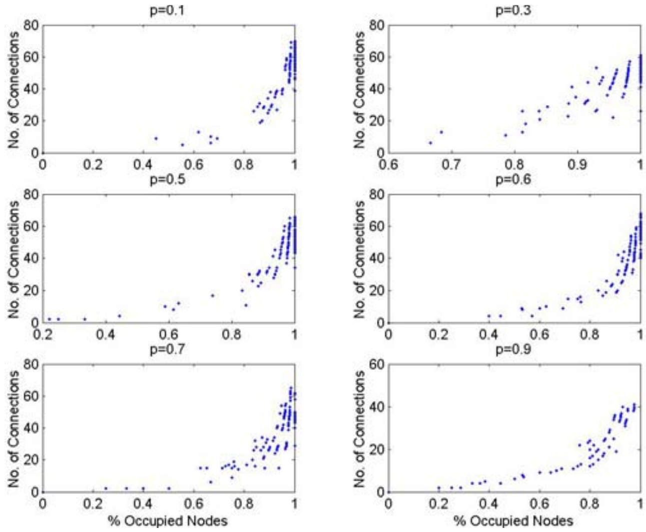

Figure 3: Communication vs. Occupation density for different levels of mobility with β=0. Graphs show how no. of connections grows exponentially as network becomes saturated. No. of connections largest for network densities approaching 100%.

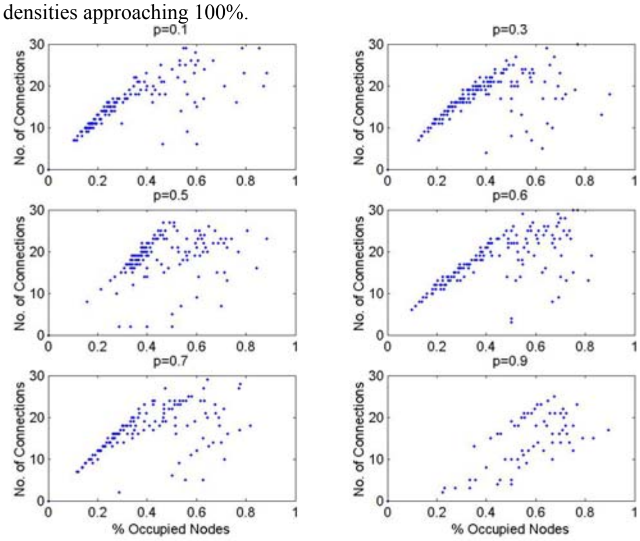

Figure 4: Communication vs. Occupation density for different levels of mobility with β=1. Graphs exhibit linearity in relationship between no. of active connections and network density, for density < 60%. Few connections for network density > 80%.

higher levels of demand (μ=80). In Figure 4 with increased mobility (p<0.6), the graphs appear dense, particularly for low levels of network density, whereas as p increases and nodes are less mobile, the graphs seem more sparse. This suggests that when interference from other nodes is considered, that mobility improves the throughput at lower levels of network density, but once the network becomes saturated, the effect mobility is less significant. Figure 5 demonstrates this trend to a lesser extent.

CONCLUSIONS AND FURTHER WORK

The main conclusions are (a) the number of active connections is highest when the SINR threshold is low (β=0), yet this number decreases with increases in β, (b) without the impact of neighboring nodes, communication is best at high levels of network density but the impact of mobility on per-user throughput is small. When interference from nearby nodes is accounted for, communication is possible across a wider range of network densities including the low to middle

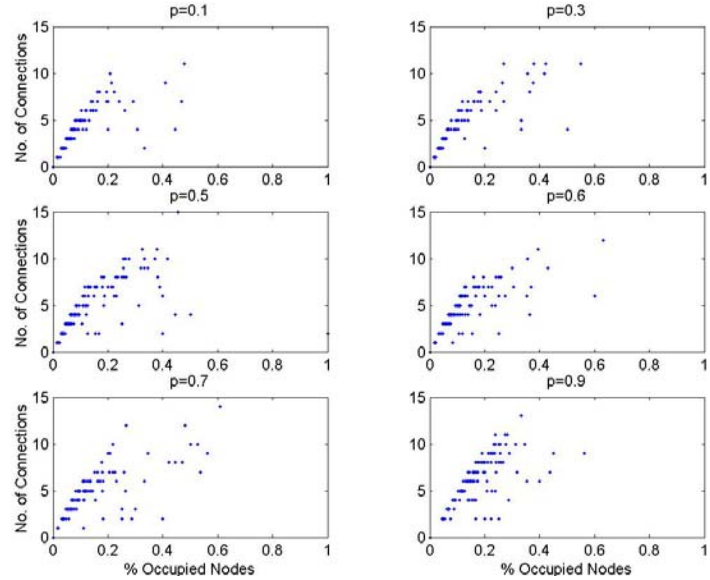

Figure 5: Communication vs. Occupation density for different levels of mobility (β=2). Graphs exhibit linearity in relationship between no. of active connections and network density, for density < 30%. Less connections possible (none beyond network density > 60%) due to higher SINR threshold.

ranges, mobility improves throughput at lower levels of network density, but once the network becomes saturated, fewer connections form and the effect of mobility is less noticeable.

There also appears to be a relationship between the SINR threshold, mobility and network density. We would like to identify the threshold which produces the largest number of connections over the widest network density spectrum and investigate the impact of mobility in this range.

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