Node mobility management for indoor optical wireless cellular networks

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***Abstract*- A novel indoor wireless network is proposed, using infrared wireless links to connect mobile units to a wired infrastructure. Given that the network relies on the medium of infrared, current radio network models need to be adjusted in order to model more accurately the different network characteristics. More precisely, an eight-directional random walk model is employed, rather than the more usual six or four directional walks. Also physical barriers are imposed on the random walks of the nodes. The physical barriers model walls through which humans cannot pass. The mathematical model developed is compared with computer simulations, whose results match the theory very closely. The model would be used to optimize the deployment of such a network in a building.**

I. INTRODUCTION

A new type of network is proposed using indoor, infrared (IR) wireless connections to support mobile terminals. This would provide low cost, flexible networking for a building or enterprise, superior in flexibility to current hardwired systems. The high bit rates and unregulated spectrum of optical wireless communications allows for greater ease of deployment than similar radio systems. Key to the set up of this system is an understanding of node motion in an indoor, optical wireless environment. Significant work has been carried out analyzing mobile unit mobility for radio cellular networks [1], [2], [3], [4], however, these models are not applicable to the different conditions imposed by indoor, optical wireless links.

The overall system would be as follows: users each have a mobile unit whose communication medium is IR (and 'wireless'). The ceilings of the environment in which they are used are equipped with interconnected satellite terminals, which together provide full ground coverage. This system of satellite terminals is directly analogous to the telepoint systems described in [5]. As users move around the building, the units switch automatically from satellite-cell to satellite-cell, similar in principle to the current GSM and UMTS standards.

The satellite terminals are interlinked by means of a low-speed connection which also connects to a base station. One base station might serve a small number of satellite terminals. The base stations in turn are connected by a high-speed ring. Figure 1 illustrates the total network concept.

More precise details of the network set-up are not described here, since they do not directly impinge on the focus of this paper. Rather, we concentrate on analyzing how often it is likely that a user will change cells, (and therefore how often a handover procedure has to be used), since this has a significant consequence on the control traffic load in the network. Some networks achieve an optimal handover procedure through use of the Global Positioning System or other node-finding techniques [6]. Since this is hard for indoor optical wireless networks, this paper assumes that the precise location of the nodes is purely random.

Models already proposed for the current radio cellular networks need to be adapted to cope with the different environment imposed by an indoor, IR system. Specifically, eight-directional random walks are considered, as opposed to the four and six directional walks usually studied [7]. Furthermore, since the satellite cells are likely to be bordered by physical barriers through which mobile nodes cannot pass: i.e. walls, the effect of such barriers is included in the model developed in this paper. These two extensions to the complementary radio models are novel contributions to this area of research.

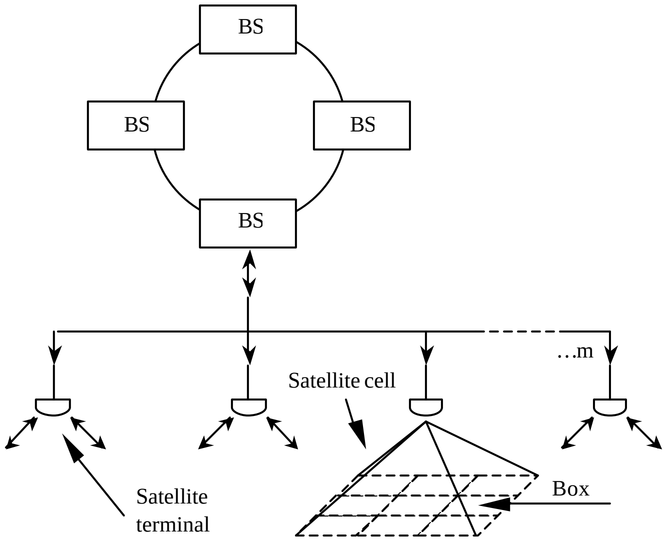

Figure 1: IR telephony network architecture

II. REAL WORLD MODEL

In order to analyze the handover times for the satellite cells, the patch of ground covered by the satellite terminal is divided into a square of $n \times n$ boxes. (see Figure 1). A node occupies exactly one box at any given point in time. We assume that a hologram is employed force the required cell geometry.

A node can move in any one of the eight compass directions; N, NE, E, SE, S, SW,W and NW, and is guaranteed to move every T seconds. This constitutes a random walk very similar to two-dimensional Brownian motion. Although the diagonal directions are physically further displacements than the horizontal and vertical ones, it is assumed that the node may travel from the center of one box to the center of an adjacent box in T seconds, irrespective of the precise length of time taken.

This type of random motion is more applicable to people moving in a building than the random motion model studied in [8], where nodes move for a random length of time in a randomly oriented straight line. It is also more representative of optical wireless networks than the more deterministic mobility model proposed and developed in [9], where a user moves through a cell in a straight line. It may also be feasible to apply a graph-based mobility model for a building similar to ones developed for ad hoc networks [10]. Such a model would be considerably harder for a building, however, since the density of meeting points for different paths is far greater than for a street map.

The other key difference between this and equivalent radio cell models, is that the barriers imposed by walls on a building alter the otherwise purely random motion of the nodes. It is crucial that this factor be taken into account when analyzing the random walks of the nodes. There are five possible combinations of physical barriers around the satellite cells, restricting the movement of the nodes. These are as shown in Figure 2. We don’t consider a cell with four barriers (and a door), since the mobility of a node in this cell is likely to be very small: such a cell would represent an office, in which a person would be expected to spend most of their time stationary.

Results are developed, both theoretically and through simulation, for each of the five cells shown in Figure 2, as well as for a variety of different cell sizes.

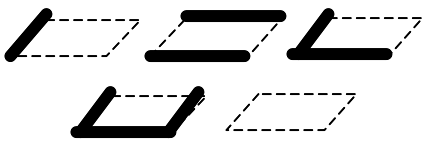

Figure 2: Barrier combinations for satellite cells

III. THEORETICAL ANALYSIS

A Markov model is used to analyze the expected time for when a node leaves a satellite-cell. The principle is very similar to that shown by Akyildiz [1], except that it is of no interest to optimize the prediction algorithms, using symmetry or otherwise, since the algorithms are unlikely to be implemented on any satellite terminal.

The procedure is as follows: the n^2 boxes of a satellite-cell are individually numbered. A transition matrix is then developed for the probabilities of moving from one box to another in the usual way: i.e. $[T_{i,j}]$ is the probability that the person (node) moves from box i to box j. If a box is on the edge of a cell where a barrier is present, then the node only has at most five possible directions, otherwise it has eight directions available. Next, a further column and row are added to the to the matrix, termed the 'out' column/row. These show the probability of the person leaving the satellite cell, given that they were in a particular cell. Clearly, $[T_{n^2+1,n^2+1}]$ is equal to 1, so that the probability of re-entering the satellite cell is zero. This is because we only concern ourselves with the time at which a person *first* leaves the cell, and not with the subsequent times at which he may re-enter. The Chapmann - Kolmogorov equation shows that multiplication of the transition matrix, $[T]$, with itself k times provides the probabilities for being in any particular state, j, given a starting state, i at time $k = 0$ [11]. So the probability of a person being outside the cell at time k, given that they started in box i is clearly

$$P_{out,i}(k) = P(i) \cdot [T_{i,n^2+1}]^k \qquad (1)$$

where $P(i)$ is the probability that the person started in state i at time $k = 0$. To find the probability of the person having left the cell at time k, irrespective of their starting state, a union of $P_{out,i}(k)$ is calculated for all i. Since the probabilities $P_{out,i}(k)$ are all independent, this union may be simplified to a summation.

$$P_{out}(k) = \sum_i P(i) \cdot [T_{i,n^2+1}]^k \ . \qquad (2)$$

However, it may be surmised that the starting state for the node is randomly distributed with a discrete, uniform distribution. In other words,

$$P(0) = P(1) = \ldots = P(i) = \ldots = P(n^2) = \frac{1}{n^2} . \qquad (3)$$

And therefore

$$P_{out}(k) = \frac{1}{n^2} \cdot \sum_i [T_{i,n^2+1}]^k \ . \qquad (4)$$

The 'out' state is a recurring state: in fact, having entered this 'out' state, the node remains there permanently. Therefore, as the time increases towards the infinite, nodes will enter this state and remain there with probability 1, irrespective of their starting state. In other words, it is certain that the node will eventually leave the cell. Differencing these results leads to the probability density distribution $P_{out}(k)'$. This distribution may then be numerically evaluated to provide the ***expected*** time for which the node leaves the satellite-cell:

$$\{E(k)\} = \sum_k k \cdot P_{out}(k)' \ . \qquad (5)$$

Implementing this theory in a computer program, the average time taken for a node to leave the different cell-structures is calculated and shown in Figure 3, for a range of cell sizes.

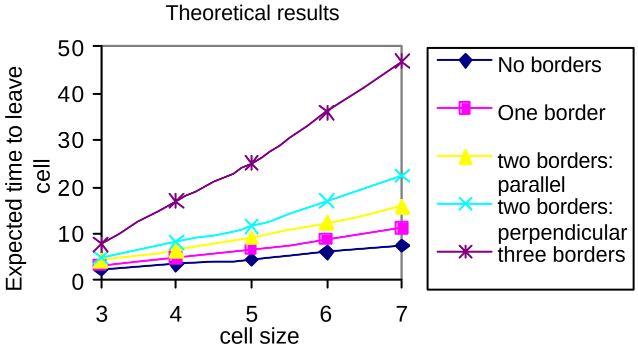

Figure 3: Theoretical times for a node's 'stay' in cells of varying structure and size.

The following remarks may be made about the results:

1) for larger cells, the time a node remains in a particular cell is also greater.
2) nodes typically remain in a cell for longer where there are many physical barriers.

The first point is very intuitive; the theory simply adds detail to describe accurately the relationship between cell size and the average length of time a user may spend in it. The second remark is a consequence of the random walks themselves: once in a corner surrounded by barriers, a node has further to go before it leaves the cell, than were there to be no barriers. Humans would not necessarily walk either deliberately or randomly towards a wall, which is a perfectly legitimate and expected characteristic of the model proposed here. This illustrates the main discrepancy between the model and a real world system: i.e. that human's motion is not random. Another aspect similar to this is that humans do not spend their time moving continuously; they may remain stationary for a considerable length of time. A model more accurate to the real world might incorporate these features of human motion.

One final, but more subtle difference between the real world and this model, is that the results generated above do not consider the passage of a node through many satellite cells; the starting box in a satellite cell is not generally random (as was assumed here for both theory and simulation); rather a node would enter it from an edge, having just left an adjacent satellite cell.

Computer simulations of this theory readily verify the results, however the detail is not included here.

IV. CONCLUSION

A theoretical model has been developed for handover times between satellite cells of an infra-red, wireless network. Computer simulations of the system agree with the theoretical results. Since the network described here is expected to carry real-time data, it is imperative that its functionality be optimal. The model outlined here may be used to optimize the size and placement of cells within a building; in turn optimizing the amount of control data flowing through the network.

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