An Analysis of the Node Spatial Distribution of the Random Waypoint Mobility Model for Ad Hoc Networks

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ABSTRACT

In this paper we analyze the node spatial distribution generated by nodes moving according to the random waypoint model, which is widely used in the simulation of mobile ad hoc networks. We extend an existing analysis for the case in which nodes are continuously moving (i.e., the pause time is 0) to the more general case in which nodes have arbitrary pause times between movements. We also generalize the mobility model, allowing the nodes to remain stationary for the entire simulation time with a given probability. Our analysis shows that the structure of the resulting asymptotic spatial density is composed by three distinct components: the initial, the pause and the mobility component. The relative values of these components depend on the mobility parameters. We derive an explicit formula of the one-dimensional node spatial density, and an approximated formula for the two-dimensional case. The quality of this approximation is verified through experimentation, which shows that the accuracy heavily depends on the choice of the mobility parameters.

1. INTRODUCTION

Performance analysis in presence of mobility is of primary importance in the design of wireless networks. For example, in cellular networks user's movement patterns are used to optimize the cell and location area layout, the dynamic channel allocation scheme, and so on. Since real movement patterns are often difficult to obtain, a common approach is to use a synthetic mobility model, which resembles to some extent the behavior of real "mobile entities". Based on this model, useful conclusions regarding critical network parameters can be provided. However, the accuracy of the results heavily depends on how close the chosen model is to the real scenario.

Mobility modeling has been extensively studied in the field of cellular networks. For example, Zonoozi and Dassanayake [20] have shown (by means of extensive simulations and "goodness-of-fit" tests) that the cell residence time of a mobile user moving according to a given mobility pattern follows a generalized gamma distribution. In the Brownian mobility model, it has been shown that, given the user's location at time t_0, the probability distribution of the physical location at time $t > t_0$ can be calculated [12]. Very accurate mobility models for cellular networks are presented in [13, 17]. For a survey of mobility modeling of cellular networks see [2].

Although interesting, these results are not applicable to ad hoc networks. In fact, most of them concern specific properties of cellular networks (e.g., cell residence time, number of handoffs during a call, and so on). Furthermore, the emphasis is usually on modeling the properties of a single mobile user, rather than on the global mobile users distribution. Finally, the mobility patterns considered resemble the typical motions that occur in cellular systems, i.e. human and vehicular motion. Hence, an accurate study of the probabilistic properties of a mobile ad hoc network is, to the best of our knowledge, still lacking.

In this paper we analyze the node spatial distribution generated by the random waypoint mobility model, which is commonly used in the simulation of mobile wireless ad hoc networks (see, e.g., [6, 7, 9, 10, 11, 15, 18, 19]). Preliminary steps in this direction have been recently done [2, 3, 5]. In [2, 3], it is observed that nodes moving according to the random waypoint model tend to concentrate in the middle of the deployment region R, originating the so called *border effect*. This indicates that the node spatial distribution *is not* uniform. To some extent, this reduces the applicability of existing theoretical results concerning mobile ad hoc networks [1, 8, 14], which are based on the so called uniformity assumption: i.e., they assume that in any snapshot of the mobile network the nodes are distributed uniformly and independently at random in the deployment area. The validity of this hypothesis has been carefully investigated in [5], where it is shown that for large values of the pause time (i.e., of the resting time between two consecutive movements) the border effect is limited, and the spatial distribution can be well approximated with the uniform distribution. However, for other combinations of the mobility parameters the border effect becomes very intense, and the resemblance with the uniform distribution is no longer valid.

A further step in understanding the node spatial distribution generated by the random waypoint model has been done in [4], where an exact formula for the one-dimensional node spatial distribution (i.e., nodes moving along a line) when the pause time is 0 is derived. In this paper, we extend the analysis of [4] to the more general case in which nodes have arbitrary pause times between movements. Further, we slightly generalize the mobility model, allowing the nodes to remain stationary during the entire simulation time with a give probability. This generalization accounts for those situations in which some nodes are not able (or willing) to move.

We derive the exact formula for the one-dimensional case, and an approximated formula for the two-dimensional case. In both cases, the node spatial distribution is composed by three distinct components: the initial, the pause and the mobility component. The quality of our approximation in the two-dimensional case is verified through experimentation, which shows that the formula fits well experimental data for some choices of the mobility parameters, while it is not very accurate when the mobility component of the distribution prevails. Finally, we briefly discuss how our analysis could be applied to a more general and realistic version of the random waypoint model.

2. THE NODE SPATIAL DISTRIBUTION OF THE RANDOM WAYPOINT MODEL

In the random waypoint model [11], nodes are initially uniformly distributed in the deployment region R. In this paper, we assume that R is of the form $[0,1]^d$, with $d = 1, 2$. Then, every node chooses a destination point uniformly at random in R, and moves towards it along a straight line with a velocity chosen uniformly at random in the interval $[v_{min}, v_{max}]$. When it reaches the destination, it remains stationary for a predefined pause time t_{pause}, and then it starts moving again according to the same rule. We have included a further parameter in the model, namely the probability p_{stat} that a node remains stationary during the entire simulation time. Hence, only $(1-p_{stat}) \cdot n$ nodes (on the average) will move. Introducing p_{stat} in the model accounts for those situations in which some nodes are not able to move. For example, this could be the case when sensors are spread from a moving vehicle, and some of them remain entangled, say, in a bush or tree. This can also model a situation where two types of nodes are used, one type that is stationary and another type that is mobile.

2.1 The density function

We are interested in characterizing the asymptotic node spatial distribution, i.e. the distribution that results from a network whose nodes move according to the random waypoint model for a very large number of mobility steps. First, we observe that in this mobility model each node moves independently of each other, hence we can concentrate our attention on the spatial distribution of a single node. More formally, we want to determine the probability density function $PDF_{X(t)}$ as t grows to infinity, where $X(t)$ denotes the position of the node in the deployment region R at time t.

As it can be easily seen, this density function is composed by three distinct components: the *initial*, the *pause* and the *mobility* component. The initial component accounts for the fact that a node can remain stationary for the entire network operational time. The pause component accounts for the fact that a node "rest" before starting a new movement. Finally, the mobility component accounts for the time that a node is actually moving. In the following, we consider each component separately.

The initial component can be easily determined by observing that a node remains stationary during the entire network operational time with probability p_{stat}, and that nodes are initially distributed uniformly at random in R. Denoting with X the coordinate vector of the node in the d-dimensional space, and observing that a stationary node will never move, the initial component f_I of the density function is:

$$f_I(X) = \begin{cases} p_{stat} & \text{if } X \in [0,1]^d \\ 0 & \text{otherwise} \end{cases},$$

independently of the time t at which we observe the node position. Hence, the initial component is the uniform distribution except for the fact the $\int_R f_I(X)dX$ equals p_{stat} and not 1 as in the uniform case[1]. Thus, the initial component can be seen as a uniform distribution "weighted" by p_{stat}.

Since the starting and ending point of a node movement in the random waypoint model are chosen uniformly at random in R, the pause component has a formula similar to that of the initial component. More precisely, we have:

$$f_{P(t)}(X) = \begin{cases} (1-p_{stat})p(t) & \text{if } X \in [0,1]^d \\ 0 & \text{otherwise} \end{cases},$$

where $f_{P(t)}$ denotes the pause component of the density function at time t, and $p(t)$ is the probability that a node is "resting" at time t. The term $(1-p_{stat})$ accounts for the fact that a resting node is not stationary. Since we are interested in characterizing the asymptotic density (i.e., the density as $t \to \infty$), we must determine the value of $p(t)$ as $t \to \infty$. This way we obtain the asymptotic expression of the pause component, denoted f_P. For the sake of simplicity, assume that $v_{min} = v_{max} = v$, i.e. that the node always moves with the same velocity v.

In the random waypoint model, a node alternates rest periods (lasting t_{pause} steps each) and movement periods. Under our simplifying hypothesis $v_{min} = v_{max} = v$, the duration of a movement period depends only on the distance between the starting and destination point of the movement. Let $i(t)$ denotes the number of movements completed before time t, and let t_{move_j} denotes the duration of the j-th movement (see Figure 1).We have:

$$\begin{aligned} \lim_{t\to\infty} p(t) &= \lim_{t\to\infty} \frac{\sum_{j=1}^{i(t)} \frac{t_{pause}}{t_{pause}+t_{move_j}}}{i(t)} \\ &= \lim_{t\to\infty} \frac{t_{pause}\sum_{j=1}^{i(t)} \frac{1}{t_{pause}+t_{move_j}}}{i(t)} \end{aligned}$$

[1] Slightly abusing the notation, we have concisely indicated with $\int_R f_I(X)dX$ the integral on the appropriate dimension. For instance, when $d = 2$ the integral should be written as $\int_R f_I(x,y)dxdy$.

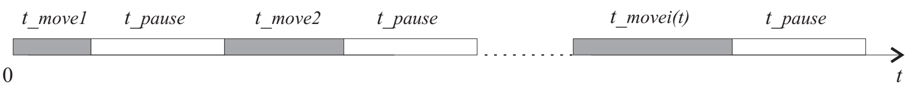

Figure 1: A node alternates between rest periods (t_{pause}) and movement periods (t_{move_j}) .

By the law of large numbers, we obtain:

$$\lim_{t\to\infty} \frac{t_{pause}\sum_{j=1}^{i(t)} \frac{1}{t_{pause}+t_{move_j}}}{i(t)} = \frac{t_{pause}}{t_{pause}+E[t_{move}]} \;,$$

where $E[t_{move}]$ is the expected duration of the movement period. Denoting with $E[dist]$ the expected distance between a pair of points chosen uniformly at random in R, we can conclude that $\lim_{t\to\infty} p(t) = \frac{t_{pause}}{t_{pause}+\frac{E[dist]}{v}} = p$.

2.2 The mobility component

Contrary to the case of the initial and pause component, the mobility component *is not* uniform. In fact, this is the component that generates the border effect observed in [2, 3, 5]. Denoting with $f_M(X)$ the limit of the mobility component as $t \to \infty$, and given the discussion of Section 2.1, we can state the following theorem:

THEOREM 1. *The asymptotic spatial density function of a node moving in $R = [0,1]^d$, with $d = 1, 2$, according to the random waypoint model of parameters p_{stat}, t_{pause} and $v_{min} = v_{max} = v$, is*

$$f(X) = p_{stat} + (1 - p_{stat})p + (1 - p_{stat})(1 - p)f_M(X)$$

if $X \in [0,1]^d$ and f(X)=0 otherwise, where $p = \frac{t_{pause}}{t_{pause}+\frac{E[dist]}{v}}$.

The formula for $f(X)$ of Theorem 1 is fully coherent with the statistical analysis presented in [5] for the case $d = 2$: the density is the sum of a uniform $(f_I(X) + f_P(X))$ and a non-uniform $(f_M(X))$ component. As p_{stat} and/or t_{pause} increase, the uniform component of the density becomes predominant, and $f(X)$ can be well approximated with the uniform distribution. Conversely, for small values of p_{stat} and/or t_{pause}, the non-uniform component dominates and generates a significant border effect. The influence of the velocity on $f(X)$ is less evident: in general, higher velocities cause a decreased value of t_{move} and, consequently, a more uniform distribution. However, for extreme values of t_{pause} the effect of the velocity is negligible. For example, if $t_{pause} = 0$ then the pause component of the density is 0, regardless of the value of v. Similarly, if t_{pause} is very large, then $p \approx 1$ regardless of the value of v.

In order to give a precise formula for $f(X)$, we need to evaluate $E[dist]$ and $f_M(X)$. The expression of $f_M(X)$ for one-dimensional motion (i.e., the node moves along a line of length 1) has been derived in [4], using a technique based on the construction of a temporal histogram that counts how often the node is observed in any point $x \in [0,1]$. Since the expected distance between a pair of points chosen uniformly at random in [0,1] is 1/3 [16], we can state the exact formula of the asymptotic spatial distribution of a node moving according to the one-dimensional random waypoint model:

THEOREM 2. *The asymptotic spatial density function of a node moving in $[0,1]$ according to the random waypoint model of parameters p_{stat}, t_{pause} and $v_{min} = v_{max} = v$, is*

$$f(x) = p_{stat} + (1 - p_{stat})p + (1 - p_{stat})(1 - p)6x(1 - x)\,,$$

if $x \in [0,1]$, and $f(x) = 0$ otherwise, where $p = \frac{t_{pause}}{t_{pause}+\frac{1}{3v}}$.

Function $f(x)$ for different combinations of the mobility parameters is shown in figures 2 and 3. The correspondent cumulative density function $CDF(x)$ is also reported. For the sake of comparison, the figures show the curves obtained with the uniform distribution. As it is seen, for increasing values of p_{stat} and/or t_{pause} the plots of $f(x)$ and $CDF(x)$ approach those of the uniform distribution. It is also seen that the non-uniform component of the density (obtained when $p_{stat} = t_{pause} = 0$) is parabolic.

Deriving the exact expression of the two-dimensional node spatial distribution is much more complicated: while the expected distance between a pair of points uniformly distributed in $[0,1]^2$ is known to be 0.521405 [16], obtaining the expression of $f_M(x,y)$ is very difficult. In fact, as observed in [4], the mobility component in two dimensions cannot be directly derived from the formula for the one-dimensional case, since the two-dimensional movement is composed by two *dependent* one-dimensional movements. Furthermore, the speed of the mobile node when projected along the x-axis in general is not constant, and is different from the (non-constant) speed along the y-axis. Determining the exact expression for $f_M(x,y)$ is an open problem, and is beyond the scope of this paper. Instead, we will use the approximated formula presented in [4], which is obtained by simple (independent) composition of the one-dimensional components of the movement.

THEOREM 3. *The asymptotic spatial density function of a node moving in $[0,1]^2$ according to the random waypoint model of parameters p_{stat}, t_{pause} and $v_{min} = v_{max} = v$, is approximated by the following formula:*

$$\begin{aligned} f(x,y) &= p_{stat} + (1 - p_{stat})p \\ &+ (1 - p_{stat})(1 - p)36xy(x-1)(y-1)\,, \end{aligned}$$

if $(x,y) \in [0,1]^2$, and $f(x,y) = 0$ otherwise, where $p = \frac{t_{pause}}{t_{pause}+\frac{0.521405}{v}}$.

In the next section, we evaluate the accuracy of this formula for different values of the mobility parameters through extensive simulation.

3. EXPERIMENTAL EVALUATION

For the experiments we have utilized the simulator used in [5] to test the uniformity of the node spatial distribution.

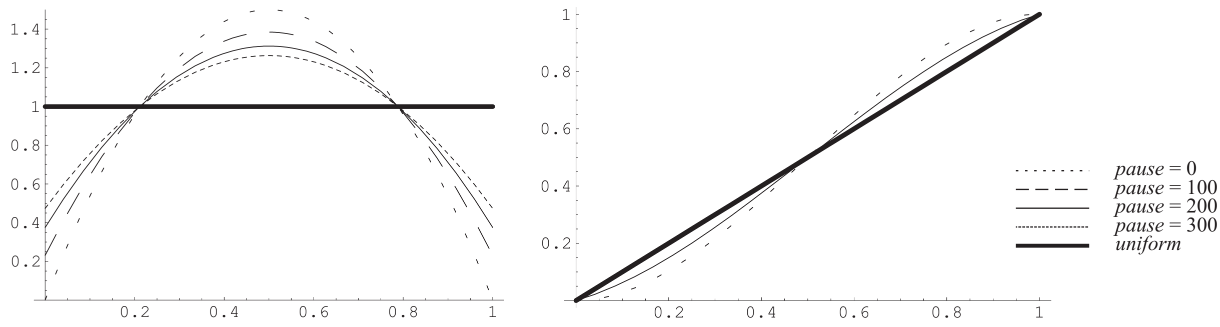

Figure 2: Density and cumulative density function of the one-dimensional node spatial distribution for different values of the pause time. p_{stat} and v are set to 0 and 0.001, respectively.

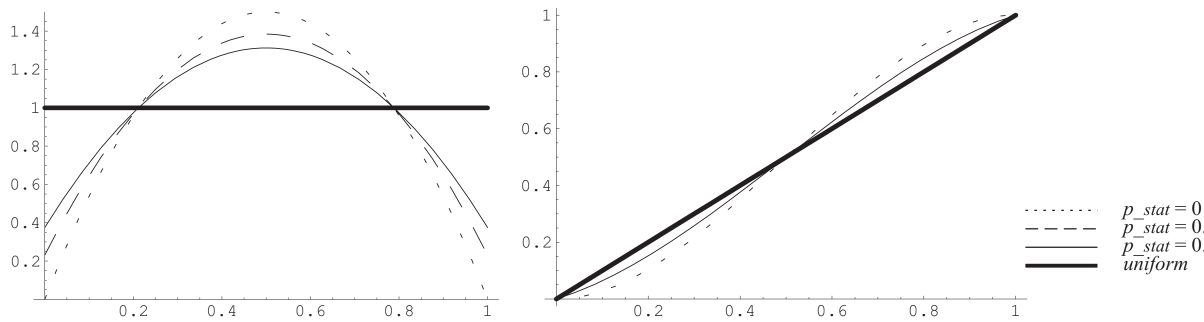

Figure 3: Density and cumulative density function of the one-dimensional node spatial distribution for different values of p_{stat}. The pause time and v are set to 0 and 0.001, respectively.

The simulator takes as input the number n of nodes to distribute, the number $\sharp sim$ of simulations to run and the number $\sharp steps$ of mobility steps to perform for each simulation. The simulator also takes as input the parameters of the random waypoint model, i.e. p_{stat}, t_{pause} (expressed as the number of steps that the node remains stationary between two movements), and the minimum (v_{min}) and maximum (v_{max}) velocity. Nodes are distributed uniformly and independently at random in $[0,1]^2$; then, they start moving according to the random waypoint mobility model. In order to record the node spatial distribution, we divide $[0,1]^2$ into a number of square cells of the same side, arranged in a grid fashion. In our experiments, we used a grid of 31×31 cells of side 1/31. After $\sharp steps$ steps of mobility, the number of nodes in each cell is recorded. These numbers are accumulated over the $\sharp sim$ simulations, and are reported as the result of the experiment. If the theoretical analysis is accurate, the 3D plot obtained using these data should closely resemble that obtained by our formula.

In the first experiment, we have evaluated the accuracy of our approximation of $f_M(x,y)$. For this reason, we set p_{stat} and t_{pause} to 0, and $v_{min} = v_{max} = 0.01$. We then distributed $n = 961$ nodes in the deployment region, and we performed 10000 simulations of 10000 mobility steps each. These numbers were chosen since they are a good compromise between statistical accuracy (we recall that our simulation corresponds to 9610000 independent experiments) and running time.

The 3D and contour plot resulting from the experiment, which are reported in Figure 4, show a certain resemblance with the plots for $f_M(x,y)$ (Figure 5). As evidenced by the graphics shown in Figure 6, referring to two cuts parallel to the x-axis (for $y = 0.5$ and $y \approx 0.21$), and to the diagonal cut of the 3D plot, the resemblance is quite close in the central cut ($y = 0.5$), while it is poor in the cut for $y \approx 0.21$ and for the diagonal cut. This is due to the fact that the approximation made in the derivation of the formula for $f_M(x,y)$ (i.e., that the two-dimensional movement can be decomposed into two independent one-dimensional components) becomes more and more relevant as we get close to the border of R.

Since the only approximation made in the formula of Theorem 3 is in the derivation of $f_M(x,y)$, we expect that the formula becomes more and more accurate as the initial and pause component of the spatial distribution get increasingly relevant. To verify this, we have repeated the experiment for two different settings of the mobility parameters. First, we set $p_{stat} = 0.1$, $t_{pause} = 100$ and $v_{min} = v_{max} = 0.01$; then, we set $p_{stat} = 0.3$, $t_{pause} = 300$ and $v_{min} = v_{max} = 0.01$ in the second. As in the previous case, we set $n = 961$ and $\sharp steps = \sharp sim = 10000$. The results of these experiments are reported in figures 7 and 8. As expected, the accuracy of the formula of Theorem 3 depends on the relative contribution of the components to the node spatial distribution: as the contribution of the mobility component lessen, our formula becomes more and more accurate. Note that, especially in the first scenario (Figure 7), the accuracy of the formula along the diagonal cut remains critical.

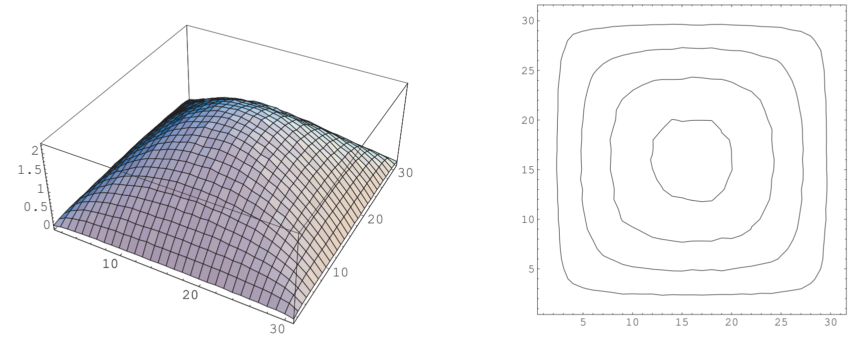

Figure 4: Three-dimensional plot of the experimental data, and contour lines corresponding to the values $f_M(x, y) = .5$, 1, 1.5 and 2.

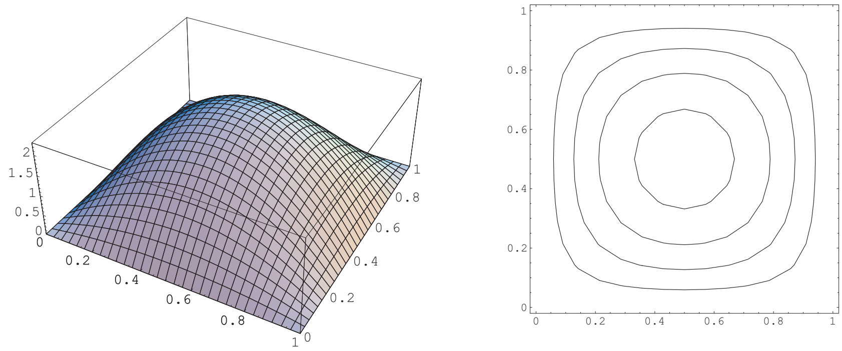

Figure 5: Three-dimensional plot of the approximate expression of $f_M(x, y)$, and contour lines corresponding to the values $f_M(x, y) = .5$, 1, 1.5 and 2.

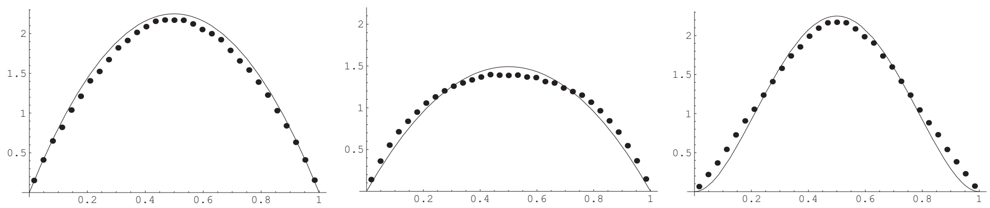

Figure 6: Cuts parallel to the x-axis for $y = 0.5$ (left) and $y \approx 0.21$ (center), and diagonal cut (right) of the 3D plots of the approximate and experimental node spatial distribution. Experimental data are represented by bold points.

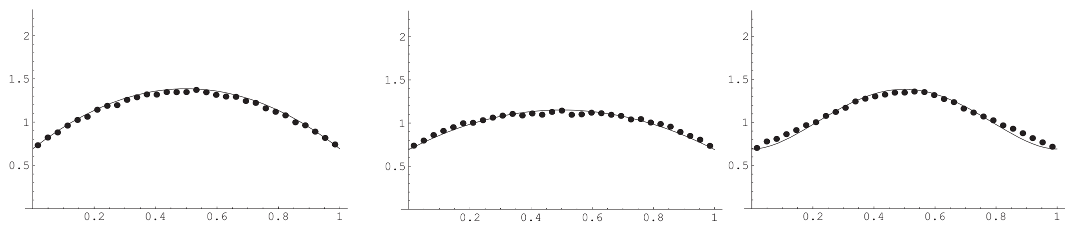

Figure 7: Cuts parallel to the x-axis for $y = 0.5$ (left) and $y \approx 0.21$ (center), and diagonal cut (right) of the 3D plots of the approximate and experimental node spatial distribution for the case $p_{stat} = 0.1$, $t_{pause} = 100$ and $v_{min} = v_{max} = 0.01$. Experimental data are represented by bold points.

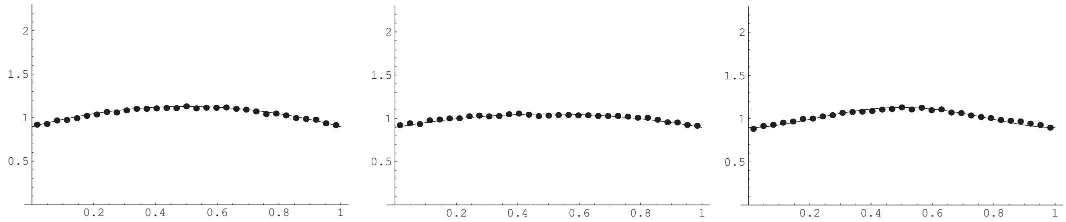

Figure 8: Cuts parallel to the x-axis for $y = 0.5$ (left) and $y \approx 0.21$ (center), and diagonal cut (right) of the 3D plots of the approximate and experimental node spatial distribution for the case $p_{stat} = 0.3$, $t_{pause} = 300$ and $v_{min} = v_{max} = 0.01$. Experimental data are represented by bold points.

4. A GENERALIZATION OF THE RANDOM WAYPOINT MODEL

In the previous sections, we have analyzed the one and two-dimensional node spatial distribution of the random waypoint model. In our analysis, we have often used the law of large numbers to estimate the asymptotic value of some parameters (e.g., the probability p that a node is resting at a given time). Hence, our results can be straightforwardly extended to a generalized random waypoint model, where the pause time and the velocity are chosen according to arbitrary probability distributions with expectation $E[t_{pause}]$ and $E[v]$, respectively. We can further generalize the mobility model by allowing the node to be initially placed according to an arbitrary density f_{init}. The generalized random waypoint model can be then defined as follows:

DEFINITION 1 (GENERALIZED RWP MODEL). *In the generalized random waypoint model, nodes are initially distributed in $R = [0,1]^d$ $(d = 1,2)$ with density f_{init}. A node remains stationary for the entire network operational time with probability p_{stat}. If the node is not stationary, it chooses its destination uniformly at random in R, and moves towards it with a velocity v chosen according to an arbitrary probability distribution $\mathcal{P}_v$. When the node arrives at destination, it rests for a time t_{pause}, chosen according to an arbitrary probability distribution $\mathcal{P}_{pause}$. Then, it starts a new movement as described above.*

We believe that this generalization of the random waypoint model allows a more accurate simulation of realistic scenarios. In fact, nodes can be initially placed according to an arbitrary distribution, rather than the uniform distribution. Thus, we can model those situations in which nodes are, for instance, initially concentrated in a subregion of R. More importantly, we do not force a node to have the *same* pause time during the entire network operational time. This is a very unrealistic aspect of the random waypoint model, which is further amplified by the fact that the pause time is assumed to be the same *for all the nodes in the network.* Conversely, we simply assume that the pause time after each movement is chosen according to an arbitrary distribution, *which does not change with time.* Furthermore, this distribution is the same for all the nodes in the network. Then, our probabilistic homogeneity assumption is far less stringent than the equality assumption of the original model. A similar generalization is made for the velocity, which is chosen according to an arbitrary distribution, which does not change with time and is the same for all the nodes in the network.

We can thus state the following theorem, which concludes this paper:

THEOREM 4. *The asymptotic spatial density function of a node moving in $R = [0,1]^d$, with $d = 1,2$, according to the generalized random waypoint model of parameters f_{init}, p_{stat}, $\mathcal{P}_{pause}$ and $\mathcal{P}_v$, is*

$$f(X) = p_{stat} f_{init} + (1 - p_{stat})p + (1 - p_{stat})(1 - p) f_M(X)$$

if $X \in [0,1]^d$, and $f(X) = 0$ otherwise, where

$$p = \frac{E[\mathcal{P}_{pause}]}{E[\mathcal{P}_{pause}] + \frac{E[dist]}{E[\mathcal{P}_v]}},$$

$E[\mathcal{P}_{pause}]$ is the expected pause time, $E[\mathcal{P}_v]$ is the expected velocity, and $E[dist] = 1/3$ when $d = 1$, and 0.521405 when $d = 2$.

Theorem 4 is interesting, since it states that as long as the motion pattern has some (probabilistic) homogeneity, the asymptotic spatial density is composed by three distinct component: the initial component f_{init}, a uniform component generated by the fact that the movement destinations are chosen uniformly in R, and the mobility component $f_M(X)$. The relative values of these components depend on p_{stat} and on the *expected value* (not on the actual distribution) of the pause time and velocity. Hence, a very large class of mobility models is captured by the formula stated in Theorem 4.

5. CONCLUSIONS

In this paper, we have analyzed the one and two-dimensional node spatial distribution generated by the random waypoint model. We have provided the exact formula for the one-dimensional case, and an approximate formula for the two-dimensional case. The quality of our formula for the two-dimensional case has been evaluated through experimentation, whose results have shown a very good fit between the experimental and approximate curves when the relative contribution of the mobility component to the spatial distribution is moderate. When the mobility component dominates, our formula is still a reasonable approximation of the central cut of the distribution, while it does not accurately resemble the actual distribution as we get close to the border of R. The main problem left open by this paper is the derivation of the exact formula (or, at least, of a better approximation) of the two-dimensional mobility component of the distribution, which is matter of ongoing work.

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