Distribution of Liveness Property Connectivity Interval in Selected Mobility Models of Wireless Ad Hoc Networks

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Abstract. The *ad hoc network liveness property* disallows permanent partitioning to occur by requiring (informally) that from each time moment *reliable direct connectivity* must emerge between some nodes from every (non-empty) subset of hosts and its complementary set within some finite, but unknown, *connectivity time interval* I. An analysis of the connectivity interval is important because its finite values legitimise the liveness property assumption. Moreover, since the connectivity interval demonstrates a crucial factor of message dissemination time in ad hoc networks, its distribution significantly affects the efficiency of all protocols based on the liveness property. Therefore, in this paper, we present the distribution of the connectivity interval determined experimentally by simulation of several entity and group mobility models and real-life GPS traces of mobile nodes. We also conduct a statistical analysis of received results and show how the connectivity interval correlates with other network parameters.

1 Introduction

Mobile ad hoc networks (MANETs) [1,2] are composed of autonomous and mobile hosts (or communication devices) which communicate through wireless links. The distance from a transmitting device at which the radio signal strength remains above the minimal usable level is called the *transmission* (or *wireless*) *range* of that host. Therefore, each pair of such devices, whose distance is less than their transmission range, can communicate directly with each other—a message sent by any host may be received by all hosts in its vicinity. Hosts can come and go or appear in new places. As such, the resulting network topology may change all the time and can get partitioned and reconnected in a highly unpredictable manner.

The highly dynamic network topologies with partitioning and limited resources are the reasons why heuristic group communication and broadcast protocols with only probabilistic guarantees have been mainly proposed for the use in ad hoc networks (e.g. [4]). On the other hand, if it can be assumed that a group of collaborating nodes in an ad hoc network can be partitioned and that partitions

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heal eventually, it is possible to develop deterministic dissemination protocols used subsequently to develop more complex distributed algorithms like consensus or coherency protocols. The liveness property disallows permanent partitioning to occur by requiring (informally) that from each time moment *reliable direct connectivity* must emerge between some nodes from every (non-empty) subset of hosts and its complementary set within some finite, but unknown, *connectivity time interval I*.

In this context, an analysis of the connectivity interval is important because its finite values legitimise the liveness property assumption. Moreover, since the connectivity interval demonstrates a crucial factor of message dissemination time in ad hoc networks, its distribution significantly affects the efficiency of all protocols based on the liveness property. Therefore, in this paper, we present the distribution of the connectivity interval determined experimentally by simulation of several entity (Random Walk, Random Waypoint, Random Direction, Chiang Model, Haas Model, Gauss-Markov Model) and group (Exponential Correlated Random Mobility, Column Model, Nomadic Community Model) mobility models and real-life GPS traces of mobile nodes. We also conduct a statistical analysis of received results and show how the connectivity interval correlates with other network parameters like partition sizes or the average number of neighbouring nodes.

The paper has the following structure. First, following [10,11], the formal model of ad hoc systems with the liveness property is described in Section 2. A short review of mobility models used in our study is presented in Section 3. Section 4 describes simulation environment that has been used to perform all of our test. In Section 5, we make a statistical analysis of received results, and the paper is, finally, shortly concluded in Section 6.

2 Ad Hoc Network Liveness Property

In this paper, the topology of the distributed ad hoc system is modelled by an undirected *connectivity graph* $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is a set of all nodes, $p_1, p_2, \ldots, p_n$, and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is a set of links (p_i, p_j) between *neighbouring* nodes p_i, p_j, i.e. nodes that are within transmission range of each other. (Note that (p_i, p_j) and (p_j, p_i) denote the same link, since links are always bidirectional.) The set $\mathcal{E}$ changes with time, and thus the graph $\mathcal{G}$ can get disconnected and reconnected. Disconnection fragments the graph into isolated sub-graphs called *components* (or *partitions* of the network), such that there is a path in $\mathcal{E}$ for any two nodes in the same component, but there is no path in $\mathcal{E}$ for any two nodes in different components.

It is presumed that the system is composed of $N = |\mathcal{V}|$ uniquely identified nodes and each node is aware of the number of all nodes in the $\mathcal{V}$ set (that is of N). The nodes communicate with each other only by sending messages (*message passing*). Any node, at any time can initiate the dissemination of message m, and all nodes that are neighbours of the sender, at least for the duration of a message transmission, can receive the message. More formally, the links can be described using the concept of a *dynamic set* function [9]. Let $\mathcal{E}'$ be a product set of $\mathcal{V}$: $\mathcal{E}' = \mathcal{V} \times \mathcal{V}$, and $\Gamma(\mathcal{E}')$ be the set of all subsets (power set) of $\mathcal{E}'$: $\Gamma(\mathcal{E}') = \{\mathcal{A} \mid \mathcal{A} \subseteq \mathcal{E}'\}$. Then, the dynamic set $\mathcal{E}_i$ of node p_i is defined as follows:

Definition 1. *The* ***dynamic set*** $\mathcal{E}_i$ *of node* p_i *in some time interval* $T = [t_1, t_2]$ *is a function:*

$$\mathcal{E}_i : T \to \Gamma(\mathcal{E}')$$
$$\text{such that } \forall t \in T : \ \mathcal{E}_i(t) \text{ is a set of all links of } p_i \text{ at time } t.$$

Let δ be the maximum message transmission time between neighbouring nodes. Then, we define *direct connectivity* as follows ([11,10]):

Definition 2. *Let* $T = [t,\ t + B]$, *where* $B \gg \delta$ *is an application-specified parameter. Then, two operative nodes* p_i *and* p_j *are said to be* ***directly connected*** *at* t *iff:*

$$\forall \tau \in T\ (\ (p_i,\ p_j) \in \mathcal{E}_i(\tau)\ ).$$

It is assumed that channels between directly connected hosts are *reliable channels* which do not alter and lose, duplicate or create messages.

2.1 Network Liveness Property

Let $\mathcal{P}$ be a non-empty subset of $\mathcal{V}$ at some time t, and $\overline{\mathcal{P}}$ be its complementary set in $\mathcal{V}$ ($\overline{\mathcal{P}}$ contains all nodes that are not in $\mathcal{P}$). Then, the *network liveness property* is specified as follows ([11,10]):

Definition 3. *A distributed ad hoc system that was initiated at* t_0 *satisfies the* ***network liveness property***, *iff:*

$$\begin{gathered}\forall t \geqslant t_0\ \forall \mathcal{P}\ \exists I \geqslant B\ (\ I \neq \infty\ \wedge\ \exists\{p_i,\ p_j\}\ (p_i \in \mathcal{P}\ \wedge\ p_j \in \overline{\mathcal{P}}\ \wedge \\ (\ \exists\{t_1,\ t_2\}\ (\ (t \leqslant t_1 < t_2 \leqslant t + I)\ \wedge\ (t_2 - t_1 \geqslant B)\ \wedge \\ (\forall t_c \in [t_1,\ t_2]\ ((p_i,\ p_j) \in \mathcal{E}_i(t_c))))))).\end{gathered}$$

Informally, the network liveness requirement disallows permanent partitioning to occur by requiring that reliable direct connectivity must emerge between some nodes of every $\mathcal{P}$ and $\overline{\mathcal{P}}$ within some finite, but unknown, **connectivity time interval** I.

3 Mobility Models

To facilitate research on the performance of numerous already existing and newly proposed protocols in the field of ad hoc networking, many synthetic mobility models (in two-dimensional space) have been proposed [3,8]. The literature categorises them as being either *entity* or *group models*.

Entity models are used as a tool to model the behaviour of individual mobile nodes, treated as autonomous, independent entities. On the other hand, the key assumption behind the group models is that individual nodes influence each other's movement to some degree. Therefore, group models have become helpful in simulating the motion patterns of a group as a whole.

3.1 Entity Mobility Models

Random Walk. In the Random Walk model, a mobile node randomly chooses its velocity, that is its speed and direction, from the predefined interval of $[\,v_{min},\ v_{max}\,]$ and $[\,0,\ 2\Pi\,]$, respectively. The new values of these two parameters are calculated each time the node moves by some constant distance d or after some constant time interval $\triangle t$. Upon reaching the area boundary, the node "bounces" off it at an angle equal to the hitting angle, and moves along until the next calculation occurs. The probabilistic variant of the model known as the Chiang Model [5] makes the node's trajectory more linear and deterministic.

Random Waypoint. In this model, at each step a node first stops for some constant *pause time*. Then, the node randomly picks a point within the simulation area and starts moving toward it with a constant, but randomly selected speed that is uniformly distributed between $[\,v_{min},\ v_{max}\,]$.

Random Direction. The Random Direction model is a modification of the Random Waypoint model. The only difference is that, instead of choosing a point, the node chooses direction (angle) from the $[\,0, 2\pi\,]$ range and travels along this direction until it reaches the area boundary.

The main drawback of the above models is that they generate unpredictable motion patterns. In particular, they allow some unrealistic movements, such as sharp turns or sudden stops, to occur. In order to eliminate these undesirable effects, other entity models allow to limit the level of randomness by making new steps more or less dependent on the previous ones.

Haas Model. The model Haas Model assumes that the movement of each node is characterised by the vector of speed and direction $\boldsymbol{v} = (\,v,\,\theta\,)$, and that the node's position is updated each $\triangle t$ time interval, according to the formulas:

$$v(\,t + \triangle t\,) = min\,[\,max\,[\,v(t) + \triangle v, 0\,], v_{max}\,]$$
$$\theta(\,t + \triangle t\,) = \theta(t) + \triangle\theta,$$

where v_{max} is a simulation constant that denotes the maximum speed, $\triangle v$ is within $[\,-A_{max}{*}\triangle t,\ A_{max}{*}\triangle t\,]$, A_{max} is constant maximum node's acceleration, $\triangle\theta$ is taken from the range $[\,-\omega * \triangle t,\ \omega * \triangle t\,]$, and ω represents the maximum angular acceleration. Parameters $\triangle v$ and $\triangle\theta$ are uniformly distributed. This movement pattern defines a Markov stochastic process, since the new position and speed at time $t + \triangle t$ depend only on their previous values at time t.

Gauss-Markov Model. In the Gauss-Markov Model, motion of a single mobile node is modelled in the form of a Gauss-Markov stochastic process, and formally is defined by the following equations:

$$v(\,t + \triangle t\,) = \alpha v(t) + (1 - \alpha)\bar{v} + \sqrt{1 - \alpha^2}V$$
$$\theta(\,t + \triangle t\,) = \alpha\theta(t) + (1 - \alpha)\bar{\theta} + \sqrt{1 - \alpha^2}D,$$

where v and θ represent the node speed and direction at timeslot t, $\bar{v}$ and $\bar{\theta}$ are constants for asymptotic speed and direction mean as $t \to \infty$, whereas random variables V and D are speed and direction random variables with a Gaussian distribution. The level of randomness is controlled by the normalised α parameter representing the preset memory level. At one extreme, if α is equal to 0, the model reduces to the Random Walk model, because the velocity in a current timeslot does not depend on its previous value at all. On the other hand, if α is 1, the random factor disappears and the velocity becomes effectively constant. For any other value of α the model has some degree of memory, which makes the node's trajectory more or less linear.

3.2 Group Mobility Models

Exponential Correlated Random Mobility. In the Exponential Correlated Random Mobility model, a new position (of a group or a single node) $Pos(t+\triangle t)$ is updated after each timestep $\triangle t$, and is given by the formula:

$$Pos(t + \triangle t) = Pos(t)e^{-\frac{1}{\tau}} + (\sigma\sqrt{1 - (e^{-\frac{1}{\tau}})^2})r,$$

where τ parameter ($\tau > 0$) controls how much two consecutive positions differ (the smaller τ the greater change), and r is a Gaussian random variable with variance σ. The model has not become popular because modelling any realistic motion pattern with its use is difficult.

Column Model. The Column Model is meant to describe a group of nodes that form a line heading in a given direction like a column. Individual nodes are allowed to deviate slightly from their reference positions (determined by the column structure) according to some entity model. The Column Model is well suited for searching and scanning applications (for instance, in a rescue team).

Nomadic Community. Sometimes, the group nodes are focused around some *reference point* (e.g. the leader node) and collectively travel from one location to another. In such settings, the Nomadic Community model is useful. In this model, the group (treated as an entity) moves randomly, because the reference point is the source of randomness. Within a group, individual nodes are free to diverge from the reference point up to some predefined maximum distance.

4 Simulator

Most available simulators provide few implementations of mobility models and usually have poor support for the creation of complex mobility models [6]. Because of that, we have decided to create a mobility model centered simulator which would facilitate fast and effortless mobility model implementations and simulations. Our simulator named MANETSim [6] was implemented in *Haskell*—a purely functional programming language. By using specific features of the language, we were able to create a *Domain Specific Language* (DSL) to describe mobility models. It enables the creation of expressive implementations which closely resemble pseudocode while retaining a high level of functionality. In order to use MANETSim as a part of another simulation environment, we have developed a communications protocol and an interoperability module for the *OMNeT++*[1] network simulation framework. We used MANETSim to analyse the liveness property in the context of different mobility models.

4.1 Measured Metrics

In order to precisely describe the measured metrics, we first introduce a definition of a *partitions set*:

Definition 4. *The* ***partitions set*** $\mathscr{Q}$ *at time* t *in the network is composed of all sets* $\mathcal{Q} \subseteq \mathcal{V}$ *such that:*

$$\mathcal{Q} \neq \emptyset \wedge \forall p_i \in \mathcal{Q}\ \exists p_j\ (\, p_j \in \mathcal{E}_i(t)\,) \wedge$$
$$\nexists \mathcal{Q}' \subset \mathcal{V}\ (\ \mathcal{Q}' \neq \emptyset \wedge \mathcal{Q} \cap \mathcal{Q}' \neq \emptyset \wedge \forall p_k \in \mathcal{Q}'\ \exists p_l\ (\, p_l \in \mathcal{E}_k(t)\,)\,)\,.$$

We also denote T_s to be the length of a simulation step, and $\mathrm{Pos}_{n-1}(p_i)$ to be the position vector of node $p_i \in \mathcal{V}$ in the $n-1$-st time step. Thus, the momentary speed of node p_i is be expressed as:

$$\mathrm{V}_n(p_i) = \frac{|\mathrm{Pos}_n(p_i) - \mathrm{Pos}_{n-1}(p_i)|}{T_s}.$$

Based on the above specification, the metrics, which are measured by MANET-Sim, are as follows:

- number of links (neighbours) of each $p_i \in \mathcal{V}$: $\frac{1}{2}|\mathcal{E}_i(t_n)|$ (since links are always bidirectional);
- momentary speed of each $p_i \in \mathcal{V}$: $\mathrm{V}_n(p_i)$;
- size of each partition $\mathcal{Q} \in \mathscr{Q}$: $|\mathcal{Q}|$;
- **value of the liveness property connectivity interval** I, as defined in Section 2.1.

4.2 Simulation Parameters

The parameters and its values which were used in our simulation study are as follows:

- **number of repetitions of each test**: *10*;
- **simulation duration**: *6000 s*;
- **simulation transient period duration** (measurements taken during this period are ignored): *1000 s*;
- **simulated area size**: *1000 m×1000 m*;
- **number of nodes**: *50*;
- **wireless range of each host**: *[30 m, 50 m, 80 m, 100 m, 150 m, 200 m, 250 m, 300 m]*;
- **frequency of node position updates**: *4 Hz*;

[1] http://www.omnetpp.org/

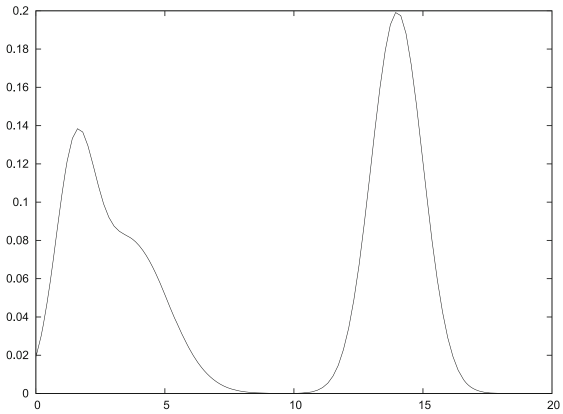


Fig. 1. The Γ node speed distribution. The X axis represents speed in m/s whereas the Y axis represents probability.

- **average node speed**: *[1 m/s, 5 m/s, 10 m/s, 15 m/s, Γ]*
- **node pause time**: *[none, Γ]*;
- B **parameter** (for how long do two nodes have to be in a wireless range for them to be considered connected, as specified in Section 2): *[0.5 s, 1.0 s, 2.0 s, 5.0 s, 10.0 s]*;
- **node interrupt condition** (when will a node change direction, speed etc.): *[collision, 30 m distance, 100 m distance, 30 s time, 100 s time]*;
- **Hass Model**: (model specific parameters) A_{max}=*0.9* m/s^2, ω=*10 deg/s;*
- **Gauss-Markov Model**: (model specific parameter) α *=[0.1, 0.3, 0.5, 0.7, 0.9].*

As a speed distribution we have also used Γ distribution, which was found by analysing GPS traces available freely on the Internet[2] [6]. The Γ distribution is shown in Figure 1, and Γ pause distribution is a uniform distribution over the range of *[10 s, 180 s].*

Most of above values were based on or follow suggestions present in the articles describing the mobility model and the liveness property. A more detailed explanation of the chosen values can be found in [6].

5 Simulation Analysis

To determine the distribution of the connectivity interval I, we have performed simulation tests with the use of the MANETSim simulator and all the unity and group mobility models mentioned in Section 3, along with each combination of the common and model specific parameters described in Section 4.2. Based on the information from the simulator, we were able to calculate values of the connectivity time I, and assess how they correlate with other network parameters.

[2] `http://www.openstreetmap.org/` and `http://www.gpsies.com`

Table 1. Percentage of simulation tests for which the value of the connectivity time interval was finite within simulation time

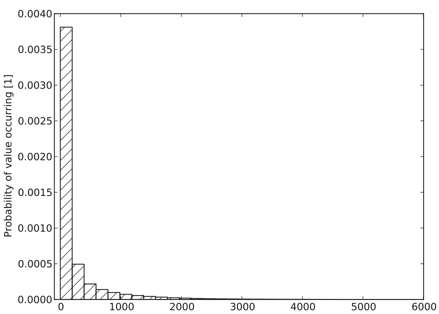
Mobility Model	**Tests with Finite Value of I**
Random Walk	98.69%
Chiang Model	99.90%
Random Waypoint	100.00%
Random Direction	97.49%
Haas Model	99.50%
Gauss-Markov Model	91.57%
Exponential Correlated Mobility	99.49%
Column Model	99.69%
Nomadic Community	100.00%

Table 1 shows the percentage of simulation tests, for which the value of the connectivity time interval was finite within simulation time, for all considered mobility models. As it can be seen, all these results are above 91% and in case of two models (Random Waypoint and Nomadic Community) all the simulation had finite values of this parameter.

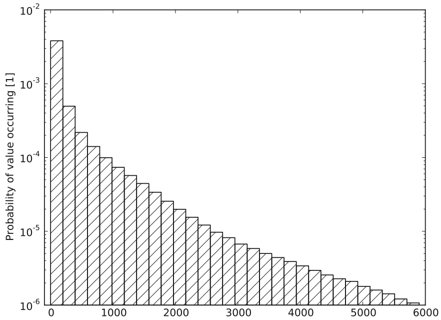
We begin our study with analysing the distribution of the connectivity interval I parameter among mobility models. Even though the values of I varies between different mobility models, the shape of the distribution is similar amongst them. This is illustrated by Figure 2, where similarities between the distribution for the Random Direction mobility model can be seen (Figures 2(a), 2(b)) and Chiang Model (Figures 2(c), 2(d)). The *same similarity* can be observed between *all* of the analysed mobility models [6]. But despite this, the distributions differ in a statistically significant way—Wilcoxon test at $\alpha = 0.05$. The distribution of I is almost exponential (as can be seen on the logarithmic plots: 2(d), 2(b)), which means that the smallest values of I are the most probable ones. That in turn means, that most of the partitions in the network exist only for a (relatively) short time (under 5 minutes in our simulations).

The value of I is not independent of other network parameters such as average node speed or the number of links. To illustrate those dependencies, we use the scatter plot depicted in Figure 3, where the following values are shown: **coverage**—percent of the area covered by a node's wireless range; **I-upper**—value which is greater than 90% of the observed I values; **neighbours**—average number of nodes to which a node has connectivity; **I-average**—average value of the observed I values; **partitions size**—average size of a partition and **speed**—average speed of nodes.

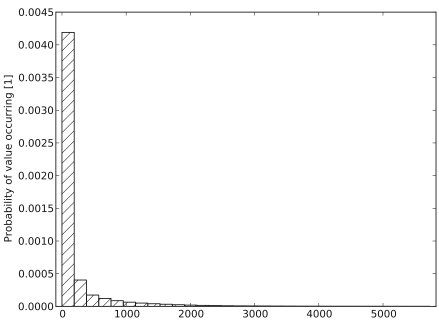
It can be seen on the basis of Figure 3 that an increase in value of partition size, neighbours number and coverage is connected with a decrease of the I-upper and I-average values. This tendency is not symmetrical as there are observations where small partition sizes with both small and large values of I-upper. Speed has a minimal impact on both values of I-average and I-upper, which means that while analysing protocols based on the liveness property it does not suffice to vary



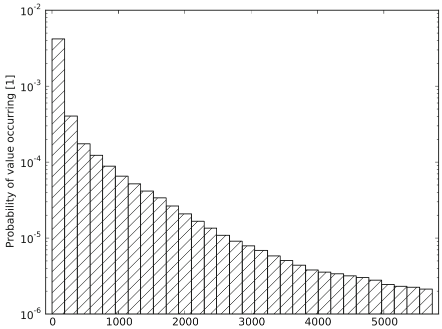
(a) Random Direction, linear scale.



(b) Random Direction, logarithmic scale.



(c) Chiang Model, linear scale.



(d) Chiang Model, logarithmic scale.

Fig. 2. Distributions of the liveness property connectivity interval I

node speed. This is contrary to common practice in MANET studies where the node speed is usually the only variable parameter of the mobility model [7]. It is worth noting that observations which do not exhibit finite values of connectivity interval I also have low coverage and a small number of neighbours.

Statistical parameters of the analysed mobility models are presented in Table 2. The results have been categorised according to the mobility model and speed distribution used: average value (denoted as *single*) and Γ distribution. To compare Γ distribution and average values results, we have used the Wilcoxon sign test. For all mobility models, the difference was found to have been statistically significant at $\alpha = 0.05$. The difference between those two types of distributions is not clear because, while most entity models with the Γ distribution had higher values of I, there were also less observations without a finite value of the connectivity interval among that group.

Finally, Table 3 depicts the percentage of observations for which I values were greater than those in the I_{cutoff} column—this can also be viewed as an approximation of the probability that a network would have not the connectivity interval for the given value of I_{cutoff}.

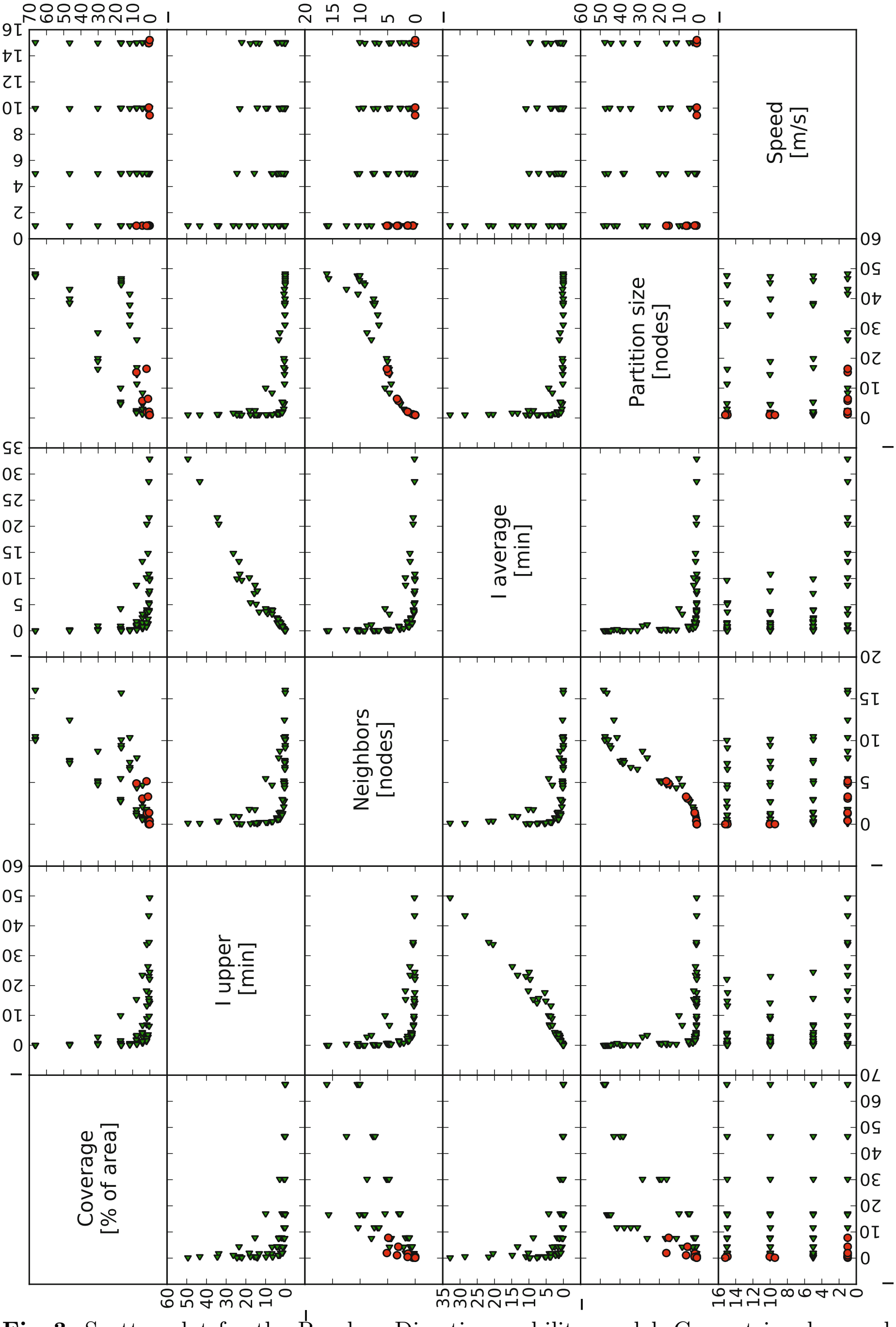


Fig. 3. Scatter plot for the Random Direction mobility model. Green triangles mark measurements with a finite value of the connectivity interval, red dots mark measurements without a finite value of the connectivity interval.

Table 2. Statistical parameters of I for all simulation experiments

Mobility Model	**Speed Dist.**	**I**						
		$E(I)$	σ_I	I_9	$min(I)$	$max(I)$	$kurtosis$	$skew$
Random Walk	single	258.74	488.07	711.00	0.25	5993.25	14.77	3.54
Random Walk	Γ	348.94	628.07	1038.75	0.25	5920.75	11.21	3.11
Chiang Model	single	205.25	388.87	519.75	0.25	5727.75	16.84	3.77
Chiang Model	Γ	120.63	214.81	217.25	0.25	5456.50	23.88	4.43
Random Waypoint	single	170.51	275.28	452.00	0.25	5903.00	17.94	3.56
Random Waypoint	Γ	188.25	357.55	362.50	0.25	4478.00	26.18	4.70
Random Direction	single	216.99	392.36	571.25	0.25	5903.75	14.98	3.53
Random Direction	Γ	384.47	571.04	959.00	0.25	5858.25	11.62	3.07
Haas Model	single	103.89	172.20	191.25	0.25	5959.50	24.41	4.45
Haas Model	Γ	91.95	191.63	153.00	0.25	5959.50	25.73	4.83
Gauss-Markov	single	235.35	371.13	687.75	0.25	5773.75	8.44	2.65
Gauss-Markov	Γ	385.00	474.05	1026.00	0.25	5309.00	3.29	1.72
Exponential Correlated	single	338.52	495.75	864.25	0.25	5860.50	10.17	2.95
Column Model	single	189.97	379.32	379.25	0.25	5699.50	28.50	4.88
Nomadic Community	single	197.06	311.80	507.75	0.25	5978.25	12.71	3.21

Table 3. Percentage of observations for which I values were greater than those in the I_{cutoff} column

Mobility Models	**Value of I_{cutoff} [s]**						
	5	10	20	50	100	200	400
All	98.0%	97.0%	96.0%	87.0%	74.0%	56.0%	38.0%
Entity	97.0%	96.0%	94.0%	83.0%	70.0%	54.0%	38.0%
Group	99.0%	99.0%	99.0%	96.0%	83.0%	61.0%	37.0%
	700	1000	2000	3000	4000	5000	6000
All	26.0%	19.0%	9.0%	5.0%	3.0%	2.0%	2.0%
Entity	27.0%	21.0%	10.0%	6.0%	4.0%	3.0%	3.0%
Group	22.0%	15.0%	7.0%	3.0%	1.0%	0.4%	0.2%

6 Conclusions

In this paper, we have presented a theoretical model of ad hoc networks with the liveness property, defined with the concept of dynamic sets, and several entity and group mobility models. We used these concepts to determine the distribution of the liveness property connectivity interval by simulation tests which build on our implementation of a mobility model centered simulator. The obtained results have shown that for all considered mobility models the probability that a network will have a finite value of the connectivity interval is very high, and that there is a strong correlation between the average number of neighbours and the value of I parameter. Other correlations were also considered, and we have observed that generally, an increase in values of partition size and coverage also is connected with a decrease of I value, while the speed of nodes have a minimal impact on the value. The distribution of I in our results is almost exponential, which indicates that the smallest values of the parameter are most probable. Consequently, it should be expected that most of the partitions in a network will exist for only a relatively short time.

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