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Studying Vehicle Movements on Highways and their Impact on Ad-Hoc Connectivity

Holger Füßler*, Marc Torrent-Moreno**, Roland Krüger*,
Matthias Transier*, Hannes Hartenstein**, and
Wolfgang Effelsberg*

* Universität Mannheim
Praktische Informatik IV
A5, 6
D-68159 Mannheim, Germany

** Universität Karlsruhe
Institut of Telematics
Zirkel 2
D-76128 Karlsruhe

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Holger Füßer* Marc Torrent-Moreno† Roland Krüger*
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While Mobile Ad-Hoc Networks are generally studied using a randomized node movement model such as the *Random Way-Point* model [8], Vehicular Ad-Hoc Networks deal with street-bound vehicles following a completely different movement pattern. This results—among other things—in a completely different connectivity situation and new challenges for data dissemination or routing/forwarding algorithms. Thus, researchers need *a)* suitable movement patterns for simulation, and *b)* a solid statistical understanding of the connectivity situation independent of the protocols utilized. In this work, we present a set of movement traces derived from typical situations on German Autobahns and an elaborate statistical analysis with respect to movement and connectivity relevant parameters. In addition, we present HWGui, a visualization, transformation, and evaluation package developed to study these scenarios. Beside the analysis capabilities HWGui is able, among other things, to generate movement files suitable for simulation with ns-2 [10].

1. Introduction

Vehicular Ad-Hoc Networks (VANETs) have recently gained increased scientific and industrial interest. Especially standardization efforts like, e.g., IEEE 802.11p [2] or the Car-2-Car Communication Consortium (C2CCC) [3] are both enablers and consumers for and of VANET research.

VANET research deals with cars equipped with short-ranged radios communicating with each other. In reality the ability of any two cars to exchange data packets depends on a number of factors. The most simple approach is the so called *Unit Disk Graph (UDG)* model [5] claiming that if and only if the geographic distance between two nodes is smaller than a given value r denoting the nominal radio range, transmission is possible. While this model is certainly not reflecting realistic radio propagation in detail [12], it gives highly explicative and easily obtainable hints on understanding the connectivity situation in a network formed by radio-equipped nodes.

In this report, we study the movement of cars on a highway with respect to network connectivity as given by a unit disk graph model. The movement data we study was generated by DaimlerChrysler by means of microscopic traffic simulation and validated against real-world movement behavior on a

*Holger Füßler, Roland Krüger, Matthias Transier, and Wolfgang Effelsberg are with 'Computer Science IV' at the University of Mannheim

†Marc Torrent-Moreno and Hannes Hartenstein are with the Institut of Telematics at the University of Karlsruhe.

German Autobahn [7]. Since understanding and using these files was a joint effort in the FleetNet [6] project, we will refer to these scenarios as FleetNet scenarios.

In the following, we will present a statistical evaluation of these FleetNet movement scenarios with respect to both the movements themselves and the network topology they represent under application of the UDG model. With the resulting data we intend to assist the design and adjustment of communication protocols tailored to vehicular environments, more specifically to highway scenarios. Note that we will make use of an arbitrarily selected scenario to clarify and visualize some parts of our work. We refer the reader to [9] for the statistical analysis of a complete set of FleetNet scenarios and to [1] for all downloadables.

The report is structured as follows. The next section gives some insights on the original data and how we have transformed it to suit our needs. Section 3 describes the statistical functions we have evaluated and gives some explicative examples. The following section, Section 4, concludes this report.

2. Original Data and Transformation

2.1. Overview of Original Data

The original movement data describes the movement of cars by giving tupels of a one-dimensional position and a lane for every car in the system and for discrete time steps of 0.5 seconds. It contains only one way traffic. Trying to put this into mathematical notation, we define

$$p_{n,t} \in \mathcal{Q}, \quad l_{n,t} \in \mathcal{N} \qquad \forall n \in N, t \in T_n, \tag{1}$$

where N is the set of nodes identified by unique identifiers and T_n is the set of time steps, where valid position information for node n exists. $\mathcal{Q}$ is the set of rational and $\mathcal{N}$ the set of natural numbers. The function $t \mapsto p_{n,t}$ is monotonously increasing for every node n, where p is the position on the road.

Note that in the final scenarios lane changes will always occur within only one time-step since the original data just provides the tuple (*position,lane*) to describe the nodes' positions. We virtually mapped the second dimension, i.e., the cars left-right position on the highway, according to an assumed but realistic highway lane's width in Germany. These parameters can be adjusted before transformation. Our setting for the simulation is depicted below.

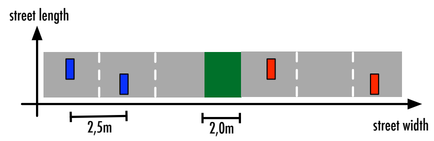

Figure 1 shows a graphical snapshot of an example of the original movement data.

Every scenario of original data consists of about 6 minutes of a validated 15km long highway area that moves together with a specific reference vehicle. During the 6 minutes, the reference node will have the same position with respect to the upper and lower bounds of the valid area. The magenta colored brackets denote this "validity range" where the realism constraints of the creators of the movement traces hold.

The original traces were created for different settings of node density and number of lanes. To keep the amount of data within reasonable limits, we have selected a subset of settings for further processing (see Table 1). The number of runs gives the number of statistical variations using different seed values which were created for the corresponding settings.

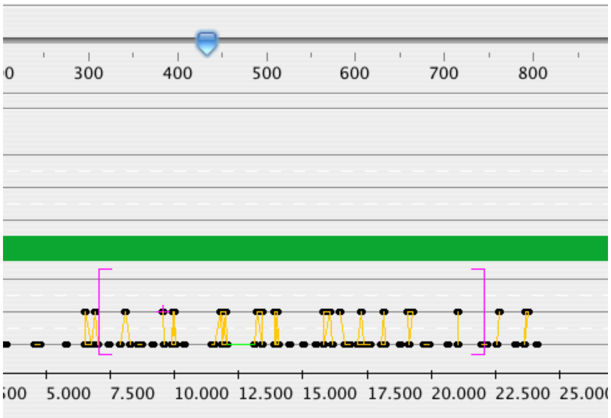

Figure 1: Snapshot of original movement data

nodes per km	number of lanes	number of runs
2	2	1
2	3	1
6	2	4
6	3	3
11	2	1
11	3	1
15	2	1

Table 1: Subset of data selected for processing

To obtain suitable movement files, three additional steps are needed.

Step 1. We cut the movement traces such that cars located outside the validity range are not considered. As a consequence, the resulting car movements are always valid.

Step 2. We select portions of the data by selecting adjacent slices of 60 seconds each, and we create 10 cuts for each of the 12 movement runs producing $10 \times 12 = 120$ cuts to play with.

Step 3. To create bi-directional movement files, we simply select two of the previously created 'cuts' and use one for each direction. Since both 'cuts' are only 15 km long we combine them as depicted in Figure 2. The upper part of the figure shows the initial placements of both 'cuts'. The red

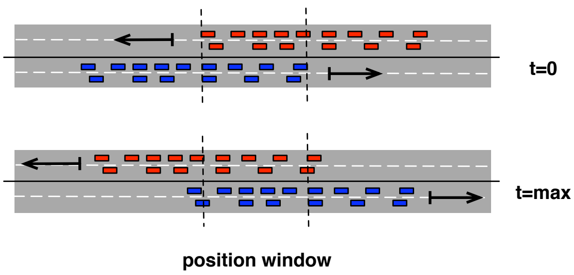

Figure 2: Combining uni-directional cuts to bi-directional scenarios

cars move from right to left, the blue ones from left to right. The dashed lines represent the borders of the *position window*, i.e., the maximized overlapping length between both directions during the 60 seconds. This borders should also be considered as the limits of any simulation scenario. Going on in time, the nodes' positions shift as depicted in the lower half of the figure. While the movements of both directions are written to the final scenario, in our simulations we also 'cut' the cars outside the dashed lines resulting in a scenario where nodes enter and leave at the respective borders. In the following, we will refer to the nodes inside the 'position window' as active nodes.

For easy usage, we have created a set of 40 scenarios, combining 5 different cuts of every node density. Note that we only combined scenarios with the same number of lanes in both ways. The resulting set consists on scenarios with the following combinations:

2 lanes/direction scenarios: 2×2, 2×6, 6×6, 6×11 and 15×15 nodes per km.

3 lanes/direction scenarios: 2×2, 6×6 and 11×11 nodes per km.

The files will soon be available at [11].

2.2. HWGui—Transform, Evaluate, and Display

To visualize the data we have created *HWGui* (for HighWayGUI), a Java-based application that is—among other things—capable of assisting in the following tasks:

- visualize the movement patterns in their different possible states
- visualize unit disk graph connectivity with a given communication range
- calculate various movement-based and connectivity-based statistics
- generate trajectory plots and position snapshot plots of the movement scenarios
- generate *Tcl* scenarios compatible with ns-2
- perform all the transformation steps described in Section 2.1

Figure 3 shows HWGui in action for a scenario with 2 nodes per km in the left-to-right direction and 6 nodes per km in the right-to-left direction.

3. Statistical Evaluation

The statistical evaluation is performed using HWGui in command-line mode. The resulting statistics document is a PDF file that contains one section for each analyzed scenario. The scenario file names are constructed as follows

```
combined-%d_nodes-%d_tsteps-%d_%d_npkm-%d_lpd-%d.txt
         (1)      (2)       (3) (4)     (5)    (6)
```

(1) is the number of nodes in a scenario, (2) the number of time steps (500ms interval). (3) and (4) are the respective node densities for the up/down direction in nodes/km. (5) denotes the number of lanes per direction and (6) the instance of the scenario, i.e., the differentiation between scenarios where all other parameters are the same.

In Appendix A, can be found an example Section taken out of the statistics document [9]. We will include forward references in the corresponding descriptions.

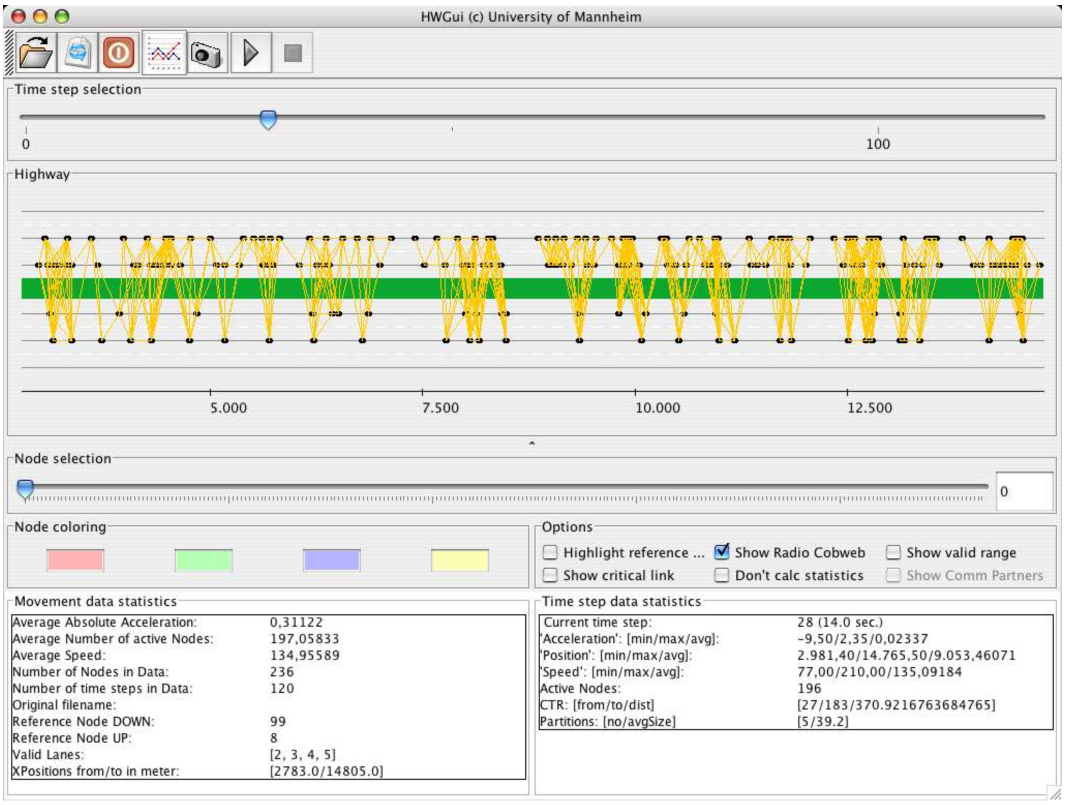

Figure 3: HWGui in action

3.1. Movement Statistics

The first statistic in each section is a graphical representation of the complete scenario using a so-called *trajectory plot* (see Appendix A.1).

In these kind of plots, one line (or trajectory) represents the whole movement of one node. In our case, a trajectory with a positive gradient represents a car with increasing position over time (moving from left to right), while lines with a negative gradient represent the oncoming traffic. Crossing lines with the same direction depict a car overtaking another. The rest of the movement related statistics are all contained in the 'single value statistics' subsection and are the following: *Directionality* (unidirectional or bidirectional), *Number of nodes*, *Number of nodes (up)*, *Number of nodes (down)*, *Nodes per km (up)*, *Nodes per km (down)*, *Number of time steps (0.5s)*, *Average node density (nodes/km)*, *Average speed of all nodes (km/h)*, *Length of valid area (m)* (length of the 'position window'), *Valid area start (m)*, *Valid area end (m)*, *Average number of active nodes* (average number of nodes inside the 'position window'), *Average number of active nodes (up)* and *Average number of active nodes (up)* (see Appendix A.2).

3.2. Communication Statistics

In the following, we have assumed a unit disk graph model with communication range ϵ, i.e., for any given time τ and every active node pair i, j, we define the ability to communicate directly c_{ij} as:

$$c_{ij} = \begin{cases} 1 & \text{if} \quad dist(i,j) \leq \epsilon \\ 0 & \text{else} \end{cases} \tag{2}$$

where *dist()* is the euclidean distance between two nodes.

On the basis of this we define i and j to be *neighbors* if they are able to communicate directly and to be *communication partners*, if they are members in each others transitive hull, i.e., the transitively extended set of neighbors.

The first communication statistic reported in the statistics document is the critical transmission range (CTR). CTR is computed as the minimum radio range required to fully connect a scenario snapshot. It is calculated by applying Minimum Spanning Tree (MST) [4] to the graph created by all nodes connected with each other with the link weight being their euclidean distance. Then the CTR is the longest link within this graph (see Appendix A.2).

In addition to the CTR, we present a number of graph types analyzing the movement patterns from a communications point of view: All analyzed parameters are presented for different configurations, i.e., with and without considering the oncoming traffic and three different communication ranges for all nodes: 250m, 500m and 1000m. The reported statistics are the following:

- *Neighbor histogram:* Histogram of the average number of neighbors of all active nodes in the scenario averaged over time. Additionally, the average, the variance and the standard deviation are calculated (A.3).

- *Communication partner histogram:* Histogram of the average number of communication partners of all active nodes in the scenario at a specific distance averaged over time. The bin size selected to represent this parameter is 250m. In addition, we have investigated different communication time spans. A time span of 1 time step means the pairs are able to communicate at one single time step, whereas a number of 10 time steps means that the communication has to be possible in each single time step during a contiguous time span of 10 time steps. (A.4).

- *Topological Change rate:* Average number of link changes per time step, i.e., the number of single-hop connections appearing/disappearing between neighboring time steps. As well, the TCR averaged over all time steps is computed (A.5).
- *Total number of communication partners:* Average number of communication partners of a node averaged over all active nodes at every time step. Additionally, the average number over all time steps and the average number of active nodes is reported (A.6).
- *Probability of being able to communicate with an arbitrary node:* Probability that two randomly chosen active nodes are communication partners of each other when all nodes have a specific communication range. This statistic is computed for 7 different possible communication ranges: 100m, 200m, 250m, 300m, 400m, 500m and 1000m (A.7).

4. Conclusions

In this report we have presented some explanations about the FleetNet highway movement patterns. We hope that the proposed scenarios can be useful for all researchers requiring realistic traffic situations with a goal of testing, developing or improving any communication protocol for highway environments. Additionally, we defined a set of statistics computed for each scenario to help the understanding of the cars' geographic distributions from a communication perspective.

Acknowledgements

Holger Füßler and Marc Torrent-Moreno acknowledge the support of the German Ministry for Education and Research (BMB+F) for the "Network-on-Wheels" project under contract no. 01AK064F.

References

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[3] Car-to-Car Communication Consortium. http://www.car-to-car.org.

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[10] The ns-2 network simulator. http://www.isi.edu/nsnam/ns/.

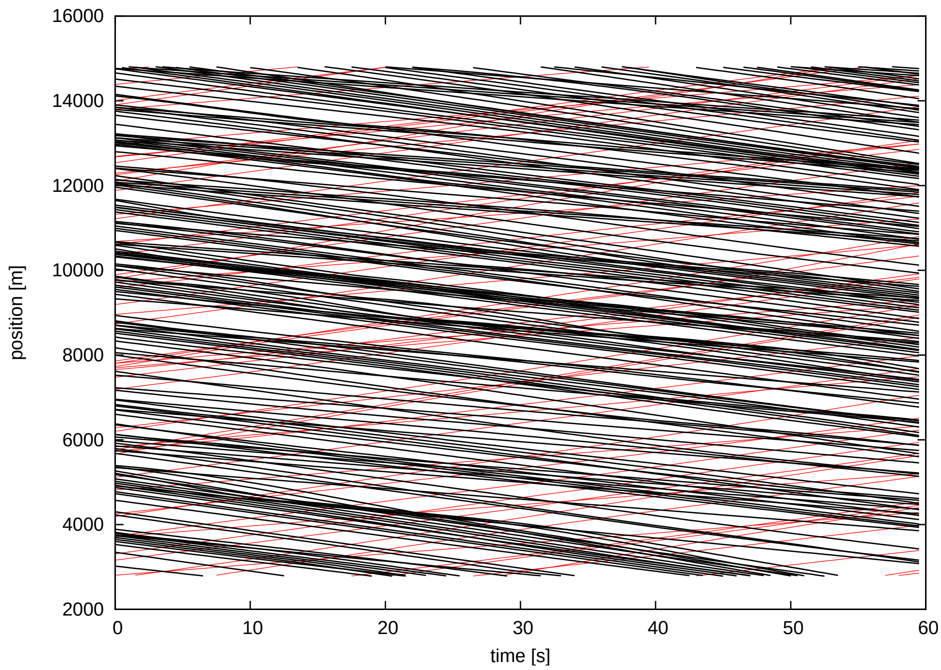
[11] Homepage MANET-Research Computer Science IV, University of Mannheim. http://www.informatik.uni-mannheim.de/pi4/projects/MANET.

[12] T. S. Rappaport. *Wireless Communications - Principle and Practice*. Prentice Hall PTR, 1996.

A. Example Statistics for one Scenario

`combined-236_nodes-120_tsteps-2_6_npkm-2_lpd-0.txt`

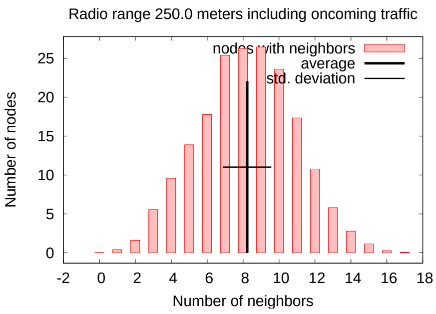
A.1. Trajectory plot



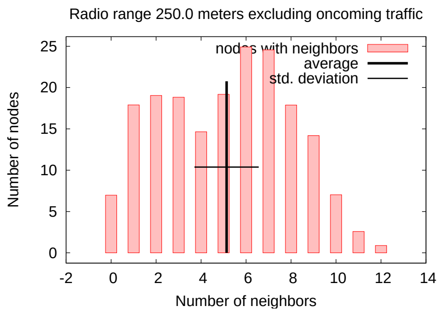
A.2. Single value statistics

Parameter	Value
Directionality	*bidirectional*
Number of time steps	120
Average speed of all nodes [km/h]	142.89
Number of nodes	236
Number of nodes (up)	59
Number of nodes (down)	177
Average node density [N/km]	16.39
Nodes per km and lane (up) $[N/(km \cdot lane)]$	2
Nodes per km and lane (down) $[N/(km \cdot lane)]$	6
Average number of active nodes	197.06
Average number of active nodes (up)	148.01
Average number of active nodes (down)	49.05
Length of valid area [m]	12022.0
Valid area start [m]	2783.0
Valid area end [m]	14805.0
Maximum CTR [m]	469.20

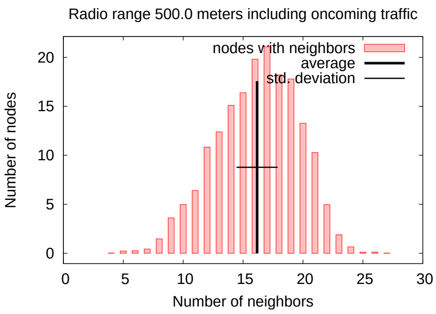
A.3. Neighbor histogram



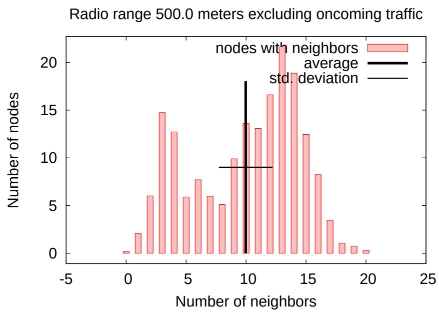
Average:	8.23
Variance:	7.18
Standard deviation:	2.68



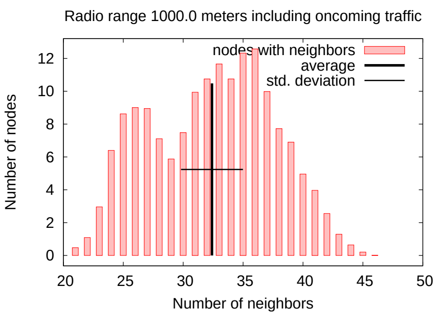
Average:	5.13
Variance:	8.17
Standard deviation:	2.85



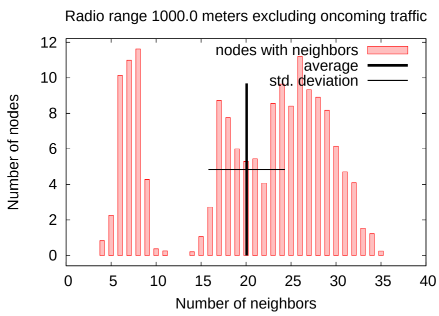
Average:	16.17
Variance:	11.76
Standard deviation:	3.43



Average:	9.96
Variance:	20.06
Standard deviation:	4.47



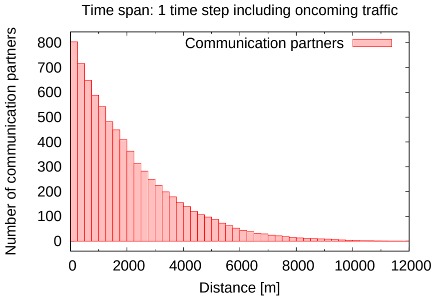
Average:	32.40
Variance:	26.67
Standard deviation:	5.16

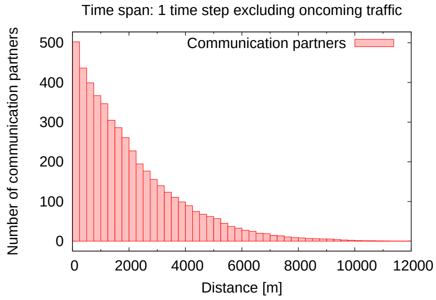


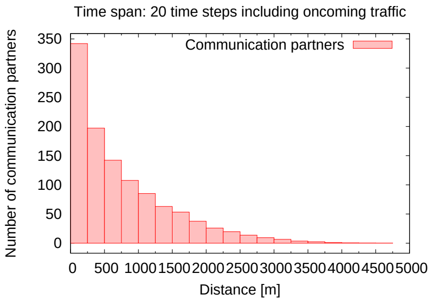
Average:	20.06
Variance:	72.41
Standard deviation:	8.50

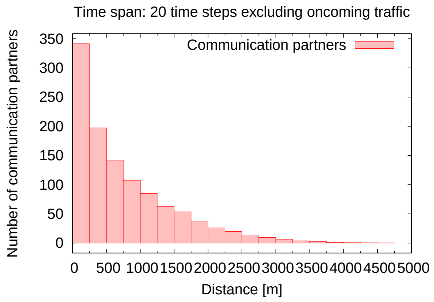
A.4. Communication partner histogram

A.4.1. Radio range: 250.0 meters, bin size: 250.0 meters

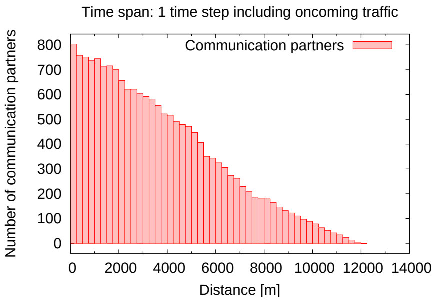


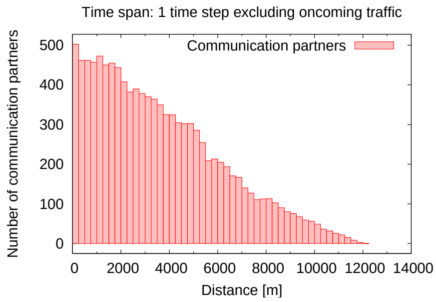


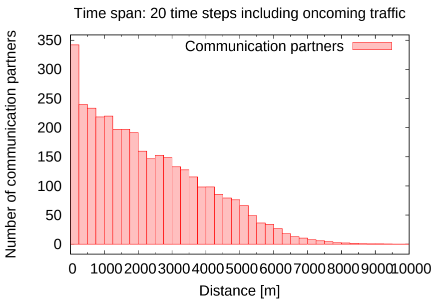


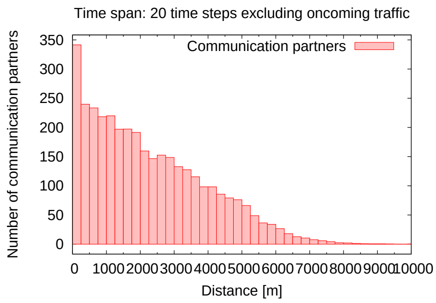


A.4.2. Radio range: 500.0 meters, bin size: 250.0 meters

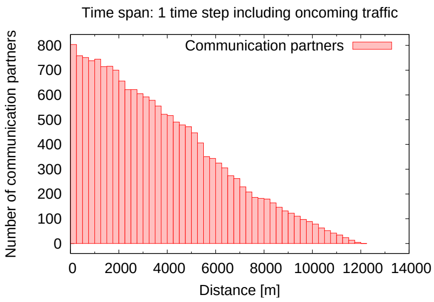


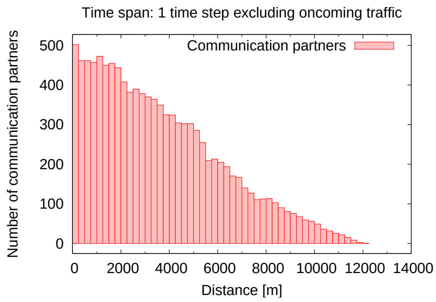


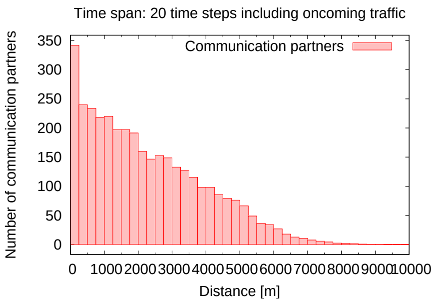


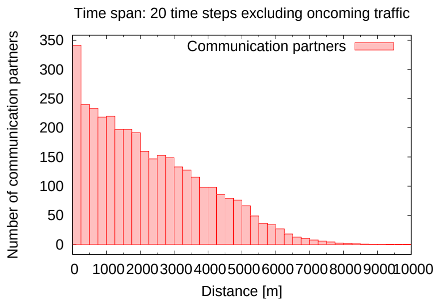


A.4.3. Radio range: 1000.0 meters, bin size: 250.0 meters

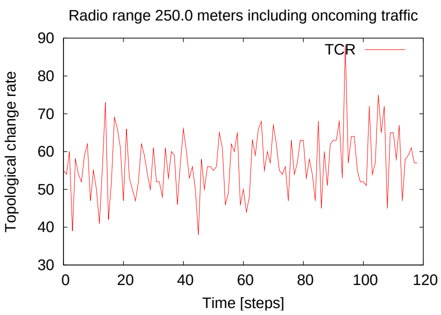


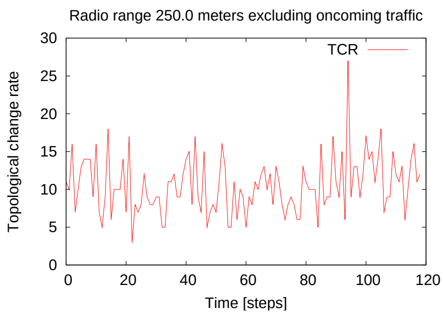






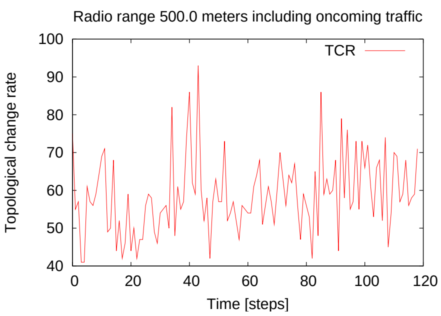
A.5. Topological Change Rate (TCR)

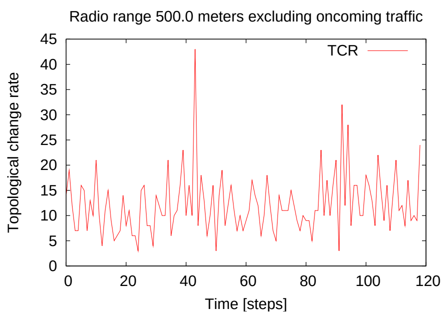




Average TCR:	56.46

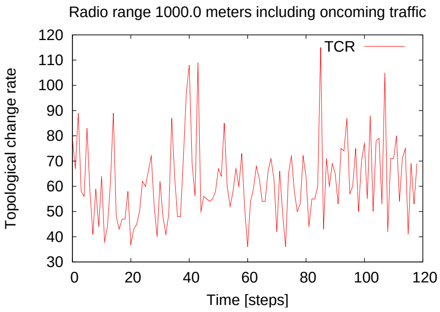
Average TCR:	10.41

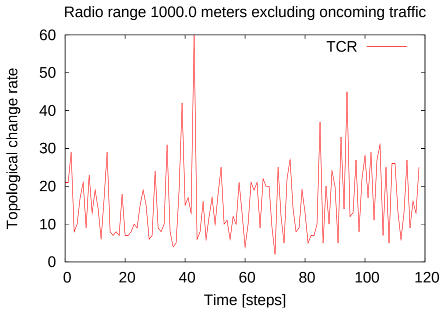




Average TCR:	58.21

Average TCR:	12.12

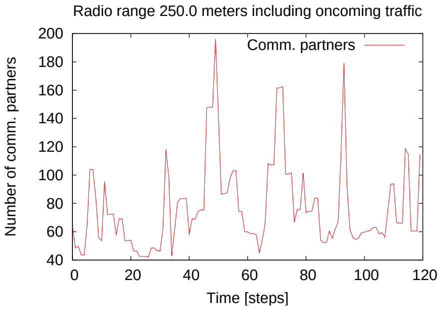


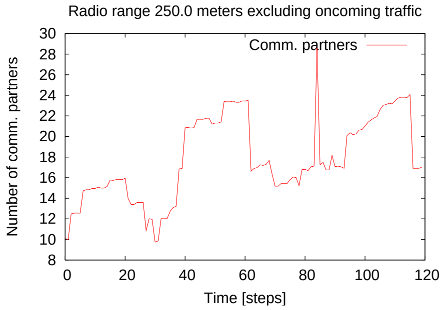


Average TCR:	61.3

Average TCR:	15.53

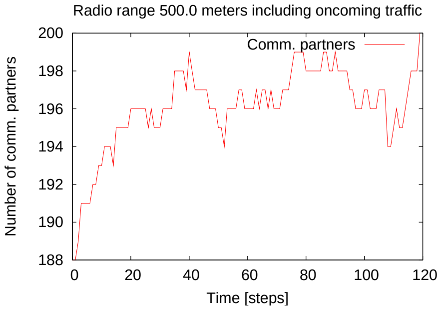
A.6. Total number of communication partners

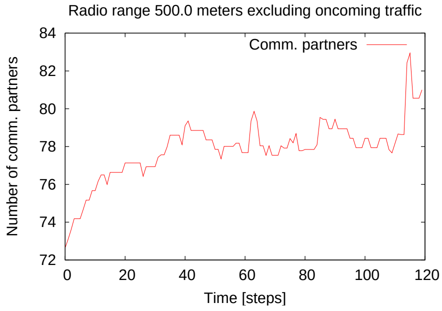




Avg. comm. partners:	77.51
Avg. active nodes:	197.05

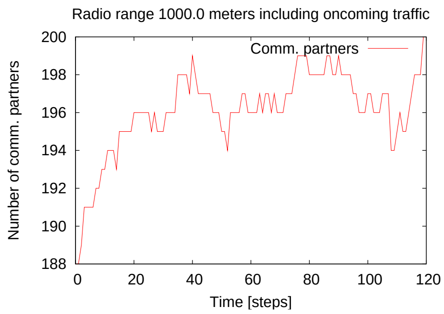
Avg. comm. partners:	17.76
Avg. active nodes:	197.05

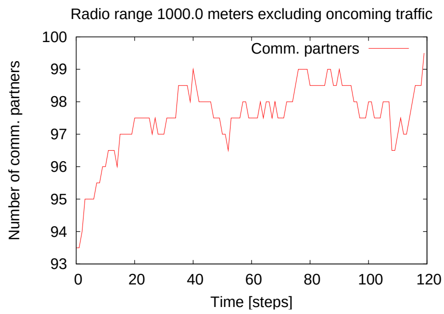




Avg. comm. partners:	196.05
Avg. active nodes:	197.05

Avg. comm. partners:	77.84
Avg. active nodes:	197.05

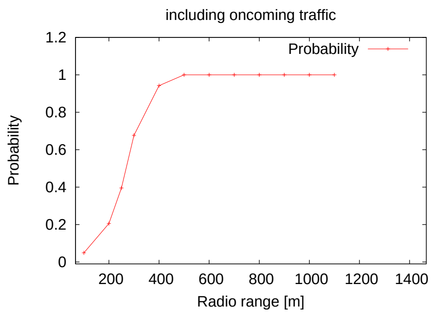


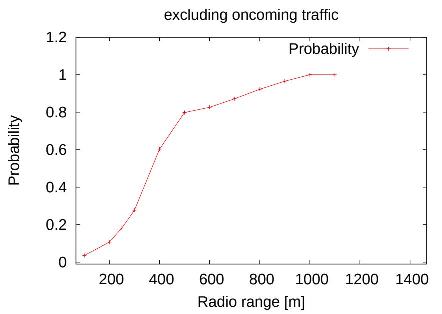


Avg. comm. partners:	196.058
Avg. active nodes:	197.058

Avg. comm. partners:	97.52
Avg. active nodes:	197.05

A.7. Probability of being able to communicate with an arbitrary node





100.0 m:	0.04
200.0 m:	0.20
250.0 m:	0.39
300.0 m:	0.67
400.0 m:	0.94
500.0 m:	1
600.0 m:	1
700.0 m:	1
800.0 m:	1
900.0 m:	1
1000.0 m:	1
1100.0 m:	1

100.0 m:	0.03
200.0 m:	0.10
250.0 m:	0.18
300.0 m:	0.27
400.0 m:	0.60
500.0 m:	0.79
600.0 m:	0.82
700.0 m:	0.87
800.0 m:	0.92
900.0 m:	0.96
1000.0 m:	1
1100.0 m:	1