Device to Device Communication in Mobile Delay Tolerant Networks

Andre Ippisch, Salem Sati and Kalman Graffi
Technology of Social Networks, Heinrich Heine University of Düsseldorf
Universitätsstrasse 1, 40225 Düsseldorf, Germany
Email: {ippisch, sati, graffi}@cs.uni-duesseldorf.de

***Abstract*—Available smartphones and smart objects can use short range connections like Wi-Fi and Bluetooth as a communication technique to exchange information with nearby devices. Those techniques are used in cases of absent end-to-end connection such as in Delay Tolerant or Opportunistic Networks. The study of message transmission processes and contact information in such networks has gained more attention nowadays, where contact information and message transfer have a great impact on Store-Carry-Forward routing decisions. The performance of routing mechanisms is measured based on bandwidth utilization and energy consumption regarding the delivery ratio. Therefore, in this paper we present a study framework to formulate the message propagation process in addition to contact information with a view on energy consumption. The study gives a detailed expression of contact information such as contact probability based on node density and transmission range in a bounded area. Furthermore, the message exchange process as element of channel utilization and energy consumption will be studied. Based on our simulation experiment results we evaluate the influence of various parameters on each other and finally on the system performance.**

Keywords: Opportunistic Communication, Neighbor Discovery, Power Consumption, Contact Probability, Routing Performance.

I. Introduction

Most Delay Tolerant Network (DTN) application scenarios take place in areas with a mixture of nodes, such as vehicular and pedestrian ones, in disaster regions, or other scenarios where node density varies over time. The main factor of varying node density are different kinds of node mobility, which create different groups of nodes, so called communication islands, within the same scenario area. To solve the problem of isolated islands with no continuous connection to each other most DTN routing protocols broadcast the messages through the network via Store-Carry-Forward. DTNs with varying node densities lead to low contact probability which yields a long delay of storage and propagation. This problem is expected to occur more frequently in DTN scenarios where the network graph with varying node density will impact the routing performance, especially when nodes are forced to forward their messages whenever there is no stable link connectivity or when the destination can not be reached. The simplest DTN routing protocol is the flooding-based Epidemic [1] which broadcasts its deliverable messages to every encountered node that has not got a buffered copy of the message yet. The number of broadcasts and message copies is increasing through the message dissemination process and depends on the nodes' contact probability and the number of neighbors. Our paper analyzes the performance of Epidemic based on node density, as opposed to previous research which depends on contact event evaluation of fixed node density scenarios in areas with a fixed size. The Epidemic dissemination speed will be neighbor reliant and is expected to perform broadcasts at a rate determined by the density of the network. It is expected that Epidemic routing copies messages with an interval based on both node density and Inter-Contact Rate between nodes. Thus, Epidemic is expected to perform the broadcasting of message copies rarely when there are only a few number of neighbors around the node. Furthermore, the low dissemination rate of Epidemic will be achieved when the number of neighbors equals one. The objective of Epidemic is to establish a high performance while keeping a low delay by adapting the amount of broadcasting messages per number of node connections or the network density. This fact may be considered as a proposal to improve the efficiency of Epidemic. It may limit the number of message copies based on the density of the nodes in the network. The messages generated by the basic Epidemic as greedy replication are not adapted according to the network topology. The basic Epidemic situation increases the possibility of consumption of resources like storage, bandwidth and energy of the system. The uncontrolled replication of the message as broadcast would then contribute to the resource problem. Reducing the number of the message copies according to the density of the network will help dense networks to reduce the amount of overhead measured in channel utilization and energy consumption. On the other hand, sparse networks would continue to perform their replication process similar to the basic Epidemic rule with a copy for every encountered node. In reality, there are mobile DTNs that have fixed sets of nodes in the bounded area of the network. This number of nodes can vary between different areas, but will be fixed for each one respectively. Both situations can occur in urban and disaster areas. Therefore, to evaluate the performance of DTN routing in an environment without considering the node density does not provide a clear picture on the scalability of the DTN routing protocols. The node density for a network can be related to the node degree which is a result of node connectivity. For this study, node density is defined as an average of node connectivity. However, when determining density for a particular network,

978-1-5386-4028-9/17/$31.00

one important parameter that influences the connectivity of the network is the transmission range of the nodes. In addition, the node density in the bounded area is impacted by the number of nodes in the network.

II. Related Work

There are a lot of research papers which analyze the impact of node density and transmission range specially for MANETs. Regarding the DTN a lot of researchers have focused on the study of message dissemination process, as in [2], without considering the density of nodes, where most of them assume that the number of messages is small concerning the number of the nodes in the network as message delivery ratio. We believe that the node density sharply impacts on the dissemination speed and the number of message copies generated by the routing protocol. The number of the generated messages will also impact on the energy resources. Most of DTN modeling such as *Markov Chain* and *SIR* model fix the number of the nodes as a parameter N of population in a bounded area A, but they do not consider the value of the density and its impact on the resources. On the other hand studying the node density as component of the network graph will help to design the utility based DTN routing protocols. Those DTN models consider the message replication based on Epidemic flooding. In [1] the authors present the simple idea of the Epidemic routing protocol where the messages replicated to every encountered mobile nodes to archive a higher message delivery ratio. In [3] a DTN model is proposed which studies networks that lack stable paths. This model is considered as the common model, in addition to the *Markov Chain* model which also is used to evaluate the performance of Epidemic routing protocol. In [4] the authors use sequences of random graphs for modeling temporal graphs for analysis of the diameter of mobile Opportunistic Networks. Also in [5] it is explored how the paths between two nodes change with increasing number of hops. Using the all hops optimal path (AHOP) problem, they construct all the contact events in a time interval graph. The authors of [6] propose a model based on the number of nodes to estimate message delay; this paper provides a comparison of analytic results with simulation results obtained from three different mobility models. By using ordinary differential equations (ODE), Zhang et al. [7] investigate how resources such as the number of generated message copies and the buffer size can be traded with the delay. In [8] the authors use the optimal replication control of Epidemic. In this paper all nodes nodes know about the number of nodes that are currently carrying the message. The optimal closed-loop control is a threshold policy which is derived by the number of intermediate nodes carrying a message copy. Compared to literature work, we offer explicit results for node density as a function of the number of nodes and their transmission range in particular areas, we analyze the density function impact on average dissemination speed and contact probability, in addition to energy analysis under the condition of numerous nodes and transmission range. Furthermore, our model takes various mobility models into consideration and can be used to compute the situation when only some of nodes must be infected, thus, used as a relay. We formulate the connectivity graph based on a discrete time graph; unlike other work, we present average contact probabilities based on network graphs in a bounded area. Moreover, our model of contact formulation is based on the simulation results. The starting point of our work is to find a method to calculate the contact probability with regard to node density and transmission range. In this paper, we set up a model that can be used to quantify various node density parameters' effect on the message transmission process. The density is also analyzed as an impact factor on the network resource consumption.

III. System Model

Due to the nodes' location properties and different mobility models in DTNs, the network should be divided into different groups. Discussing such a complex situation is useful for routing protocol design, as we have to pay attention to the number of infected nodes in each group which is impacted by the dissemination speed. The message transfer will occur when two nodes are in each others' coverage area, moreover the Inter-Contact time will be impacted by the node density in addition to the transmission range. The message replication process will also impact on the network resources in terms of storage, bandwidth, and energy. In this section, we will describe our model and out assumptions. In Table I we specify the notations and quantities which we use in this paper. From the modeling of the mentioned DTN networks, we define out network as a mobile DTN network that has the following properties:

1) The network consists of N different devices as nodes placed in an (L, W) rectangle bounded area A
2) The position of each node considered as a random variable uniformly distributed over the given area A
3) Each node has a transmission range of r, where r is small compared to length or width of particular area A
4) Any two nodes that are within the transmission coverage of each other will have a Contact probability

We are investigating the impact of the number of nodes and transmission range in fixed size areas, on the mobility model and its contact probability. Furthermore, we consider the well-known routing performance metrics of delivery, overhead ratio and delay. Finally, we analyze the impact of the node density as a function of transmission range and a number of nodes on the resource limitation. We will measure the amount of relayed messages as a metric for saving bandwidth and energy. It is commonly believed that future contact occurrences in DTNs depend on contact history only. However, we discovered that it is possible to estimate future contacts with a function. The expected node degree as contact probability and the expected number of contacts in a DTN can also be obtained.

A. Inter-Contact Time Impact By Density

The connection between two nodes only takes place when they are in each others coverage area. The Inter-Contact Rate λ_c is assumed to be exponentially distributed. The model

Table I
USED NOTATIONS AND QUANTITIES

No	Parameters	Description
1	N	Number of nodes in the network
2	A	Rectangular Area of Length L and Width W
3	ICT	Inter-Contact Time
4	r	Transmission range (m)
5	R	Transmission range (km)
6	C_P	Contact Probability
7	C_h	Contacts per hour
8	C_T	Total Contacts per Scenario
9	$G(V, E)$	Network Graph which models the contact events
10	V	Vertex set of nodes
11	E	Edges set of all pairwise contacts
12	D_n	Density of node
13	DS_T	Density/Sparse Threshold
14	λ_c	Average Inter-Contact Rate between two nodes
15	DS_R	Density/Sparse Ratio
16	E_{IPND}	Energy consumed by IPND traffic
17	C_m	Minimum Amount of Contacts
18	C_{r_0}	Number of Contacts when r equal 50 meter
19	α, β	Constants
20	C_{r+r0}	Number of Contacts when r is increased by r_0
21	BI	Beacon Interval of IPND protocol
22	CT	Contact Time
23	P_B	Power consumed by single UDP message of IPND

assumes that the contact duration is short as opposed to the Inter-Contact Time of the two nodes. Our model is defined as a combination of two different mobility models which are Shortest Path and Random Route.

Previous researches noticed that the Inter-Contact Time of Random Direction and Random Waypoint mobility models can be calculated based on the area size and transmission range between the nodes. For each model, we assume that the nodes move within a rectangular area. For the random direction mobility model the expected Inter-Contact Rate λ_c can be calculated as follows ([9]):

$$\lambda_c \approx \frac{2rE[v]}{A} \tag{1}$$

where $E[v]$ is the average relative speed between encountered nodes. Regarding the Random Way Point mobility model, the expected Inter-Contact Rate λ_c can be calculated as follows:

$$\lambda_c \approx \frac{2r\omega E[v]}{A} \tag{2}$$

where ω is a constant specific to the Random Way Point model ([9]). In order to apply those functions to our model we need to identify the parameters of the exponential Inter-Contact Time distribution. The Eq. (3) of our model shows that the Inter-contact Rate λ_c can be calculated as a linear function of transmission range R in kilometers regardless of the number of nodes in the scenario.

$$\lambda_c \approx \alpha R \tag{3}$$

The value of the constant α with $0 < \alpha < 1$ will adapt the average Inter-Contact Rate λ_c to be accurate for the density based on the transmission range r, no matter the number of nodes in the scenario, as shown in both Eq. (1) and Eq. (2).

B. Contact Probability Impact By Density

Node density for a network can be considered as density per area, or the contact probability for an average number of neighbors. Before defining the Dense/Sparse threshold DS_T we specify how the Density/Sparse Ratio DS_R is calculated to classify the network of the scenario as a dense or sparse network. This function considers the two parameters of the density function which are number of the nodes N and the transmission range r, in addition to the boundaries of the particular area A as follows:

$$DS_R = \frac{N\pi r^2}{A} \tag{4}$$

In this paper, according to the Dense/Sparse Threshold DS_T, the network density is defined as dense if it fulfills the following condition:

$$\frac{N\pi r^2}{A} > DS_T \approx 1 \tag{5}$$

The density is considered sparse for a value less than this threshold.

However, when determining the surrounding density for a particular node which has the bounded movement area A, the node density is an important component which has impact on the contact probability of the node. The node density D_n is calculated as follows:

$$D_n = \frac{N}{A} \tag{6}$$

Thus from Eq. (4), Eq. (5) and Eq. (6) the network density determined in this paper is based on the density of the nodes which then again is based on the number of nodes found in a particular area. Therefore, considering the number of nodes found in a bounded area as well as the transmission range r it can be determined that the network of that particular area is dense or sparse. Given either a very large area or a low transmission range will impact on the network density.

Now we will consider the contact event, more precisely the minimum number of contacts C_m, which is calculated for a transmission range r that is equal to one ($r = 1$). The results are collected in a network graph $G(V, E)$, which models all connections to one hop encountered nodes. We calculate the amount of contacts per hour C_m by the following equation, with the set of nodes as vertices V and the relayed nodes as edges E:

$$C_m = E \log V \tag{7}$$

Now we look at the number of contacts of our first experiment regarding all scenarios when transmission range of the node r is equal to r_0. We can calculate the number of contacts when the transmission range r is equal to r_0 based on Eq. (7) as follows:

$$C_{r_0} = C_m \log 30 \tag{8}$$

As the transmission range increases by r_0, the number of contacts per hour C_h for all scenarios is calculated as follows, with β as a constant $0 < \beta < 1$

$$C_h = C_{r_0} + \beta N(N-1) \tag{9}$$

We present the equation for calculating the average number of contacts per hour for all experiments of all scenarios with the following equation:

$$C_{r+r0} = C_h + \beta N(N-1) \tag{10}$$

Finally, from Eq. (10) we can calculate the contact probability percentage of the maximum amount of contacts in the network which consist of N nodes and $(N-1)$ outgoing edges for the directed graph $G(V,E)$:

$$C_P = \frac{C_h}{N(N-1)} \tag{11}$$

As Eq. (11) shows, the contact probability C_P is mostly influenced by the transmission range r, regardless of the number of the nodes N, where the value of $N(N-1)$ is assumed to be constant during the same scenario experiment of different transmission ranges r.

C. Routing Metric Impact By Density

This section presents the routing metrics which are used to evaluate the different network densities. This evaluation will consider metrics related to resource consumption, beginning with end-to-end delay for deep analysis. Furthermore, we will focus on the main component of channel utilization which is the amount of relayed messages. For the analysis of the impact of network density on the performance we use application-related metrics, which are delivery ratio and delay. The performance metrics used for comparison are:

1) *Delivery Ratio* is the ratio of the number of delivered messages to the total number of generated messages.
2) *Relayed Messages* is the total number of intermediate nodes used for delivering messages.
3) *Average Delay* is the average delay of all successfully delivered messages.

The Impact of node density as a function of both number of nodes and transmission range is conducted with flooding-based DTN routing protocols, which is termed as the greedy uncontrolled Epidemic routing protocol. Epidemic is evaluated with different numbers of nodes and different transmission ranges. Where the Epidemic routing protocol dissemination speed will impact by contact probability, the contact probability is a function of the number of nodes and transmission range in the bounded area. For the performance evaluation of Epidemic routing we select *FIFO* (First In First Out) as our forward and drop policies for the nodes buffer management. The routing performance is impacted by node density because the node density has a higher impact on the buffer and routing performance. Obviously, the buffer management and routing performance is based on the overhead variables which are the hop and replication counter of the message. The main performance factor is the number of relayed messages when the performance impact of node density evaluated using a different number of nodes and transmission range, as this factor is related to the resources of both a single node and the network. Due to Epidemic's behavior of the unlimited replication of messages, Epidemic is suffering from a very high consumption of the before mentioned resources. Furthermore, we look at the average end-to-end delay which we use as a performance metric for different DTN applications and scenarios.

D. Energy Metric Impact By Density

This section will consider both Wi-Fi and Bluetooth interfaces which use a discovery mechanism that allows the node to detect the directly connected neighbors using the same wireless technology. This feature is to be considered as a more energy consuming process. On the other hand, Wi-Fi infrastructure mode periodically broadcasts its Service Set Identifier (SSID) which can be seen by any Wi-Fi-enabled node as a control signaling beacon. Wi-Fi-enabled nodes typically listen for these announcements in regular intervals as a passive scan. In order to set up a connection, one node must initiate it and the other node must accept it. Therefore control traffic such as beacons will consume the bandwidth of the radio channel. Furthermore, the beacon message will consume some of the energy resources of the nodes. Also, the beacon interval will impact the contact event as it delays the detection of one hop connection partners. Furthermore, the most important reason why two encountered nodes disconnect is when the distance between the two nodes surpasses the transmission range. The lower the node density, the lower the chance of connection in the first place. The other important reason for the disconnection of encountered nodes is the energy limitation. DTN nodes, like smartphones and smart objects, mostly suffer from resource limitations in terms of storage, bandwidth, and energy. To improve the mechanism of neighbor discovery in a DTN environment, the DTN IP Neighbor Discovery (IPND) [10] was implemented and published by the IETF in an Internet draft. IPND is a method for nodes to discover the existence, availability, and network addresses of encountered nodes which serve as one hop connections. IPND periodically transmits (as a broadcast) and receives beacons in ad hoc fashion. These beacons are considered small UDP messages and contain information about the node and its available services. We define a consumption model to calculate the energy needed for sending IPND messages as beaconing messages and for an enabled radio interface. We will consider the transmission of UDP message beacons of the IPND protocol with different intervals. Our energy model will consider different interface states like *Idle*, *Send*, *Receive* and *Scan*.

The computation of the energy consumed by the radio interface during the beaconing as UDP message of IPND protocol is described in the following equation:

$$E_{\text{IPND}} = NP_B\frac{CT}{BI}, \text{ where } BI > 0 \tag{12}$$

Table II
SIMULATION SETTINGS

Settings	Value
Map	Downtown of Helsinki, Finland
Simulation time	12 h
Number of Nodes	66, 126, 246
Group Type with Speed	Pedestrians (0.5-1.5 km/h) Cars (10-80 km/h) Trains (10-80 km/h)
Simulation area	Helsinki, Finland Map (4500, 3400 m)
Routing protocols	Epidemic
Interface type	Bluetooth, High Speed
Transmission range	50, 100, 150, 200, 250 m
Bandwidth	250 kBps, 10 MBps
Buffer Management	FIFO
Message size	0.5-1 MB
Message creation interval	25-35 s
Time-to-live (TTL)	300 min
Default buffer size	Pedestrians: 5 MB Cars, Trains: 50 MB
Mobility Model	Pedestrians: Shortest Path Map Based Cars, Trains: Map Route

with CT being the Contact Time, BI the Beacon Interval of the IPND protocol, and P_B the power consumed by a beacon. The computation of the beacon power consumption is based on the power consumption values of the interface states.

IV. Experiment Scenario And Results

To reflect different network density situations, we consider three different scenarios for our experiments. Scenario 1 considers 66 nodes with a message creation interval between 25 s and 35 s, and a message size ranging from 500 kB to 1 MB. The 66 nodes consist of 60 pedestrians and 6 cars and trains. In Scenario 2, in addition to those 66 nodes from Scenario 1, 60 more nodes join in to double the amount of pedestrians. This reflects a node density that is approximately doubled in respect to Scenario 1. Finally, in Scenario 3 we investigate the effects of larger scale networks with a high node density in the same fixed area size. 120 nodes are added to the nodes of Scenario 2 which means that Scenario 3 has twice the density of Scenario 2 and four times the density of Scenario 1. The different number of nodes and transmission ranges which are applied to the three scenarios are all in relation to the same world size which is bounded to the length of 4500 m and width of 3400 m. The nodes in Scenarios 2 and 3 keep the same message creation interval and size. In our three different scenarios for the simulation, we change the node radio transmission r from 50 to 250 m by steps of 50 m for each experiment of each scenario. With five different values for the transmission range r, we are able to completely catch the quality of our model in comparison to the simulation results. For evaluation of the routing performance of Epidemic with different node densities, we choose the buffer management of *FIFO* selecting messages with minimum arrival time for both the index and drop rules.

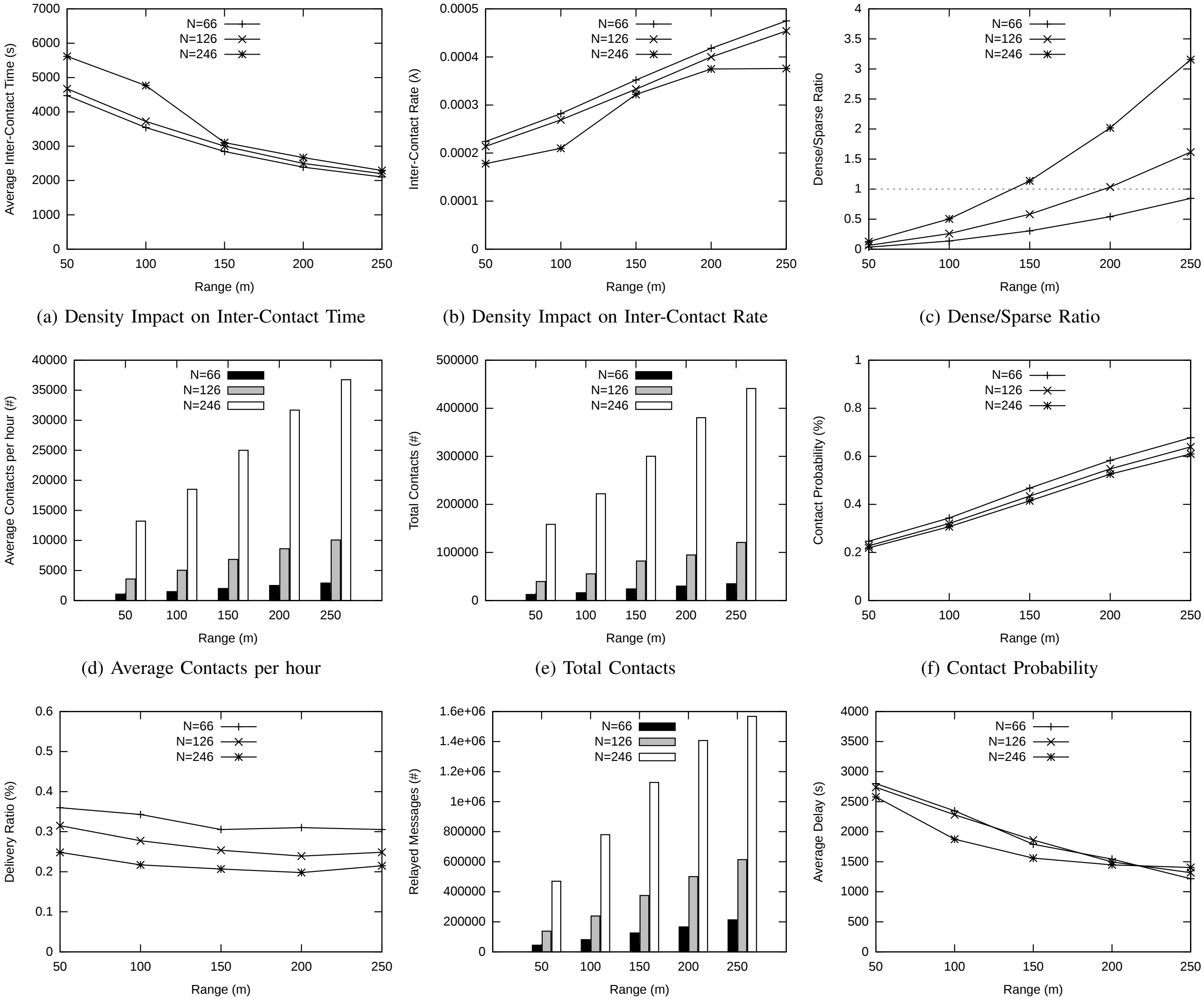
We change the transmission range r by steps of 50 meters for the three different scenarios and the parameters listed in Table II and compare their impact on node density with regards to the different before mentioned metrics under different radio ranges and number of nodes in a particular area. The scenarios were simulated with the default settings of the ONE Simulator [11], [12]. We use the Epidemic routing protocol and the *FIFO* buffer management strategy as seen as in Table II. The scenario settings listed in Table II can be used to calculate the values of constants α and β. Additionally we simulate the scenarios to measure the Inter-Contact Time (ICT) between nodes that encounter each other in each scenario, this value, in all scenarios, was averaged in seconds. From the ICT we can now calculate the Inter-Contact Rate λ_c in the system which equals the inverse of the averaged ICT, this rate, which is called λ_c, is not impacted by the number of nodes. Furthermore, λ_c can be determined from Eq. (3). From Eq. (7) we can calculate the minimum contact probability of different scenarios, therefore using Eq. (8), Eq. (9) and Eq. (10) we can calculate the average contacts per hour of each experiment of each three scenarios. Using the Eq. (11) we can determine the contact probability of each experiment.

A. Inter-Contact Time Impact By Density

In this section we will look at the Inter-Contact Time (ICT) and the Inter-Contact Rate λ_c among different node transmission ranges. Figure 1(a) shows the graph of Inter-Contact Times under different node densities for the three scenarios. To find the relationship between Inter-Contact Rate λ_c and node transmission range R in kilometers in a particular area A, we perform linear incrementations of both the number of nodes N and transmission range r to plot graphs of three data sets. Recorded Inter-Contact Times are used to generate fitting functions with the same average as the one of the experimental results. For linear fitting, we consider the coefficient in Eq. (3) as constant of λ_c. With a constant $\alpha \approx 0.000215$, Figure 1(b) shows the Inter-Contact Rate λ_c is not impacted by the node density, especially if the Dense/Sparse Ratio DS_R exceeds the value of the threshold as shown in Figure 1(c). Figures 1(a) and 1(b) shows the average Inter-Contact Rates λ_c between different encountered nodes. Figure 1(c) shows the experimental results for Dense/Sparse ratio for varying node densities in a rectangular area of the same world size (4500 m, 3400 m). Eq. (3) accurately explains the shown differences with different values. Although, it has been shown that the Inter-Contact Rate λ_c can be approximated closely as linear function of transmission range R in kilometers for our experimental settings. This approximation should be considered for simulations that assume that the Inter-Contact Times are strictly exponential, especially for small Inter-Contact Times.

B. Contact Probability Impact By Density

The node density is a very important factor of the contact event, therefore, we return to the three different density situations and quantify the performance of contact event occurrences derived from the three scenarios to evaluate various parameters' influence such as contact probability C_P and contact per hour C_h. The different scenario settings are shown in Table II. Figures 1(d) and 1(e) describe the relationship



(a) Density Impact on Inter-Contact Time (b) Density Impact on Inter-Contact Rate (c) Dense/Sparse Ratio

(d) Average Contacts per hour (e) Total Contacts (f) Contact Probability

(g) Delivery Ratio (h) Relayed Messages (i) Delay

Figure 1. Measurement Results with regard to the three scenarios of different node densities

between the average contacts per hour and the number of nodes for different node transmission range r and a fixed area A. Figure 1(d) shows for each scenario regarding different number of nodes that the average contacts per hour increase with higher node transmission range r. Such a phenomenon might be attributed to the fact that, as the density and the transmission range r increase, the number of intermediate nodes in the network graph potentially gets higher. We compute the minimum number of contacts C_m of the three scenarios by Eq. (7), where the edges for Scenarios 1, 2 and 3 are 425, 1225 and 3900 respectively while the transmission range r of the nodes is equal to one. The value of the constant β is 0.1 for all three scenarios, where the contacts per hour C_h of scenarios 1, 2 and 3 are approximately 500, 1500 and 6000 respectively while the transmission range r increases by steps of $r_0 = 50$ meters. This is made clear by Figure 1(d). Furthermore from Figure 1(e) we can see that with the same number of nodes in each scenario, the increase of transmission range r gives chances of more message copies because of the growth of the number of neighbors. Figure 1(e) plots the total number of contacts per experiment C_T as a function of a number of nodes and transmission range r. The number of total contacts C_T is proportional to the number of nodes or the transmission range. For the contact probability C_P, shown in Figure 1(f), the value is higher as either number of nodes or transmission range increase. Furthermore, from Figure 1(f) we can see the minimum contact probability for different scenarios is achieved when the transmission range is equal to r_0 which is approximately 0.25. This value is similar for all three scenarios, regardless the number of the nodes, which means that the link availability is similar regardless of the node density value D_n.

C. *Routing Metric Impact By Density*

For the comparison of the impact of node density to the Epidemic routing protocol we apply three different scenarios which all consider *FIFO* as the buffer management strategy for Epidemic. As shown in Figure 1(g), for all three scenarios, the delivery ratio of Epidemic is decreasing the larger the number of nodes. The figure also shows that the delivery ratio of Epidemic with *FIFO* buffer management strategy is staying stable regarding the increase of the node transmission range r, especially when the Dense/Sparse ratio DS_R greater than 1. The delivery ratio of Epidemic decreases by $\approx 10\%$ when the node density increases by $\approx 100\%$. The delivery ratio of Epidemic has better performance when the transmission range r is less than 100 meters. This is because, when the transmission range r decreases, the dissemination speed is also reduced, which decreases the message drop rate and increases the delivery probability. To evaluate the performance of Epidemic with a variety of different node densities, it is also important to measure the number of relayed messages. Figure 1(h) shows that the number of the message copies increases proportionally to the transmission range r and number of the nodes N. This is because of the increasing dissemination speed when increasing the transmission range r. With the same available buffer space of all nodes, when increasing the number of the nodes in the scenarios, that means we increase the buffer space of the whole network. Also, Figure 1(h) shows that, as the transmission range r increases, the number of relayed messages increases while keeping the delivery ratio stable, as shown in Figure 1(g). This means that the resources of the network (bandwidth and energy) are consumed without any efficient delivery ratio improvement. As a metric for routing, we consider the end-to-end average delay. This metric is used as a performance metric for multiple scenarios in different Delay Tolerant Network applications. Figure 1(i) shows that Epidemic has a lower delay when the transmission range r is increased by r_0. This is because the criteria of the buffer management is based on the *FIFO* strategy. This means that the messages with a high buffer delay will be removed faster as the rate of dissemination speed increases when the buffer is highly occupied with messages or even full. Moreover, the message Time-To-Live (TTL) is calculated by summing up all transmission times and all buffer times. The buffer time of each message has the highest impact on the TTL of the message. This means that long buffered messages are either dropped because of full buffer space or expired TTL of the message. By increasing the transmission range r the delay inside the network will be less. But, because of more relayed messages in the network, the performance of Epidemic might be reduced.

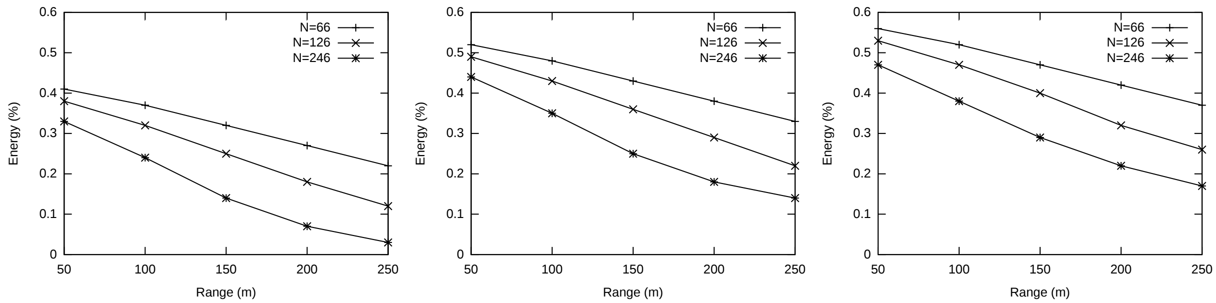
D. *Energy Metric Impact By Density*

As described in the system model section III, participation in Opportunistic Network environments consumes energy and may make devices run out of battery easily when using uncontrolled Epidemic routing. We observe that the Epidemic routing dissemination speed can be affected by the node density which is a function of number of nodes and transmission range.

Table III
ENERGY MODEL SETTINGS

Parameter	Idle	Scan	Send	Receive	Network Energy
Value	979 mW	1125 mW	1629 mW	1375 mW	10 KWh

We provide a simple energy efficiency model in which node density alters between network node size and node transmission range of the node in a particular area. This allows nodes to still send and receive messages but minimizes their energy consumption. All nodes use an energy model that has the same network constant energy resources as shown in Table III with equal values of different states considered in all scenarios. The device chosen for the simulation is a Nokia N95 [13] and the whole network energy that is considered for all three scenarios is 10 KWh. With this value for network energy all nodes are always on charge and their interfaces can be enabled permanently. We use a simple energy model using the ONE simulator which reflects energy consumption for the following modes: idle, scanning, sending, and receiving, all for ad hoc mode. As proposed by [14] we choose one IPND interval to be 2 seconds, in addition, we choose the IPND beacon default value of IBR-DTN [15] which is 5 seconds, and also the default value of the implemented IPND beacon of DTN2 [16] which is 10 seconds. Figure 2 shows the energy resources for all nodes and for every experiment over our simulation time. We plot the results for the nodes' energy after the simulation time ran out. All nodes run Epidemic router with fully cooperative mode. We calculate the remaining energy of all nodes with respect of those that run out of energy. Figure 2(a) shows the energy levels in the three different scenarios of the 2 second IPND beacon. As we can see from the graph, at a transmission range of 50 meters the energy consumption increases by 5% when node density is duplicated. At a transmission range of 250 meters the energy consumption increases by $\approx 10\%$ because the dissemination speed of Epidemic increases as the transmission range increases. This means that a higher number of copies is generated by Epidemic. Regarding the scenario of 246 nodes ($N = 246$) we can see that the incrementation of energy consumption is duplicated compared to the scenario of 126 nodes ($N = 126$) This is because the Dense/Sparse Ratio DS_R is also duplicated compared to other scenarios at a transmission range of 100 meters, as seen as in Figure 1(c). Furthermore, we can take a look at Figure 2(a) and the scenario with 66 nodes ($N = 66$), which shows a minimum variety with respect to the x-axis, meaning that the scenario of $N = 66$ has a minimal slope compared with other scenarios. This comes from the low density, low range and low number of nodes, which gives priority to achieving the desired delivery (Figure 1(g)) with low energy consumption Figure 2(a). From Figures 2(a) and 2(b) which have an IPND beacon interval of 2 and 5 seconds respectively, we can see that the final



(a) IPND interval of 2 seconds (b) IPND interval of 5 seconds (c) IPND interval of 10 seconds

Figure 2. Energy Percentage of the network with regard to the different IPND Beacons Intervals

energy level of the network is improved by $\approx 10\%$ when the beacon interval is changed from 2 to 5 seconds. When the beacon interval is 10 seconds, as shown in Figure 2(c), the improvement on the energy resource increases by $\approx 5\%$ compared to the 5 seconds IPND beacon interval shown in Figure 2(b).

V. Conclusion and Future Work

In this paper, we use our performance model to analyze the contact times and energy consumption of a DTN network with different node densities. We evaluate the performance of Epidemic routing with energy consumption on the aspects of routing metrics in terms of message delivery delay and energy cost in form of relayed messages. The important parameters in our evaluation include the contact rate λ_c, an energy constraint of the neighbor discovery protocol IPND, the number of nodes in the network, and the node transmission range inside a particular area. We analyze the impact of network density on routing and energy of Epidemic routing protocol. Furthermore, we analyze the relationship between density and the Inter-Contact Time and contact probability of the network graph of different Dense/Sparse DTN networks. We propose a function which calculates those parameters based on our model, our simulation result graphs show the accuracy of our model. Our extensive results state that in the Epidemic routing, as the node density increases, the delivery delay will decrease with the result of increasing delivery costs and bandwidth. We conclude that a higher node density can increase message dissemination speed of Epidemic routing which is harmful to the system resources in terms of delivery costs as energy metric and transmission contention as bandwidth metric. Next, we use a real devices test bed [17] instead of simulations to verify all conclusions. In the future we try to improve the mechanism of Epidemic spreading speed through a monitoring and reconfiguration loop [18]. In addition, we plan to analyze the scalability issues in the environment of Delay Tolerant Networks.

References

[1] A. Vahdat and D. Becker, " Epidemic Routing for Partially-Connected Ad Hoc Networks," *Technique Report, Department of Computer Science, Duke University, USA*, vol. vol.20, no. 6, 2000.

[2] S. Sati, C. Probst, and K. Graffi, "Analysis of Buffer Management Policies for Opportunistic Networks," in *Proceedings of the International Conference on Computer Communication and Networks, (ICCCN)*, 2016, pp. 1–8.

[3] K. R. Fall, "A delay-tolerant network architecture for challenged internets," in *Proceedings of the ACM SIGCOMM*, 2003, pp. 27–34.

[4] A. Chaintreau, A. Mtibaa, L. Massoulié, and C. Diot, "The diameter of opportunistic mobile networks," in *Proceedings of the 2007 ACM Conference on Emerging Network Experiment and Technology, CoNEXT 2007, New York, NY, USA, December 10-13, 2007*, 2007, p. 12.

[5] S. Bayhan, E. Hyytiä, J. Kangasharju, and J. Ott, "Analysis of hop limit in opportunistic networks by static and time-aggregated graphs," in *2015 IEEE International Conference on Communications, ICC 2015, London, United Kingdom, June 8-12, 2015*, 2015, pp. 3287–3292.

[6] R. Groenevelt, P. Nain, and G. Koole, "The message delay in mobile ad hoc networks," *Perform. Eval.*, vol. 62, no. 1-4, pp. 210–228, 2005.

[7] X. Zhang, G. Neglia, J. F. Kurose, and D. F. Towsley, "Performance Modeling of Epidemic Routing," *Computer Networks*, vol. 51, no. 10, pp. 2867–2891, 2007.

[8] G. Neglia and X. Zhang, "Optimal Delay-power Tradeoff in Sparse Delay Tolerant Networks: A Preliminary Study," in *Proceedings of the SIGCOMM Workshop on Challenged Networks*, 2006, pp. 237–244.

[9] M. Abdulla and R. Simon, "The Impact of Intercontact Time within Opportunistic Networks: Protocol Implications and Mobility Models." "41st Annual Simulation Symposium, 2008, pp. 92–105.

[10] D. Ellard and R. Altmann, "DTN IP Neighbor Discovery (IPND)," Internet Engineering Task Force, Internet-Draft draft-irtf-dtnrg-ipnd-03, 2016. [Online]. Available: https://tools.ietf.org/html/draft-irtf-dtnrg-ipnd-03

[11] A. Keränen, J. Ott, and T. Kärkkäinen, "The ONE Simulator for DTN Protocol Evaluation," in *Proceedings of the International Conference on Simulation Tools and Techniques for Communications, Networks and Systems (SimuTools)*. ICST/ACM, 2009.

[12] A. Keränen, T. Kärkkäinen, and J. Ott, "Simulating Mobility and DTNs with the ONE (Invited Paper)," *Journal of Communications*, vol. 5, no. 2, pp. 43–50, 2010.

[13] G. P. Perrucci, F. H. P. Fitzek, and J. Widmer, "Survey on Energy Consumption Entities on the Smartphone Platform," in *Proceedings of the 73rd IEEE Vehicular Technology Conference, VTC Spring 2011, 15-18 May 2011, Budapest, Hungary*, 2011, pp. 1–6.

[14] A. Hess, E. Hyytiä, and J. Ott, "Efficient Neighbor Discovery in Mobile Opportunistic Networking using Mobility Awareness," in *Proc. of COMSNETS'14*, 2014.

[15] M. Doering, S. Lahde, J. Morgenroth, and L. C. Wolf, "IBR-DTN: an efficient implementation for embedded systems," in *Proceedings of the Third Workshop on Challenged Networks, CHANTS 2008, San Francisco, California, USA, September 15, 2008*, 2008, pp. 117–120.

[16] N4C, "Functional specification for dtn infrastructure software," 2008. [Online]. Available: http://www.n4c.eu/N4C-info.php

[17] A. Ippisch and K. Graffi, "Infrastructure mode based opportunistic networks on android devices," in *2017 IEEE 31st International Conference on Advanced Information Networking and Applications (AINA)*, 2017, pp. 454–461.

[18] K. Graffi, "Monitoring and Management of Peer-to-Peer Systems," Ph.D. dissertation, Technische Universität Darmstadt, 2010.