A System Design Framework for Scalability Analysis of Geographic Routing Algorithms in Large-Scale Mesh Networks

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ABSTRACT

It is important to evaluate the performance of large communication networks prior to their deployment, in particular if economic interests are involved. In wireless multi-hop mesh networks, a communication message is transferred from a source to a destination via multiple nodes. Typically the message can be transferred via multiple routes in a mesh network, because several nodes are in communication range. During the design phase of such a communication network, specific characteristics need to be considered in order to avoid boundaries like bottlenecks and dead-end problems of the deployed system. Hence these kinds of problems must be avoided prior to the network deployment. In this paper, we present a system design framework for the OMNeT++ simulation environment, which is able to identify potential bottlenecks and maximum loads of multi-hop networks. The process is presented via a realistic use case scenario for an Energy Management Application, in which geographic routing algorithms are used to identify the shortest route to a destination. The results of the performance evaluation enabled us to support the communication design process with information about reliability, data rate and routing schemes.

Categories and Subject Descriptors

I.6.4 [**Simulation and Modeling**]: Model Validation and Analysis; I.6.5 [**Simulation and Modeling**]: Model Development; I.6.6 [**Simulation and Modeling**]: Simulation Output Analysis

General Terms

Design, Performance, Verification

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Keywords

Realistic Simulation, Dynamic Scenario Generation Process, Performance Evaluation, Wireless Communication Networks

1. INTRODUCTION

Energy providers started to deploy smart meters at their customer's homes recently. On the one hand these meters enable the customers to determine their actual energy consumption in near real time and on the other hand the energy provider gets to know which customer consumes how much energy. For this, the collected data has to be transferred to a centralised server, in which it is stored or further processed. To save costs, smart meters are connected to the server via an independent wireless multi hop network. Due to the high building density in equipped areas, cheap wireless transmitters with limited communication range are utilised. The meter information is forwarded from each hop to the direction of the server, until it is reached.

In recent work [7], data collection of sensor networks were evaluated through probabilistic models. Wireless data collection networks, e.g. sensor networks, usually have resource constraints. Metered data has to take multiple hops to a dedicated data collector. Within the network, some entities are more often frequented than others. This is due to the centralised topology of such networks.

In this work, the evaluated network topology is modelled using real positions of possible customer's homes. The routing is implemented using a geobased routing algorithm which sends the data to the node within the transmission range with the shortest distance to the server. This kind of routing is called greedy forwarding. Besides meters, which can create and forward data, and servers, which are also called data collectors, another type of nodes appears: Routers with enhanced transmission range and no capability of creating new data.

The paper is structured as follows: After analysing related work within the context of simulation generation and modelling realistic scenarios, the problem of design and development of large scale networks is described in detail, including the introduction of our exemplary use case scenario. The simulation framework for OMNeT++[1] is explained in

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[1] The GeoDatabase module for OMNeT++ is available online at http://www.cni.tu-dortmund.de

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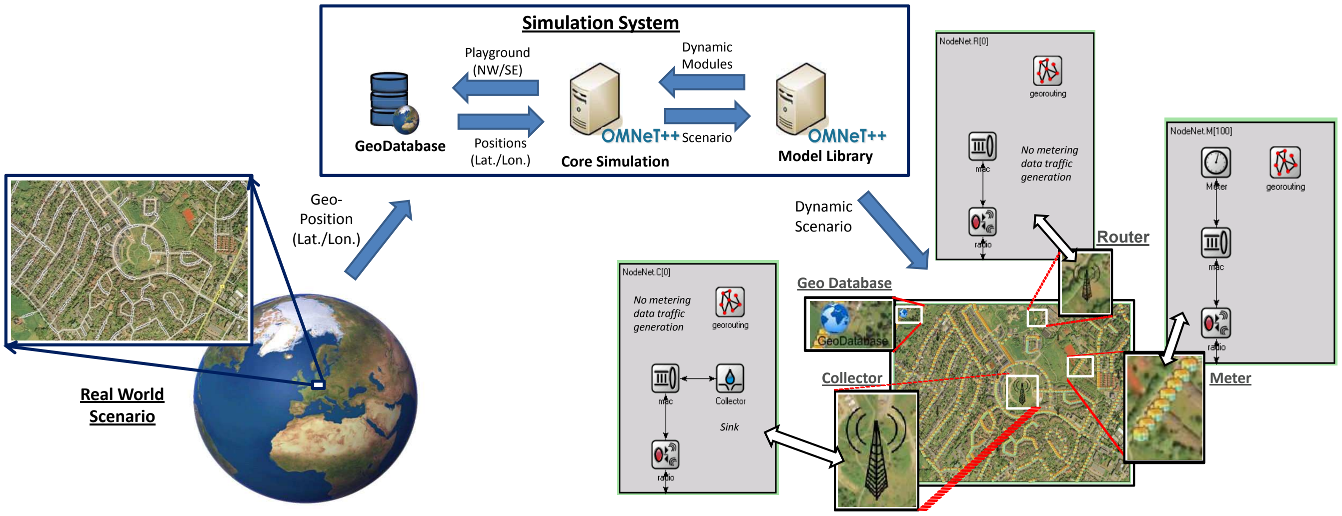

Figure 1: Exemplary Simulation Scenario for Energy Management Applications

the following, with a focus on the detailed description of the implemented modules within the nodes. The application scenario is defined in Section 4, focusing on the used future technology for next generation smart meters. The performance analysis is described in the following section, using two expansion stages. In basic stage, only meters and collectors are included. In a second step, extensions are added. The extensions are routers, which allow to optimize the topology and the overall performance. Prior to our conclusion, a stress-test is presented, which figures out the maximum capacity of the Energy Management Application.

2. RELATED WORK

Different ways for creating large-scale networks automatically are possible; in general three different procedures are discussed in related works. The basic approach, which is used in the OMNeT++ simulation environment [7] by default, is the generation process by a predefined description file, which defines the number, types, parameters and positions of the communication nodes. In order to place a large number of nodes, an automatic positioning algorithm can be used to place all nodes into the simulation playground, which is presented for example in [6]. The manual approach is suitable for a limited number of nodes, whereas the automatic positioning approach does not represent a real network topology and distances.

The second approach for generating large-scale simulation scenarios and topologies is based on external tools, for example BRITE [5] or ReaSE [1], which can not be integrated or linked directly to the simulation environment OMNeT++. In these approaches the nodes can be placed randomly or heavy-tailed, which is a satisfying solution for statistic analysis, but not for realistic scenarios. In order to generate positions by these algorithms, specific data formats (e.g. XML) or a plugin can be used for creating the position files.

In comparison to related work, our approach is based on an automatic simulation generation process using geographic positioning for modelling realistic scenarios. Our solution has the advantage that the topology is presented in the same dimensions and scale of the real world scenario, which allows the analysis of geographic specific problems. Furthermore, this approach is implemented as an independent framework, whereas integration into other frameworks, like INET [8] or MIXIM [3], will be evaluated in future works.

3. PROBLEM STATEMENT

During the process of system design, critical decisions have to be made. In the early stages, there is a lack of experience-based data, especially if fundamental parameters have not been set (e.g. required data rate, packet length, used protocols). Some of these parameters could be estimated in a first step, but with a growing complexity of the system, estimations are not advisable. Even more challenging is the design of a new wireless communication system for embedded devices. Because of resource constraints, full-blown standard protocol stacks cannot be utilized due to the protocol overhead. This also forbids the use of optimization techniques like present in related works [9].

Scalability is another important aspect, which must be considered during the design process. Embedded devices are mostly used in large-scale systems, which in some cases consist of up to hundreds or thousands of autonomous nodes. In such a context, minor changes in the system design can have an enormous impact on the overall system performance, which can today not be estimated at the beginning of the development. Especially a generalized simulation setup [6] could cause wrong assumptions for a realistic scenario, because some of the effects as described later in Section 6 only occur within a realistic allocation of the nodes (e.g. Dead-End-Problem, Bottlenecks). To avoid negative effects during deployment of the system, we present a tool for a top down approach, in which new concepts can be evaluated during early design and development stages for realistic scenarios.

Our tool is suitable for rapid system design and prototyping. It supports fast development and analysis, including the early steps as well as stress and performance tests of existing systems in later phases. The scalability is made possible through a lightweight simulation structure and the comprehensive use of databases, which is described later.

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3.1 Supported System Applications

Supported application scenarios could be derived from a wide range of industrial applications, where systems with thousands of nodes need to be installed. In this paper, the development of a system of wireless *Energy Management Application* is assumed. These nodes need to be optimized concerning the costs as well as complexity. Simplicity is necessary because Energy Management System should be installed in every house which leads to a huge amount of nodes. For a successful commercial launch, the overall costs must be financial acceptable.

3.2 Simulation Environment

Our simulation model is based on version 4.0 of the discrete event simulator OMNeT++. Due to the resource constraints of the investigated embedded systems, no additional simulation framework is used for the protocol simulation.
The developed geo-position scenario generator acquires the coordinates from different offline sources. This includes own acquired data and governmental/commercial data products, as well as online sources, like the Google Maps API (Premier) or OpenStreetMap. Due to the limitations in requesting data from the online sources, the online procedure is reasonable for smaller scenarios, but in case of a large-scale scenario the acquisition of the geo-positions can be performed by offline sources.

4. FRAMEWORK DESCRIPTION

The proposed simulation framework targets system evaluation of large scale (wireless) networks. In contrast to similar work [6], we especially consider the particular problems of the simulation generation process of a large-scale network and the simulation overhead of the whole protocol stack.

4.1 Dynamic System Design

In order to generate a large-scale network with thousands of nodes, a dynamic network creation is imperative necessary. This avoids a manual, time-consuming static generation and configuration of each node. In our approach, we use geographic positions of real locations, e.g. houses, as input parameters for the automatic network generation. This ensures a close to reality network topology. The overview of the simulation environment is presented in Figure 1.

ID	Street	House Number	Latitude	Longitude

Table 1: Identifier of nodes

Initialization, creation and configuration of the network are executed by the core simulation. A set of preconfigured geographic positions (north-west and south-east corner coordinates) mark the simulation playground. The core simulation can receive the positions of nodes, which are located within the playground, from an offline source and online from an external SQL database, e.g. the geo-position database *GeoDatabase*. Via a connection between the core simulation and the GeoDatabase [4], all information about existing nodes within the playground and neighbours of particular nodes can be retrieved, including the information listed in Table 1. The dynamic node creation is based on the received geographic positions. Nodes are placed on the Cartesian positions (x,y), which are calculated using Mercator projection of GPS position data of real locations.

4.2 Dynamic Node Generation Process

Our dynamic node design leads to an easy expandability and adaptation to new scenarios. Furthermore, it allows the reduction of the protocol overhead and minimizes the execution time of the simulation. Generally, any kind of module can be generated dynamically, but for a better handling, the dynamically generated modules should base on a basic standard module. This standard module only consists of the elementary communication layers reduced to a minimum of necessary functionalities. Various additions to the functionality can then be added to the basic module by multiple sub-modules according to the intended application (see Figure 2).

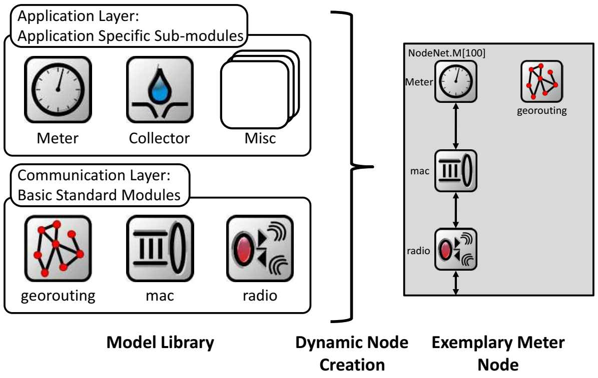

Figure 2: Dynamic node design

Referring to Figure 2, dynamically created nodes consist of the basic standard modules, which compose the communication layer, and one or more application specific sub-modules. All available application specific sub-modules and basic standard modules are combined in a *Model Library*. Because of the application scenario, all existing nodes are focusing on Geo-Routing in mesh networks. Therefore the communication layer consists of modules for Geo-Routing, medium access and radio. For the use-case scenario described in Section 5, new modules have been implemented for the communication layer. In general, the modules of other frameworks like INET or MiXiM can be used for the communication layer, if modules, which model the desired communication process, are available.

During the initialisation phase of the simulation, the dynamic node creation takes place. The dynamic node creation consists of the following steps:

1. Query GeoDatabase for node positions in a given area. The area is defined by its north/west and south/east coordinates.

2. For each node within this area, the GeoDatabase returns the position (latitude/longitude), the type of the node and optional parameters.

3. For each node, the basic standard modules are added.

4. Depending on the type, one or more application specific sub-modules are added to the previously added node.

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5. Communication and application layers are connected.
6. The position of the node is scaled to the OMNeT++ playground and the node is moved to the corresponding Cartesian x,y positions as described in 4.1.

The presented framework for dynamic network creation allows analysis of heterogeneous application scenarios. An example is presented in the following section.

5. APPLICATION SCENARIO

In this paper the introduced an Energy Management System example is networked via wireless mesh communication. Details of the system design are given in this section.

5.1 Energy Management System Application

Future energy systems rely on meters which allow to determine the actual energy use on a day-by-day or even near real-time basis. This is needed to manage the balance in the energy system despite fluctuating energy production by renewable energy sources. Current research shows a large demand for such energy management systems, which combine wireless technology with Internet technologies [10]. While existing systems focus on industrial customers, in the future every household must be connected to this intelligent energy management system. Therefore communication technologies are challenged by scalability requirements. In the following, an exemplary analysis for a wireless mesh-based system design (inspired by projects as the Zigbee city project in Göteborg [11]) is shown.

5.2 System Architecture

Each household in the simulation model is represented by an Energy Management Node, which is equipped with the metering application and a radio networking interface. The positions of the households, which are provided by the overlaying GeoDatabase, are based on a realistic topology. Our exemplary use case scenario is based on an exemplary European city environment. Each dynamically generated scenario (see Section 4) has at least one data collector, which represents the data sink. This data sink needs to be placed by the public utility company in order to collect the customers' data. Additional to the pure sink-source meshing algorithms, a new network component is introduced in order to circumvent the drawbacks of bottlenecks in the Geo-Routing algorithm.

- Energy Management Node (Smart Meter) - The nodes act on the one hand as a data traffic generator for smart metering messages. On the other hand meters are able to receive relayed messages within the mesh network by operating on a single shared radio (transmitter and receiver).
- Collector - Collectors receive messages with extended radio module from shared channels (on up to 4 parallel transmissions allowed in a slot) and provide statistics about overall success ratio for a given time frame.

As a first extension, an additional node type has been created. This was necessary because of the detected problems during the simulation runs.

- Routers - Router nodes relay messages with a greater transmission range and bandwidth, because they represent nodes with a wireless WAN connection in our system. The routers provide a queue for 160 packets, check if the time-to-life or hop limitation is reached and can operate at higher data rates for connections to other routers/collector, transferring multiple packets per slot.

5.3 Communication and Routing Protocols

The radio meshing transmission technology used in this scenario is based on a basic greedy Geo-Routing algorithm, which is described in [2]. Because we are focusing on a network with fixed topology, the routes for the whole network are set during the initialization phase. It is assumed that every node is aware of the positions of all other nodes in the scenario. Our Geo-Routing algorithm works as follows:

1. For each node, the distances to all other nodes are calculated and stored in a node specific neighbour list.
2. Nodes, which are out of communication range, are deleted from the neighbour list.
3. For each node, the neighbours in communication range are stored, with respect to the distance to the next router or collector, in ascending order.

As a reference, we have chosen a Zigbee-like system design [12] with several simplifications, such as constant bit rate (independent of channel characteristics) and a maximum range of 100 m. The medium access to the shared channel is synchronized by slotted ALOHA. The transmission speed is 100 kBit/s within a maximum range of 100 m. Because of varying legal regulations in different countries, the simulation is not focused on a particular operating frequency. Instead, the overall performance limits should be probed. A payload of 2 k Byte size is carrying energy management data (assumed header included) and is sent in a 400 ms slot followed by an acknowledgement. The slot time enables the nodes to process the received payload with limited resources. Therefore, the slot time is chosen according to the limitations of the maximum required transmission time. For the router to router communication, a three times higher transmission rate is assumed. This enables the router to enhance the capacity of the network. In addition, a greater transmission range of 2 km is assumed due to directional antennas. Each node maintains an output queue of messages towards the shared channel and the routing algorithm addresses the next hop by calculating - based on the information provided in its neighbour list - the nearest-to-destination node and tries to send the packet to. As soon as the transmission of the packet is acknowledged by the receiving node, the packet gets dropped from the transmission queue. In two cases the transmission fails:

1. The receiving node is either permanently unavailable due to a failure or
2. the receiving node is temporary unreachable because of a collision within the same time slot.

The sending node recognizes a transmission failure by a time-out period and it starts sending the packet to the same node after waiting for a back-off timer. After three retries the sending node chooses an alternative link through the next best nearest-to-destination node and restarts the process. The packets are forwarded until the maximum time to live expires, which is set to 300 seconds by default. A packet

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is also dropped if the maximum number of hops is reached, which was set to a default value of 40.

Additional to the basic routing algorithm, router nodes are introduced in order to enhance the performance of the presented topology as well as different variations in the behaviour of the nodes are implemented and tested:

- Router Priority - Each Node sends packets prioritised to an router in-range, even if they are not located in the direction the data collector.
- Dynamic Distance - The radio module is able to adapt the transmission range dynamically in order to avoid interference and communication gaps.
- Dynamic Router Distance - The routers consist of separate incoming and outgoing communication interfaces, which can base on different technologies with varying transmission ranges and data rates.
- Dead-End Problem - If a particular node receives a packet, which was created by itself, this particular route is marked as a dead-end route.

6. ANALYSIS

The results of the conducted simulation runs are presented in the following section. The first results focus on the routing algorithm by using only nodes and a collector as communication nodes. The following considerations show the impact of the additional routers in the mesh network which are placed on random positions. Final results on a performed stress test are presented.

The focus of the following experiments lies on the system behaviour by applying a basic Geo-Routing algorithm in the example network shown in Figure 3.

Figure 3: Test Scenario Network

6.1 Performance Analysis

The network consists of 2504 nodes within an area of $1,5km \cdot 1km$ with a single data collector located in the middle of the scenario (see Figure 3). Each node sends a data packet towards the data collector with a randomised starting time every hour. The percentage of successfully received packets - from the source Energy Management Node to the sink (data collector) - depending on the geographical position is illustrated in Figure 4.

The results presented in this figure show that only a small number of packets are received from the western part of the scenario. The reason for this is a bottleneck at one node. All packets from the region behind have to pass a single node which can not forward all of the packets to the next nodes in the direction of the collector. Because of a communication gap, no other nodes are available to be used as an alternative route. In this case an additional node is required to bridge the gap.

In order to analyse the failure rate of the network, Figure 6 displays the detected collisions. The increase of collisions at the collector is caused by the higher signalling load on the mesh, because all packets are forwarded into the direction of the collector.

Overall only 27% of packets are transmitted successfully.

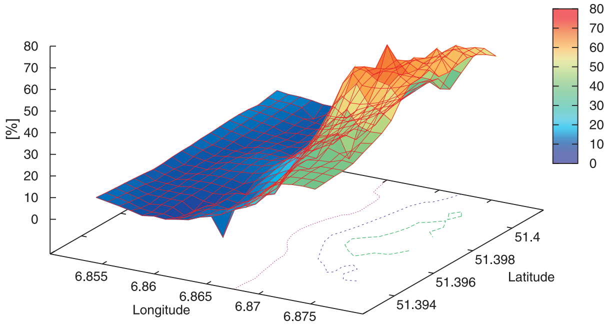

Figure 4: Percentage of successfully transmitted packets without routers

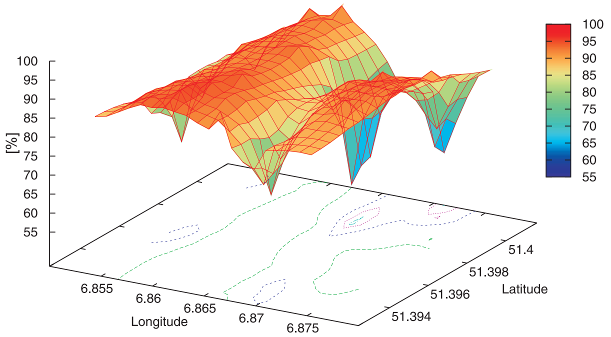

Figure 5: Percentage of successfully transmitted packets with routers

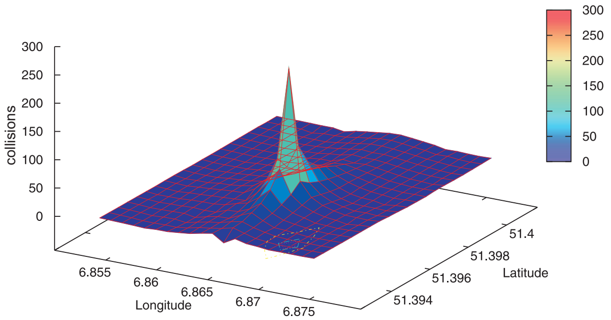

Figure 6: Detected number of collisions of packets from the source to the sink without routers

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A complete statistic of the received packets is presented in Table 2. It can be assumed that only a few nodes are responsible for the most failures (dropped packets). The maximum queue length indicates collisions as the reason for dropped packets. In order to balance the signalling load throughout the entire network, additional routers are installed to concentrate the traffic load at locations with high signalling load and bridge communication gaps. Figure 5 shows the number of successfully received packets from the source to the sink by using routers.

Stats	Min	Max	Mean	Dev.
Received Packets	0	24	6.4	10.6
Transit Packets	0	65435	224	1935
Dropped Packets	0	32616	17.6	677.2
Generated Packets	24	24	24	0
Collided Packets	0	32315	16.1	651.2
Hops per Packet	0	10	1.5	2.7
Queue Length	0	26	0.01	0.5

Table 2: Number of packets per node without routers

The more balanced overall network load together with reduced number of collisions (see Figure 7) is the result of the new network topology. The enhancement of the new network topology can be summarised with a receiving rate of more than 87% of successfully transmitted packets. The complete statistic of the received packets is shown in Table 3. While this first analysis should show the general benefit of routers, in the following section a scenario is shown, in which the required success rates for Energy Management Systems in the range of 100% can be achieved.

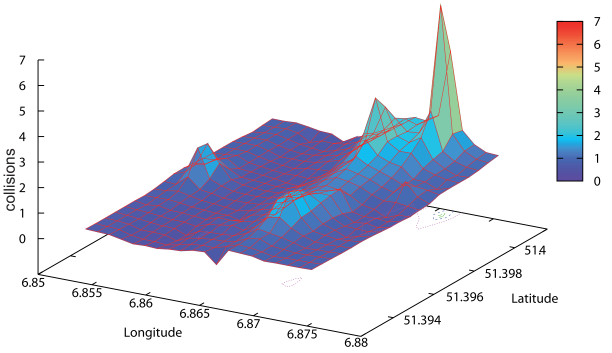

Figure 7: Detected collision of packets from the source to the sink with routers

Stats	Min	Max	Mean	Dev.
Received Packets	0	24	20.9	8.1
Transit Packets	0	28734	167.6	1594.1
Dropped Packets	0	1242	3.1	54.7
Generated Packets	24	24	24	0
Collided Packets	0	20555	10.4	411.8
Hops per Packet	0	5	2.1	1.3
Queue Length	0	1	0.0004	0.02

Table 3: Number of packets per node with routers

6.2 Stress Test

The previous experiments have shown the impact of the network topology on collisions and network load. For future network extensions, more detailed information on the overall performance of the algorithm together with the network topology can be gained by performing stress tests with a higher data frequency than in reality. Therefore the message frequency is varied between less than one minute and two hours. In the previous section the focus lies on pointing out specific effects which occur in geobased scenarios. Therefore a smaller scenario was chosen for the experiments to make the visual analysis easier. For the following stress test a more complex scenario with around 9000 nodes is introduced.

The results of the stress tests are shown in Figure 8. The probability of a successful or unsuccessful transmission is shown on the primary y-axis, whereas the successful transmission is presented by the dashed line, the unsuccessful by the dashed-dotted line. The transmission rate of successful delivered packets decreases drastically beyond a message frequency of 1/8h, which can be explained by the packet loss after reaching the maximum time to live or maximum number of hops. The number of collisions per packet is shown on the secondary logarithmic y-axis, whereas the collisions of a single packet on its way from the source to the sink are shown by the dotted line. If two packets collide, both packets get retransmitted up to three times after a random back-off timer until an alternative route is chosen. This procedure is repeated until the maximum number of hops is reached or the time to live has been expired, which results in a packet loss. As a result of an overall lower network load, probability of a collision drastically decreases with the message frequency beyond 1/16h.

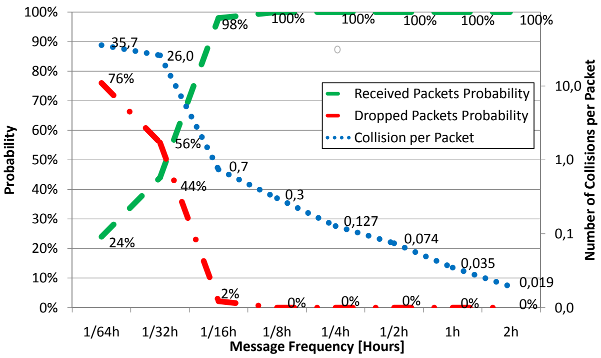

Figure 8: Stress Testing

7. CONCLUSION AND OUTLOOK

In this paper we presented a new simulation framework for evaluating communication system performance of realistic large-scale scenarios. This framework can act as a standalone simulation as presented in this paper as well as an addition to other existing OMNeT++ frameworks. Due to the ability of creating scenarios dynamically based on geographical positions of network nodes, almost every combination and size of scenario can be evaluated in a short-term. In addition to the flexible scenario generation, different technologies can be evaluated using rapid system design in early development stages in terms of system behaviour and bot-

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tlenecks. Our use case scenario demonstrates the capability of designing a mesh network based on a Geo-Routing algorithm with a short range radio transmission technology. Especially identifying bottlenecks or points of failure in a real world roll-out has been shown in early stages of the system design and improvements have been obtained early.
Our future work will build upon this framework in order to gain more findings and improvements on Geo-Routing algorithms in large network topologies as well as evaluating different technologies for mesh sensor networks and smart grid infrastructures. In particular, we will investigate scenarios for different radio technologies, such as Zigbee, WLAN, Mobile WiMAX and LTE relaying as well as wired technologies such as PLC and DSL.

8. ACKNOWLEDGMENTS

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