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Visual PeRF-Mesh: A comprehensive geographical tool for large scale RF-mesh AMI planning and performance Evaluation

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Abstract: This work presents *Visual PeRF-Mesh*, a tool that addresses the performance analysis and simulation of Advanced Metering Infrastructure (AMI) RF-mesh smart meter communication system. The tool encompasses several aspects of the network performance evaluation: from network planning to topology definition, from mathematical analysis to stochastic simulation. The tool can also prove easy to use and not computationally hungry while providing valuable insights on RF-mesh systems. The modular structure of the tool can allow high flexibility in tuning the input parameters and the integration with complex optimization models.

Key Words: RF-mesh, performance analysis, simulation, Advanced Metering Infrastructure, Smart grid

There is a wide range of AMI applications [1, 2], such as demand-response, integration of electric vehicles, load management, etc. that require a solid and steady communication infrastructure that provides a certain quality of service (e.g., in terms of delay, availability, resiliency, data throughput, etc). To assess the impact of such applications in the communication infrastructure, there is the need for performance tools that can capture the complexity and large-scale nature of AMI networks. Among the technologies deployed in AMI, RF-mesh systems seem to be gaining popularity mainly because of their proprietary infrastructure, low Capital Expenditures (CAPEX), and Operational Expenditures (OPEX). However, RF-meshes [3] have a very low data rate to start with and operate in the unlicensed Industrial Scientific and Medical (ISM) band, which makes them even more vulnerable to capacity degradation due to different types of interference. Therefore, before using those systems for advanced AMI applications, there is the need for comprehensive performance assessment tools to capture both the large-scale nature and the complexities of the system [4, 5, 6, 7].

There are several reasons why current tools may not be appropriate for the assessment and optimization of large-scale realistic deployments. First of all, there is a lack of publicly available material about implementation details (e.g., type of routing, position of routers and data collector), the power utility must therefore depend on "black-boxes" studies without the possibility of performing what-if optimization analysis. Moreover, the large scale nature of this kind of systems causes some issues to both analytic and simulation studies, highly increasing the computational burden. This is why many performance studies focus on smaller instances. Despite the quality of these studies, considering a subset of the nodes does not permit to gain a deep insight into this kind of systems since the findings on few hundred node instances cannot be easily extended to actually implemented systems with several thousands of nodes. Finally, the topological aspects of the deployment are in many cases neglected.

In this paper, we present Visual PeRF-mesh, which is a comprehensive tool for the performance assessment of RF-mesh AMI that was designed to tackle the aforementioned issues. The architecture of *Visual PeRF-Mesh*, depicted in Figure 1 presents three main modules:

1. Topology generation
2. Mathematical modelling
3. Network simulation

The tool also includes a Geographic Information System (GIS) data interface to build the system topology in a more realistic way and perform what-if for planning and optimization. The topology generation, that exploits GIS data to produce consistent network instances is described in detail in Section 1. Visual PeRF-Mesh offers then the possibility to continue the performance study through a mathematical model, described in Section 2.1. The analysis can be completed by network simulation, presented in 2.2. The simulator allows for a detailed representation of the main features of a RF-mesh system. Note that simulations need to be run over long periods in order to restrict the confidence interval of the simulated parameters while the mathematical model reduces that time but needs some simplifying assumptions. The combination of the consistent topology generator, the mathematical analysis and the network simulation enriches the quality of the assessment. In Section 3, numerical results obtained with the analytical engine and with the network simulator are reported, and finally concluding remark can be found in Section 4.

1 Topology generator

Topology generation takes on great importance when it comes to studying the performance of AMI systems: the characteristics of the topology considerably affect the performance analysis. For instance, densely populated areas are subject to a high level of interference that needs to be properly addressed. On the other hand, the performance in less crowded countryside regions is undermined by low network connectivity and, as a consequence, network planning and design becomes fundamental to guaranteeing a suitable system operation.

Nevertheless, a good deal of research uses randomly distributed topologies, since they are simple to generate and can be easily integrated in a mathematical formulations. However, random topologies do not

reflect the fact that smart meters, the principal involved nodes, are far from being randomly distributed since they are mainly installed in the residential premises. To this purpose, we decided to build a dedicated module to get more consistent topologies.

Another important issue with AMI topology generation is size: deployed AMIs are composed of several thousands of nodes. Moreover, the position of nodes, other than smart meters, are not easily retrieved in publicly available maps, and in some case (i.e., for routers and collectors) they are undisclosed and protected by confidentiality agreements.

The implemented topology generation tool has three main use modes:

1. use existing data to position nodes
2. positioning nodes by manual draw
3. use open-source databases

In the first case, the user provides a file with the list of nodes location. Then, the points are represented on a map, and the topology is completed with the definition of the links. In this first phase, the presence of a link between two nodes is defined based on the geometrical distance between the two points: covering rays are defined for each type of node, and a link is said to exist if, and only if, the nodes fall within each other covering areas. More detailed propagation models are sought and currently investigated, but this simplified mechanism is extensively used in communication performance literature.

The second possibility is to let the user manually draw the position of nodes in a map. Then, the latitude and the longitude of the selected points are retrieved using Google Maps APIs. The manual choice of the points might be a good option for routers and collectors, which are in the order of few tens. On the other hand, smart meters, which can be in the thousands for large AMI implementations, are far too numerous to be manually selected on a map. As a consequence, it is more convenient to use publicly available information (the third use mode) about residential addresses (e.g., list of postal codes, municipality's databases) to create the topology.

The different options can be put together in order to better customize the instances to the user needs. In Figure 2, the creation of a topology is described with more details. We chose to focus our analysis on a neighborhood in the municipality of Montreal, for which we found a database of all the residential addresses.¹ In subfigure 2a, we can notice that the user can choose the area on which setting up its topology. The tool then queries the aforementioned database with all the residential addresses, and identifies all the points falling in the area selected by the user. In a second phase, the current implementation of the tool lets the user choose where to place routers and collectors on the map (see subfigures 2b and 2c). At the end of the topology generation, two files are produced: one with the list of nodes along with their characteristics (e.g., ID, type, coordinates), and one with the list of links with the optional parameter of the geometrical distance. The two files are used as inputs to the analytic tool and the network simulator. An optimal location model for the location of routers and data collectors is currently under study for integration. Such a model will provide the user with an additional tool to optimize system design.

2 AMI performance evaluation

As shown in Figure 1, *visual PeRF-Mesh* has two main approaches for RF-AMI performance evaluation: the first consists in mathematical modelling and the second is stochastic simulation.

2.1 An analytical performance engine for large scale AMI

A schematized structure of the analytical mathematical model implemented in Visual PeRF-Mesh is reported in Figure 3. As one can see, the model is represented, and will from now on referred to, as an *engine* with a modular structure and a clear distinction between inputs and outputs.

¹A file with the list of all the residential addresses in the island of Montreal can be found at <http://donnees.ville.montreal.qc.ca/dataset/adresses-ponctuelles>

Details about the modelling of the system, the mathematical formulation, and some of the numerical results, were previously included in [8, 9]. The analytic tool proved fast, successful, and reliable in the evaluation of the performance of large scale AMIs. The tool not only helps in assessing currently implemented systems, but can also be used to carry out extensive what ifs studies, highlighting potential system bottlenecks in the design phase.

The main issue undermining the formulation of analytical mathematical models of AMI is the difficulty in representing complex implementation details by means of mathematical equations: simplifications are unavoidable and the risk of having a blurred picture of AMI performance is not negligible. However, despite the reliance on inevitable simplifications, mathematical modelling can give valuable insights into large AMI systems in a reasonable amount of time. Furthermore, the mathematical model on the performance study proved highly scalable and flexible in the choice of inputs: several types of instances and scenarios can be evaluated with few or no changes in the modelling. Although the formulation was kept simple for computational reasons, important system implementation details were considered, such as the Frequency Hopping Spread Spectrum (FHSS) algorithm.

As shown in 3, the main inputs of the engine are the topology definition, the routing and the traffic characterization. The topology generator, extensively described in Section 1, is used to build a topology that best reflects the users needs. Nevertheless, the user is also given the possibility to do some modifications to existing topology, such as changing the covering rays of devices, or varying the number of nodes.

A simple static routing protocol was adopted, based on the computation of bidirectional shortest paths from the source to the destination. The shortest paths are calculated using the Python module *NetworkX* and are used to route all packets from the data collector to the smart meters, and in the opposite direction. The simple routing mechanism was important to be able to get a closed formulation for the delay, and consequently to obtain numerical results. The integration of more complex routing algorithms into the analytical model are currently under study.

The traffic characterization is used to define the set of applications the AMI in question is suitable for. Every application can be identified by the rate of packet generation at node level. In our study, we anticipated two different packet generation rates: one from the smart meter to the data collectors and one in the opposite direction. The traffic generation was assumed to be Poisson distributed to simplify the mathematical formulation of the problem.

The main element that degrades AMI systems is the wireless interference: many nodes are sharing the same transmission medium, and the eventual simultaneous transmission of two or more nodes in the same frequency channel provokes a collision of the involved packets, which need to be retransmitted. It is then important to calculate the probability of collisions, in order to define the average number of transmissions and, consequently, the average delay. Fundamental findings in wireless networks literature are used to compute the average collision probability of the different packets exchanged throughout the network.

Once the probability of collision for every node in the system is found, other performance indexes are computed. The first element is the average delay in the uplink and downlink directions. The characterization of delay provides several what ifs studies: for instance, to estimate the average delay in a system with respect to the traffic generation rates in uplink and downlink. This analysis is important to assess the feasibility of generic smart grid applications.

Despite the analysis on average values of collision probability and delay, the engine also provides the possibility of identifying the so-called *critical nodes* in the system under consideration. A node is considered *critical*, if its collision probability is above a certain threshold. This analysis proved favorable in the identification of bottlenecks in the system, consequently offering large improvement possibilities in the design phase.

A valuable insight on the efficiency of the system under consideration, and its suitability for smart grid applications, can be delivered by the knowledge of the portion of smart-meters with an uplink or downlink delay greater than a certain threshold. In the smart grid context, it is fundamental that the transmitted data be up-to-date, in other words every application has a delay threshold, above which packets are considered

old. A well known mathematical function, namely the *survival function*, was used to carry feasibility analysis: given a certain threshold d , the survival function tells the percentage of meters in the system whose average delay is larger than d . This analysis proved useful in the feasibility assessment of smart grid applications with delay requirements limited to a portion of the nodes in the network.

2.2 Network simulator

As highlighted in the previous section, a pure-analytic performance study entails some drawbacks. Despite the advantages in terms of flexibility, ease of computational and scalability, a mathematical representation of a RF-Mesh AMI misses to catch important features. In order to go beyond the analytic limits, a network simulator was developed to represent AMI systems in a more realistic fashion.

The theme of performance study of wireless mesh network has been extensively treated in literature. A proliferation of commercial and/or open source simulation software paved the road to a multitude of works that dealt with the evaluation of several communication systems for smart grid applications. Despite the availability of several simulation platforms, a dedicated module for the RF-mesh technology was not found on-the-shelf. Moreover, the performance studies focused their analysis on systems of no more than few hundreds of nodes, definitively lower than actually implemented systems, whose number of nodes is rather in the thousands. One of the advantages of general purposes simulation software is that they span across a wide variety of systems and technologies. However, they are not generally optimized for a single type of system: this leads to a lack of computational efficiency for not standard systems, such as RF-AMI.

As a consequence, a new simulation tool was developed by scratch, using well known open-source programming languages, such as Java and Python. The tool was customized according to the RF-AMI specifications and proved computational efficient allowing for the evaluation of several thousand node instances in a reasonable time.

Similarly to the performance analysis engine presented in the previous section, the simulator under consideration was conceived to accept as input the topology produced by the topology generator described in Section 1. The analogies with the analytic tool are not restricted to the topology: among the inputs of the simulator, there is also the characterization of traffic and routing. Nevertheless, the simulator offers a higher level of complexity in the input definition. The generation of packets can follow distributions other than the poisson-type that was used in the analytic tool. The simulator also offers the possibility to generate deterministic traffic: nodes can randomly transmit at each time interval as well as generate packets at predetermined instants (e.g., a scheduled broadcast transmission from the collector to all the smart meters at a specific time of the day). This variety in the traffic characterization permits to represent a broad set of different smart grid applications. Accounting for several applications in the same communication system is a feature that might be envisioned by power utilities in order to design its own communication infrastructure: the use of AMI for different smart grid applications is fascinating but needs to be priorly assessed by performance studies.

Furthermore, a more realistic routing algorithm was adopted in order to grasp the dynamic nature of the mesh system under study. The so-called *layer-based* routing [10] was implemented and used for simulations: this mechanism is very popular because of its simplicity and robustness at the same time.

The simulator undergoes three main phases:

- *initialization*, in which all the parameters concerning topology, routing and traffic characterization are set up
- *simulation*, in which the instance generated in the previous phase is simulated over a desired time interval
- *results analysis*, in which the data produced in the simulation phase are elaborated and translated into targeted analyses to define the performance

The second phase, core of the simulator, is in turn divided into three sub-phases:

- traffic generation
- collision check
- packet forwarding

In the first phase, each node generates packets for transmissions according to the specifics defined in the initialization phase. In the second one, there is a check for mutual interferences of the active transmissions. As already mentioned, packets experiencing a collision are not correctly received and need to be retransmitted in one of the following time intervals. Packets which are transmitted and correctly received are then forwarded to the next node until they reach the intended destination. The simulator keeps track of all the relevant events (e.g., packets generation, transmissions, collisions) taking place in the simulated horizon and use them in the *results analysis phase*.

Some numerical results obtained by means of this simulation tool are reported in Section 3.

3 Results

In Figure 4 four examples of output of the performance analysis engine are reported. Performance indexes are calculated and computed by our tool in less than 10 minutes, on average. The results are extracted from studying the topology of Mansonville, a rural area in the Province of Québec, Canada. The topology, that was extracted from Google maps and inserted into our topology generation module, is composed of 3300 smart meters, 115 routers and 1 data collector. The number of routers is quite large for the given network, since there is a limited possibility to use smart meters for mesh routing given the scarce connectivity of the mostly rural area. We were able to determine the exact location of routers and collectors because the information was available from [11].

Figure 4a shows the average collision probability with respect to mean packet generation time, that represents an increasing level of traffic. Then, the curve helps to evaluate the impact of potential smart grid applications on the average collision probability expected in the system.

The collision probability is also used to compute the end-to-end delays of packets from smart meters to the data collector (i.e., downlink) and vice versa (i.e., uplink). This is reported in Figure 4b. The delay estimation is very important because it quantifies the ability of the application to arrive on time. The survival function analysis, represented in Figure 4c, is very important to assess the feasibility of applications, whose delay requirements are restricted to a portion of the population. The x-axis represents the delay threshold D , the y-axis the probability P that a generic node in the system has an average delay greater than D . The curve, that is traced according to the collision probability values, divides the xy space in two areas: one feasible (light blue) and one unfeasible (red). Each point (D_α, P_α) represents a generic smart grid application α : if the point is in the red area the application α is considered unfeasible, whereas in the blue area it is supposed to be feasible. In the example, two generic applications are taken into account: α , that requires that a maximum of 20% of packets be received with a delay greater than 20 seconds, and β , that tolerates 10% of packets after 20 seconds. Reporting the two points (D_α, P_α) and (D_β, P_β) on the map, it is shown that α is feasible in the system under study, whereas β is not.

In Figure 4d, we show what are the critical nodes in the example used. In the map that contains the 3416 node topology, the collector is represented by a blue cross, the routers by smaller blue stars, and the smart meters by tiny blue points. The fourth element in the figure is the set of *critical nodes*, represented by red circles. Recall that nodes are defined *critical* when their collision probability is above a given threshold. In the example, a threshold of 60% was used. This analysis permits to visually represent the position of critical nodes in the topology under consideration.

The above figures were obtained using the analytical engine. With the simulation engine, other type of results can be obtained such as the one displayed in Figure 6, where a heat-map of the delay is reported. Each point in the curve represents a node in the system, and the color corresponds to a delay value, according to

the color bar reported in the right side of the figure. In the particular example considered in the figure, lower delays are observed in the surroundings of the collector, whereas nodes that are farther experience higher delays. This type of analysis permits to highlight trends, patterns, and variations that are not easy to be discovered with the analytic models, that just provide average values for the delay.

Many other analyses can be carried out with the proposed simulator: for instance, the operation of a network in a given time interval is recorded in a video in which, each node is represented by a point, packet transmissions by arrows² and the collision by larger points covering the collided area. A screen-shot of a video is reported in Figure 5. As one can observe, in the top right corner the current time is indicated and several arrows are displayed representing the simultaneous transmissions taking place at the analysed time. In particular, two of the transmitting nodes use the same frequency channel (i.e., arrows with the same color) and a collision is provoked (red points).

Note that a different topology was used to generate results with the network simulator. The topology, that was extracted from Google maps and inserted into our topology generation module, is composed of 3514 smart meters, 4 routers and 1 data collector. The topology is densely populated: smart meters, that are closer each others, contributes to the mesh routing and, consequently, a limited number of routers is required with respect to the previously analysed rural area. The location of routers and collector was chosen on the map, by means of the topology generator tool.

4 Conclusions

With the proliferation of AMI installations around the world, the set of possible applications is constantly increasing. Therefore, power utilities need to be more aware of the possibilities and limitations of their communication systems. This is only possible by means of thorough performance analyses. In this paper, we presented *Visual PeRF-Mesh*, a comprehensive performance analysis tool that aims at defining the performance of a particular type of AMI, using RF-mesh technology.

A *topology generator* was included in the tool to exploit the geographical peculiarities of AMI, and to be able to use the tool to carry out performance evaluations of systems that are as close as possible to currently implemented AMIs.

The performance evaluation methodology follows two complementary approaches: the analytic modelling and the network simulation. The implemented performance analysis engine is based on a mathematical model that uses fundamental findings in wireless networking to analytically estimate the collision probability of packets. Moreover, a closed formulation of the delay is proposed, based on the computed collision probabilities. Other performance metrics, such as critical node and survival function, complete the analysis: the first proved useful in visually acknowledging design impairments and bottlenecks of the system; the second resulted valuable in the feasibility assessment of potential smart grid applications on a RF-AMI.

The network simulator permits to go beyond the limits of the performance analysis engine by taking into account important implementation details that are difficult to be represented in a mathematical model. The simulation tool, built from scratch in open-source programming languages, such as Java and Python, proved computationally efficient and able to simulate several thousands node instances in a reasonable time.

²The color of the arrows represents the frequency channel used in the transmission.

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Annexes

In this section we report figures and tables, as requested in the author guidelines.

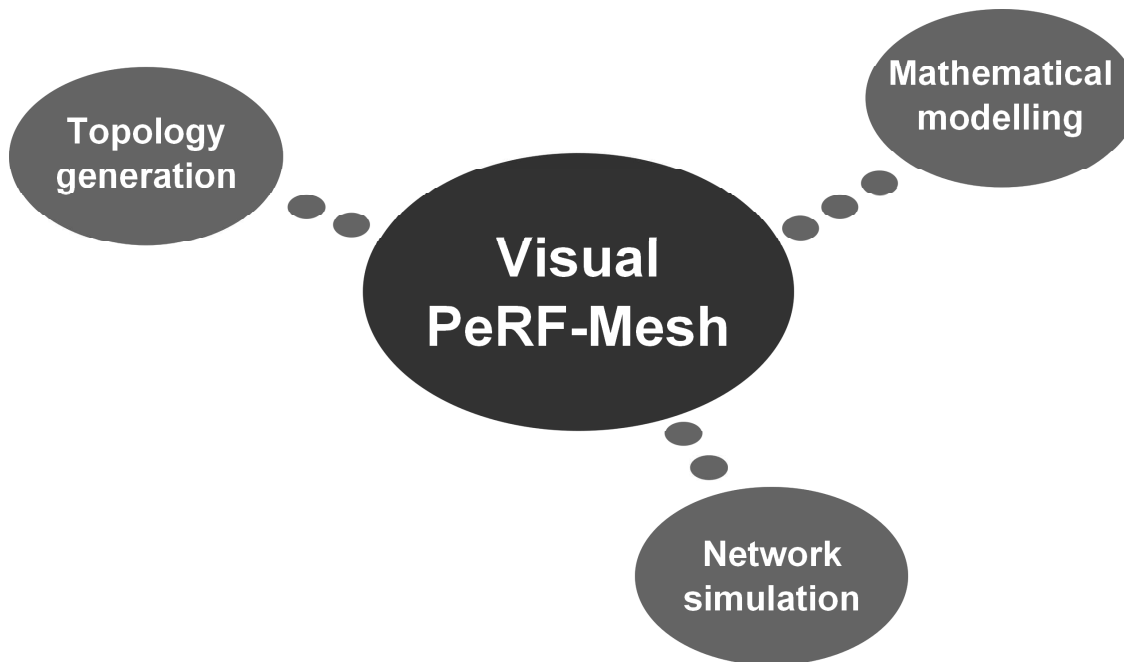
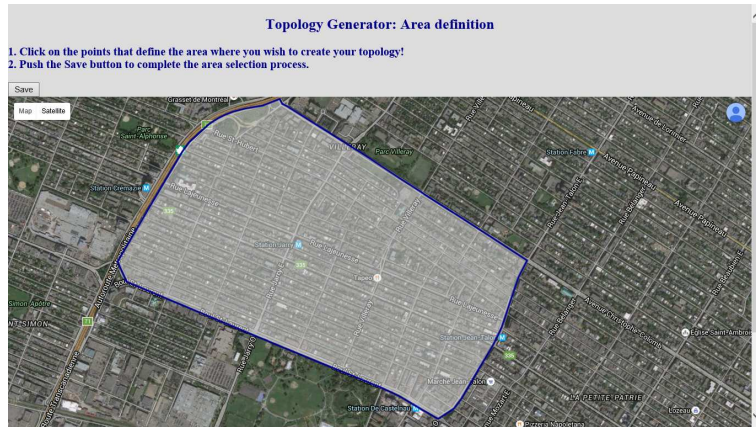
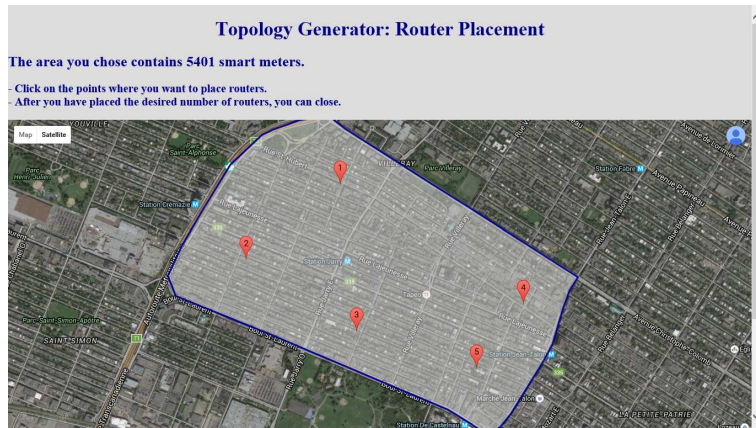


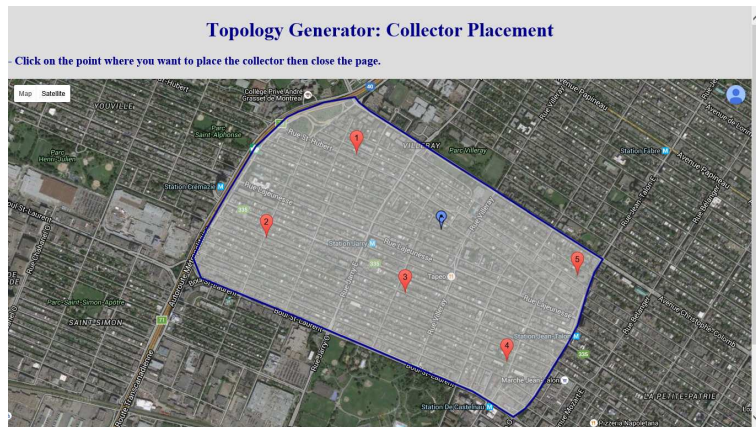
Figure 1: Simplified architecture of the *Visual PeRF-Mesh* tool.



(a)



(b)



(c)

Figure 2: Illustration of the topology creation with the definition of a new area (Figure 2a), the choice of routers (Figure 2b), and collectors (Figure 2c).

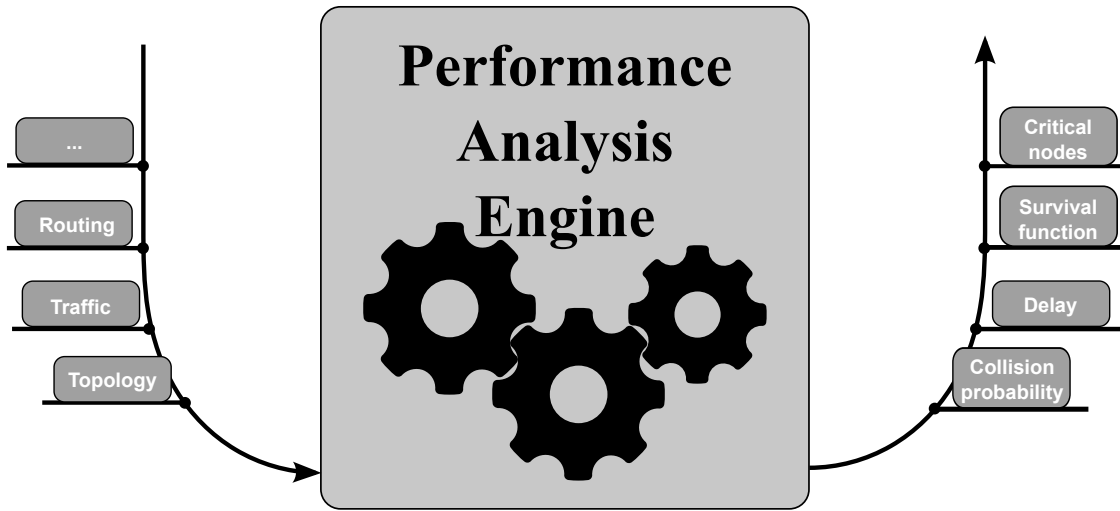
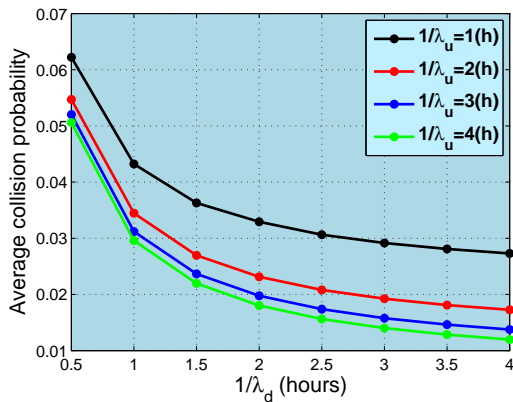
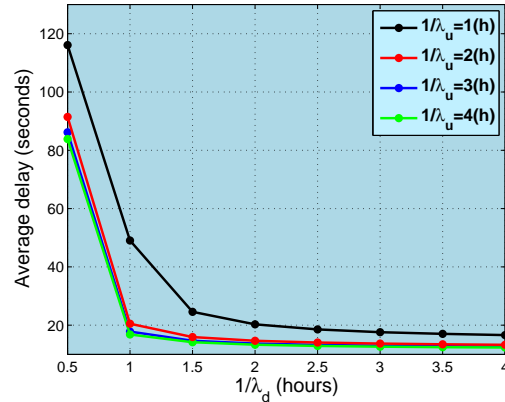


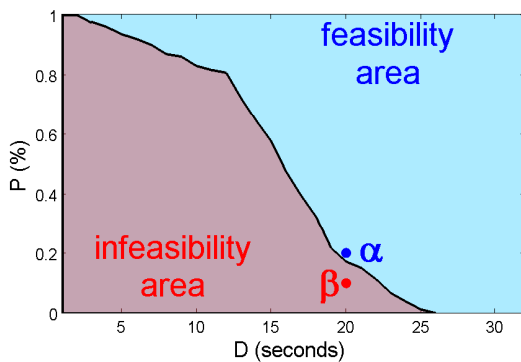
Figure 3: Working flow of the performance analysis engine.



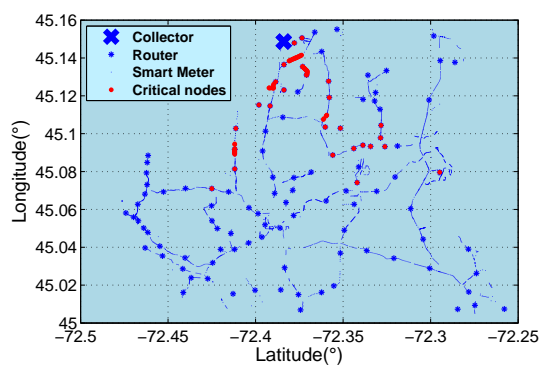
(a)



(b)



(c)



(d)

Figure 4: Some examples of the numerical results generated by the performance analysis engine: collision probability in 4a, delay in 4b, survival function in 4c, and critical nodes in 4d. Note that $1/\lambda_u$ and $1/\lambda_d$ represent the mean packet generation time in respectively uplink and downlink direction.

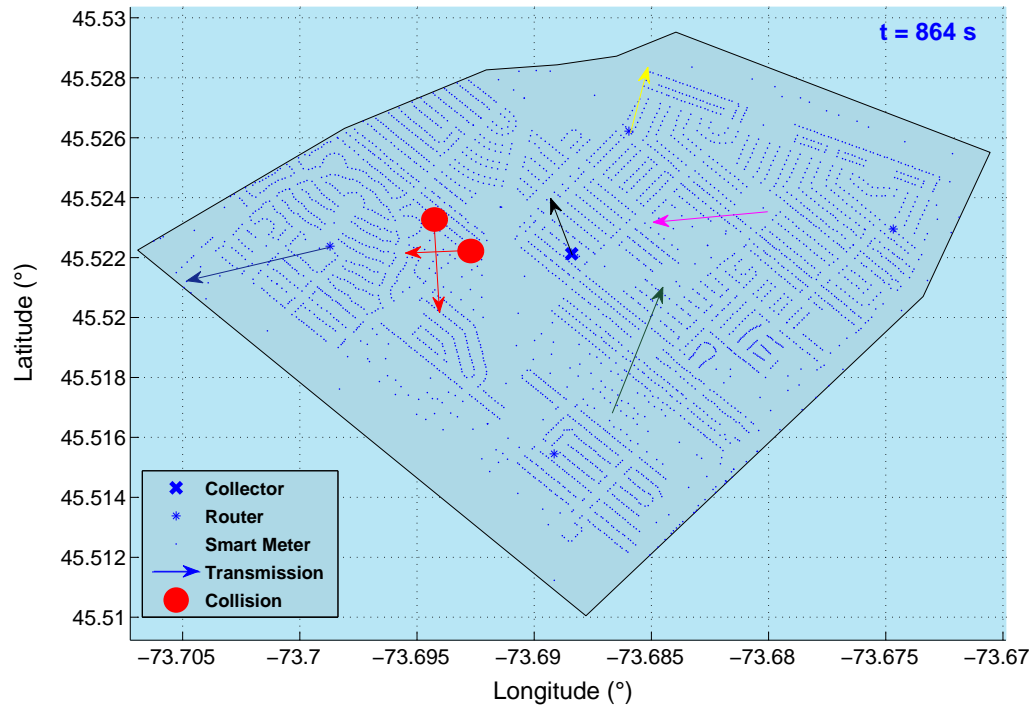


Figure 5: A screen-shot of a video generated with the network simulator. A different color is assigned to each frequency channel used for the transmission.

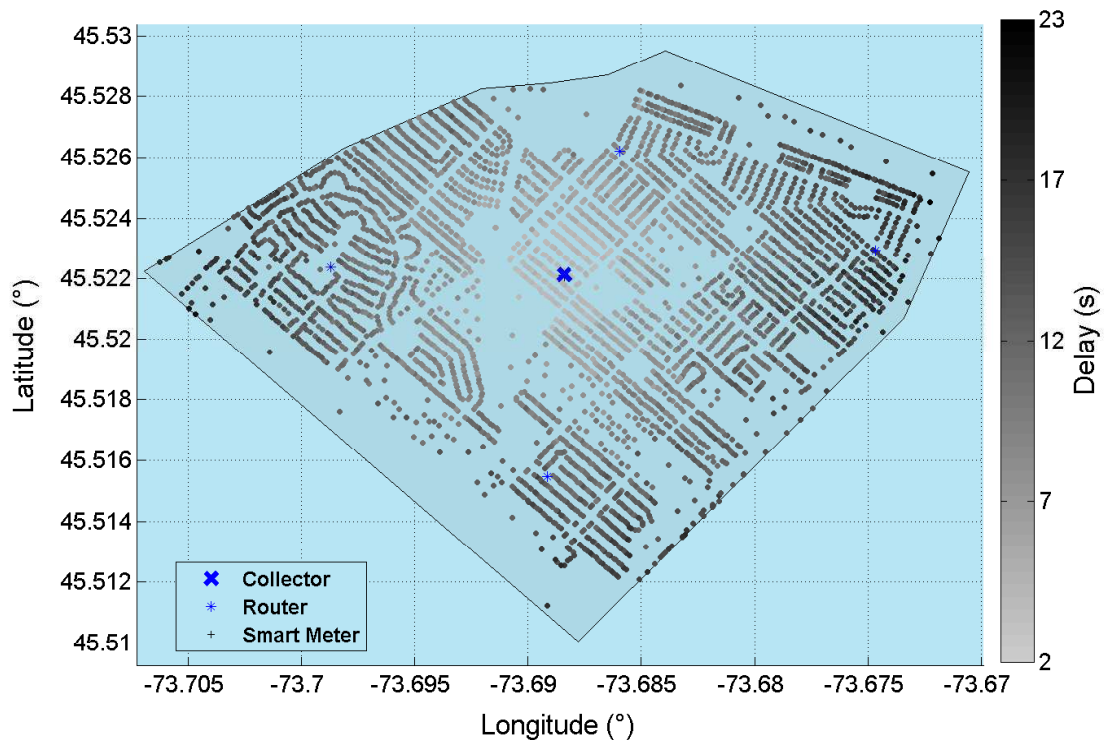


Figure 6: A heat-map of the delay in a urban topology with 1 collector, 4 routers, and 3514 smart meters.