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A Java-based simulation tool for the performance analysis of large-scale wireless mesh networks

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Abstract: Driven by the need of robust, cost-effective, and ready-to-use solutions to connect wirelessly thousands to million of nodes, an increasing number of applications (e.g., Smart Grid, IoT, Big Data) use large-scale Wireless Mesh Networks as transmission support. Tools and methodologies to study the performance of such systems are constantly sought and, in particular, they become fundamental in the feasibility assessment of the high number of possible applications. In this paper, a simulation tool is proposed to study the performance of a particular kind of wireless mesh networks, based on the RF-mesh technology. The tool was used in the context of a large-scale smart grid AMI (Advanced Metering Infrastructure) system. The modular nature of the implemented tool allows a smooth extension to the performance analysis of other types of Wireless Mesh Networks using technologies similar to RF-mesh. The tool, coded in Java and Python, considers different types of traffic and provides the packet collision probability, the end-to-end delay, and several other performance indexes of large scale (i.e., up to 6 thousand nodes) instances in a reasonable time.

Key Words: Wireless Mesh Network, FHSS, ALOHA, performance analysis, RF-mesh

1 Introduction

Wireless Mesh Networks (WMN) are currently being used as the transmission support of several emerging applications (e.g., Smart Grid, IoT). Those applications require the communication of a large number of nodes (e.g., smart meter, smart appliances, sensors) over extended and heterogeneous areas. The need of easy and quick deployments, the harsh and variegated propagating environments, and the large number of nodes fostered the choice of WMNs over other types of systems. Among the adopted technologies, the RF-mesh seems to be one of the most popular thanks to the ease of implementation, the limited cost of the equipment, and the use of the free and unlicensed ISM bandwidth centered on 900 MHz. RF-mesh systems are highly adopted in Advanced Metering Infrastructures (AMIs).

When it comes to the definition of the applications to be enabled by RF-mesh networks, whose implementation features are treated in detail in Section 2, few questions arise: How many nodes can be connected in such a system? What is the bandwidth utilization? What is the average delay at node level? What are the limits and the advantages brought by this technology? The difficulty in answering to these question comes from the lack of thorough performance study of RF-mesh systems, that are usually sold as *black boxes*, and many implementation details are undisclosed. The performance evaluation is key to the feasibility assessment of different applications and represents a barrier to the widespread adoption of RF-mesh systems.

The current literature on the performance evaluation of RF-mesh systems substantially followed three main approaches: 1) analytic studies, 2) field trials, 3) stochastic simulation. The first approach, used in [1, 2], consists in analytically computing the packet collision probability exploiting fundamental properties of wireless communications. This approach proved computational efficiency and flexibility in the application field. On the other hand, it requires the adoption of some assumptions that can reduce the fitness to actually implemented RF-mesh systems. The second approach is based on the use of actually implemented systems in order to measure packet delays and other sensitive parameters. This methodology permits to catch features and analyze details that are difficult to be included in analytic formulations of the problem. Possible drawbacks of this kind of solutions are the high implementation cost and the difficulty to extend the findings of a study to other kind of instances and scenarios. Stochastic simulation lies in between the two aforementioned approaches. It is based on the development of a software that tries to faithfully reproduce the operation of actually implemented RF-mesh systems. Software programming can permit to go beyond the limits of analytic modelling, enabling the representation of complex implementation details. Moreover, the same simulator can be applied to different instances and scenarios providing a larger flexibility with respect to field trials. For this reason, we decided to use stochastic simulations in order to evaluate the performance of large scale RF-mesh systems

Several performance frameworks and platforms are currently used. The most widespread simulation tools being NS-2 and NS-3 (e.g., [3, 4, 5]), Castalia (e.g., [6]), OPNET (e.g., [7, 8, 9, 10, 11, 12]) and OMNET++ (e.g., [13], [14]). Despite the large number of on-the-shelf simulation packages, we did not find any module dedicated to the RF-mesh technology, able to study the performance of large scale RF-mesh systems in a reasonable time. Therefore, we decided to build from a scratch a new simulator in order to increase the computational efficiency, by customizing the design around the peculiarities of the RF technology.

In this paper, we propose a thorough and flexible simulation tool whose main objective is to shed some light on RF-mesh systems, highlighting both the advantages and the limits of this particular technology. The tool was tested in the context of a Large AMI (Advanced Metering Infrastructure) system. It proved to be very useful in the definition of what applications can be enabled, based on its communication requirements.

The reminder of this document is structured as follows. Section 2 describes the system under consideration. Section 3 provides some implementation details about the simulator. Section 4 shows some numerical results obtained with the simulation tool. Section 5 includes concluding remarks and future extension of the present contribution.

2 Description of the RF-mesh system

Figure 1 shows that an RF-Mesh Advanced Metering Infrastructures (AMIs) have a layered architecture divided as follows:

- **Home Area Network (HAN)**. This includes electric vehicles, space heaters, water heaters and all the smart appliances within a home and it is characterized by short range communications. All the involved nodes communicate with the smart meter, who act as a gateway to the upper layers The main adopted technologies are ZigBee and Bluetooth, but also WiFi and Power Line Communications (PLC) are being increasingly used.
- **Neighborhood Area Network (NAN)**. This is a wireless mesh network in which all the smart meters are connected to a data collector. Wireless routers are also installed in order to increase connectivity and extend area coverage. The adopted technology is RF-Mesh, in which the Industrial Scientific and Medical (ISM) band of 900 MHz is used to transmit data on a mesh topology.
- **Wide Area Network (WAN)** is the IP-based backhaul of the communication system: data collectors communicates with the power utility Metering Data Management System (MDMS) by means of satellite and cellular transmissions.

The performance analysis presented in this paper is centered on the NAN layer.

The RF-mesh system under consideration, analog to the one described in [1, 2], is composed of:

- *Data collectors*, that are gateways between the NAN and the WAN. They have enhanced radio capacities (e.g., bandwidth, covering ray) with respect to other nodes. They produce packets directed to smart meters at a rate that depends on the implemented smart grid applications.
- *Routers* are devices used as relays between meters or between a meter and a data collector. They do not produce their own packets but are equipped with stronger radios than those of the smart meters.
- *Smart meters* represent the gateways between the HAN and the WAN; they produce packets towards the data collector at a rate that depends on the implemented smart grid applications.

The main features of a RF-mesh AMI to be taken into account in the simulation framework can be summarized as follows.

Large number of nodes Smart meters are the most numerous devices in the topology: their number ranges from roughly a thousand per neighborhood in a rural environment up to tens of thousands in densely populated urban environments. The number of routers vary according to the scenario: in urban instances, very few are required since the connectivity of the network is already high, while in rural environments a higher number might be necessary in order to have a fully connected topology, since nodes are far from each other. The high number of nodes also affects the size of the simulations, increasing computational burden as network size increases.

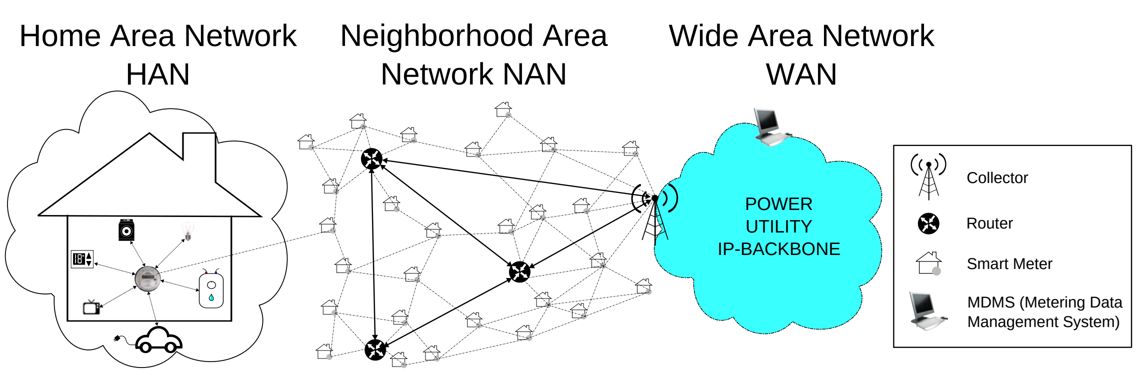


Figure 1: Architecture of the RF-Mesh AMI.

Low throughput Several factors (e.g., the interference, the use of public frequency bandwidth, and low quality devices) make the nominal rates of the wireless link low (e.g., 19.2 kbps for links between routers and data collectors, and 9.6 kbps for other links).

Black-box nature of the system and undisclosed features AMI systems are often sold to power utilities as real black boxes for which very technical details are only provided under strict non-disclosure agreements. Moreover, once installed, smart meter data is considered very sensitive. As a result, some of the characteristics of RF-mesh AMIs are not publicly disseminated, despite their importance in network performance. In the process of designing our framework, we did some reverse engineering and carefully scanned any publicly available piece of information to validate the simulator, while making the modules as flexible as possible to encompass many different types of undisclosed features.

MAC layer Two packets that are simultaneously transmitted on the same wireless channel create a *collision*. Wireless systems react in different ways after a collision, depending on the implemented Media Access Control (MAC) layer protocol. For the given simulation framework we considered a smart-meter communication system using a MAC layer based on time-slotted ALOHA according to which time is further divided into time slots and a node is allowed to transmit at the beginning of each time slot. When a node has a packet ready, it waits until the beginning of following time slot to transmit it. When the correct reception of a given packet i by node A is prevented by a concurrent transmission on the same time slot, node A is *backlogged* and will attempt a retransmission of packet i in one of the following time slots with probability p_r. Packets retransmission degrades the overall performance because it increases system delay.

Wireless interference issues AMI RF transmissions take place in a free unlicensed band, leading to severe interference issues. Thus, even though interference can come from external devices, such as cordless phones, we neglected those sources and only model the interference from the same RF mesh. The presence of thousands of potential simultaneous transmitters in a given area entailed the adoption of strong measures to mitigate the effect of interference. Among the spread spectrum techniques on-the-shelf, Frequency Hopping Spread Spectrum (FHSS) was chosen for its capacity to reduce co-channel interference. The mechanism of FHSS is based on the subdivision of the bandwidth in a number θ of channels. The same sequence of channels is used by each node, opportunely shifted over time. This technique greatly reduces the impact of interference on performance and facilitates the communications even in very densely populated environments.

Network layer An active role in the dynamics of a mesh system is played by the choice of the routing protocol that can greatly impact network performance. To the best of our knowledge, there is no one routing mechanism prevailing and in implemented systems, details about the routing in place are scant. Geographical routing seems to be one of the most popular mechanism in RF-Mesh AMIs but it requires each node to be equipped with a GPS antenna and to know the coordinates of all the other nodes. The so called *Layer-based* routing is also used: in this routing protocol, the word *layer* is used to identify the hierarchical division of the nodes: every node is assigned a layer number (i.e., collector has 0, its neighbors number 1 and so on). The downlink path is decided by the collector based on the information collected in the layer formation phase. On the other hand, each smart meter transmits packets in uplink direction using one of the neighbors in the upper layer. The advantage of this mechanism is that it is very simple on the smart meter side. A modified version of this mechanism is adopted by this simulator.

3 Simulation framework

The main architecture of the simulator is depicted in Figure 2. The operation of the simulator can be subdivided in three different phases: the *Initialization* (see Section 3.1), the *Simulation* (see Section 3.2), and the *Results analysis* (see Section 4).

3.1 Initialization phase

The main objective of the initialization phase is to perform all the preliminary operations to the subsequent *simulation* phase.

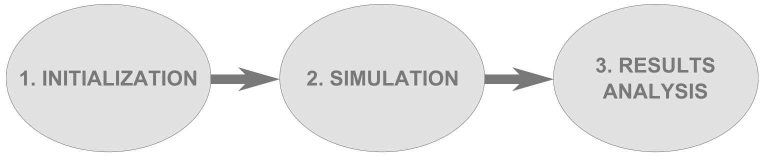


Figure 2: Simplified architecture of the simulator.

At first, one of the previously generated topology is chosen or a new one is created. A topology is defined by a list of nodes (identified by an ID, and the GPS coordinates) and links between them (chosen according to fixed covering rays, that depends on the propagating environment). Then, the user is given the possibility to tune some relevant parameters (i.e., simulation horizon, packet generation rate, buffer size) according to its needs. Finally, the routing mechanism is defined, based on bidirectional shortest paths from each smart meter to the data collector.

3.2 Simulation phase

The *simulation* phase, whose scheme is reported in Figure 3, represents the core of the implemented tool.

The simulation horizon is subdivided in time steps of fixed duration $\tau = 0.7$ s and three main operations are performed during each time step:

- **packet generation:** smart meters and data collectors generate packets according to some Poisson distribution whose parameters are defined in the previous *initialization* phase.
- **collision detection:** for each of the transmitted packet there is a check for possible collisions with other simultaneous transmissions in the same transmission range of the receiving node. Involved packets are flagged for *collision.*
- **packet forwarding:** flagged packets are to be re-transmitted in one of the following time slots, all the others are forwarded to their destination.

4 Numerical results

Numerical results are shown in order to show the capabilities of the proposed tool, and some of the possible analyses that can be performed on large scale RF-mesh systems. Numerical results include collision probability, delay, and activity time evaluation in a scenario obtained using publicly available data.

Mansonville, a small village in the south of Quebec, was used to obtain numerical results. It was one of the three sites that were used for a pilot project of smart meter installation in Québec [15]. The topology

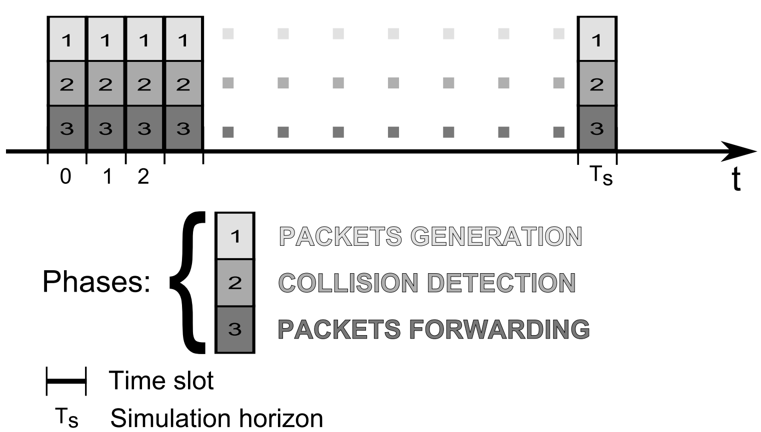


Figure 3: Scheme of the simulation phase.

includes 1 data collector, 115 routers, and 3300 smart meters. The location of routers and collectors were derived from [15]. The latitude and the longitude of smart meters, not included in the previous document, were computed using some APIs provided by Bing Maps.

Once the topology was created, three traffic streams were defined, in order to represent the communications required by some smart grid applications:

- α Poisson distributed packet generation from each smart meter to the data collector (mean parameter λ_u)
- β Poisson distributed packet generation from the data collector to each smart meter (mean parameter λ_d)
- γ broadcast transmission from the collector to all the smart meter at a predetermined time of the day.

40 traffic scenarios were used according to different values of $1/\lambda_u p$ (0.125, 0.25, 0.5, and 1 hour), and of $1/\lambda_u p$ (0.5, 1, 2, 3, and 4 hours). Moreover, in half of the scenarios only α and β were considered, whereas in the other half a daily broadcast transmission (i.e., γ) was also scheduled. The time horizon was $T_s = 86400$ s for all the simulations.

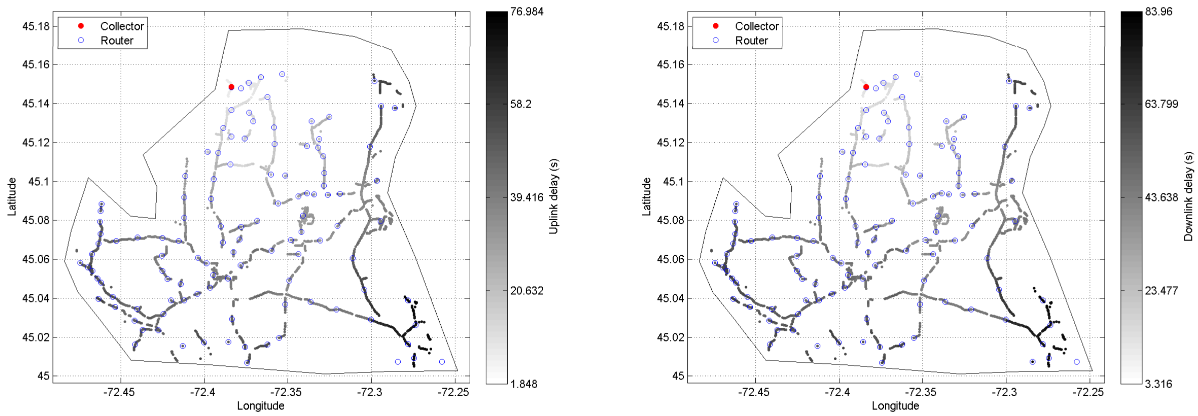
In Table 1, the average collision probabilities are reported. In the upper part of the table, the results corresponding to the scenarios with α and β are included, while the lower part includes the three different traffic streams. The average collision probability slightly increases as the mean packet generation time raises (both in uplink and downlink). The variation in the average collision probabilities is more remarkable in the cases with broadcast transmissions, showing the higher negative impacts of γ brings on the overall performance, with respect to α and β. This is due to the fact that packets generated by α and β are spread over time, whereas packets from γ are generated at the same time, leading to congestion problem, and enhanced chances of collisions.

The average delay in uplink and downlink in the traffic scenario with $1/\lambda_d = 0.5$ h and $1/\lambda_u = 0.25$ h was reported in Figure 4. Two heat-maps of the delays are reported, where the collector is represented by a red spot and the routers by blue circles. Each smart meter is represented, on this map, by a spot whose color depends on its average delay, according to the color-bar reported on the right of each sub-figure. We can notice that the average downlink delay is larger than the average uplink delay. This is due to the presence of broadcast transmission, which is in the downlink direction. Despite slightly different average values, the uplink and downlink delays smoothly increase at a similar pace as the distance from the collector increases. The aforementioned figure does not highlight the presence of congestioned area in the topology under consideration.

Another relevant parameter in the performance analysis is the activity time $\chi(i)$. It represents the percentage of time slots in which node i is transmitting. Consequently, χ_m, χ_r, and χ_c represent the average activity times of respectively smart meters, routers, and data collectors. The χ parameter is useful to identify eventual bottlenecks in the system. Moreover, it is also used to represents the amount of wireless transmissions generated by the smart meter communication system under consideration. This analysis was driven by the current public concerns against smart meters installation, based on the negative impact of wireless transmissions on human health. Numerical results of χ_m, χ_r, and χ_c are reported in Table 2.

Table 1: Average collision probability according to different levels of $1/\lambda_u$ (rows) and $1/\lambda_d$ (columns).

$1/\lambda_d$	$1/\lambda_u$ (hours): 1			0.5			0.25			0.125			
(hours)	N_t	N_c	π	N_t	N_c	π	N_t	N_c	π	N_t	N_c	π	
4.0	148944	129	8.66E-04	150876	116	7.69E-04	150313	99	6.59E-04	149301	111	7.43E-04	
3.0	195977	194	9.90E-04	194134	218	1.12E-03	196607	189	9.61E-04	195984	159	8.11E-04	
2.0	285241	435	1.53E-03	282684	415	1.47E-03	284333	492	1.73E-03	286244	498	1.74E-03	α, β
1.0	498660	1188	2.38E-03	493503	1310	2.65E-03	497974	1243	2.50E-03	494252	1380	2.79E-03	
0.5	807269	4304	5.33E-03	805981	2872	3.56E-03	800189	3122	3.90E-03	806862	3930	4.87E-03	
4.0	661317	3090	4.67E-03	1026368	6211	6.05E-03	1608900	14337	8.91E-03	2571199	30492	1.19E-02	
3.0	706039	2840	4.02E-03	1065649	5980	5.61E-03	1649842	14176	8.59E-03	2613064	46711	1.79E-02	
2.0	794501	4959	6.24E-03	1155567	9867	8.54E-03	1723175	18446	1.07E-02	2681605	47261	1.76E-02	α, β, γ
1.0	984949	6118	6.21E-03	1339916	12129	9.05E-03	1900347	22405	1.18E-02	2836581	47614	1.68E-02	
0.5	1268901	9216	7.26E-03	1611587	18067	1.12E-02	2157842	33926	1.57E-02	3057271	58343	1.91E-02	



(a) uplink (b) downlink

Figure 4: Heat-map of the delay in the scenario with $1/\lambda_d = 0.5$ h and $1/\lambda_u = 0.25$ h.

The structure of the table is akin to Table 1. It is important to remark that the activity times for smart meters are in every scenario between 0.02 and 0.5 %, very small values if compared to other wireless devices (e.g., WiFi routers, smart-phones, smart TVs).

Table 2: Average activity times for smart meters (χ_m), routers (χ_r) and data collectors (χ_c).

$1/\lambda_d$ (hours)	$1/\lambda_u$ (hours): 1			0.5			0.25			0.125			
	χ_m	χ_r	χ_c	χ_m	χ_r	χ_c	χ_m	χ_r	χ_c	χ_m	χ_r	χ_c	
4.0	2.17E-04	3.54E-03	8.30E-02	2.20E-04	3.60E-03	8.36E-02	2.20E-04	3.56E-03	8.36E-02	2.18E-04	3.55E-03	8.34E-02	
3.0	2.85E-04	4.68E-03	1.09E-01	2.82E-04	4.64E-03	1.08E-01	2.86E-04	4.70E-03	1.09E-01	2.86E-04	4.66E-03	1.09E-01	
2.0	4.14E-04	6.84E-03	1.59E-01	4.09E-04	6.82E-03	1.58E-01	4.14E-04	6.76E-03	1.58E-01	4.15E-04	6.87E-03	1.60E-01	α, β
1.0	7.19E-04	1.21E-02	2.75E-01	7.12E-04	1.20E-02	2.73E-01	7.17E-04	1.21E-02	2.75E-01	7.14E-04	1.20E-02	2.73E-01	
0.5	1.17E-03	1.98E-02	4.08E-01	1.17E-03	1.97E-02	4.06E-01	1.16E-03	1.97E-02	4.03E-01	1.17E-03	1.98E-02	4.10E-01	
4.0	1.06E-03	1.55E-02	8.31E-02	1.67E-03	2.37E-02	8.38E-02	2.67E-03	3.61E-02	8.45E-02	4.38E-03	5.48E-02	8.56E-02	
3.0	1.12E-03	1.66E-02	1.10E-01	1.72E-03	2.47E-02	1.09E-01	2.73E-03	3.70E-02	1.11E-01	4.45E-03	5.56E-02	1.11E-01	
2.0	1.25E-03	1.87E-02	1.62E-01	1.86E-03	2.67E-02	1.60E-01	2.83E-03	3.89E-02	1.59E-01	4.54E-03	5.73E-02	1.61E-01	α, β, γ
1.0	1.52E-03	2.33E-02	2.75E-01	2.12E-03	3.13E-02	2.74E-01	3.09E-03	4.29E-02	2.71E-01	4.77E-03	6.06E-02	2.76E-01	
0.5	1.93E-03	3.05E-02	4.06E-01	2.52E-03	3.78E-02	4.06E-01	3.47E-03	4.90E-02	4.10E-01	5.10E-03	6.57E-02	4.06E-01	

4.1 Computational time

RF-mesh systems are characterized by a large number of nodes (i.e., in the thousands) and the computational time might seriously undermine the performance analysis and need to be seriously considered. In our simulations, however, the average computational time to study 3416-node instances over a simulated time of 24 hours is 195 seconds, obtained on a machine with a processor *AMD A8-4500M APU* working at 1.90 GHz. This is a remarkable result because it proves the possibility of analyzing large-scale systems in a considerably short time. It is also worth highlighting that the elapsed time of 195 seconds amounts to the 0.23% of the total simulated time of 86400 seconds: on average, 2.3 ms are necessary to simulate 1 second of operation of the network.

5 Conclusion

The research area of Smart Grid and IoT are growing and the number of related applications is proliferating. This growth is expected to increase in the short and long-term future, therefore it is essential for the involved actors (e.g., power utilities) to use tools able to study the performance of large scale communication systems, in order to assess the feasibility of smart grid applications. In this paper, a simulation tool to study the performance of large scale wireless mesh networks, based on the RF technology was presented and analyzed within the context of a smart-grid AMI system, The tool proved computational efficiency by analyzing several thousand node instances with a computational time of just few minutes. Moreover, the tool provides flexibility in the choice of parameters entailing customized solutions to the user. The simulator can work well both with already built topologies or in combination with an optimization model to select the position of routers and data collectors.

Numerical results showed the wide range of analyses that can be carried out on the system under consideration. A degradation of the performance was observed when using broadcast traffic, and in particular the downlink delay appears to be larger, on average, than the downlink one. The use of the activity time parameter enriches the analysis and represent a good support towards massive smart meters installation.

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