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Abstract: This work deals with the performance analysis of a particular type of AMI: the RF-mesh based smart meter network. The system implements a MAC access with a time-slotted ALOHA with the Frequency Hopping Spread Spectrum (FHSS) to reduce co-channel interference by other users. We developed the PeRF-mesh analytic tool to study the performance of such systems, taking into account the combined effects of ALOHA access and of FHSS on the performance. The tool allows the evaluation of currently deployed systems and can also help in the design phase of new ones.

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1 Introduction

In many countries around the world, power utilities have already equipped a large percentage of households with smart meters; others are planning on a comprehensive installation process in the forthcoming future. Smart meters assume a key role in many smart grid applications because of their double nature of sensing and communicating devices. In order to accomplish their functions, smart meters need to have a two-way communication link with the power utility management system: this is the main reason why the penetration of Advanced Metering Infrastructure (AMI) is very deep within smart grid systems.

AMIs are large scale systems in which thousands of nodes are involved (e.g. sensors, smart meters, routers, data collectors) and many applications are enabled (e.g. remote reading, load management and Vehicle-to-Grid). They are usually proprietary systems, owned by power utilities and installed by third party companies. Several technologies have been adopted and installed for AMI so far: some are based on the use of the Internet, employing different types of access (mainly cellular or WiFi), while others exploit the presence of electric wires by using Power Line Communication (PLC). Further solutions consider the use of radio frequencies in free and unlicensed bands: for example, for RF-mesh, the Industrial, Scientific and Medical bandwidth from 902 to 928 MHz is used.

RF-mesh is considered one of the most popular technologies within AMI systems and it will be presented with further details in Section 3. It is characterized by a simple architecture composed of smart meters, routers and data collectors; RF antennas are cheap and the infrastructure is proprietary, feature researched by the power utilities that do not want to rely on telecommunication providers, mainly because of cost and data confidentiality reasons. Nevertheless, some of the advantages of this technology can also be seen as shortcomings: the absence of a recognized standard within the plurality of vendors jeopardizes the interaction of one system with another; also, it is difficult to define the performance of proprietary systems because many features of the devices are covered by confidentiality agreements. Moreover, a very low data-rate is achievable with this technology: the nominal throughput is in the order of tens of kilo-bits, a number that sounds anachronistic but which can still enable many smart grid applications. The multitude and vicinity of nodes, which especially characterize urban environments, can lead to severe interference problems. The issue is tackled by employing Frequency Hopping Spread Spectrum (FHSS) protocol. To the best of our knowledge, none of the existing comprehensive analytic studies on the performance of large scale mesh systems considers the effect of FHSS protocol. However, as showed in Section 5, where we compare numerical results with and without FHSS, this protocol has a fundamental importance in large scale RF-mesh systems.

RF-mesh systems are usually sold as *black boxes* to power utilities and many questions arise when it comes to the analysis of the performance: what is the average delay? How many routers are necessary to cover a given area? How many packets can be received on time, coping with peculiar applications requirements? The objective of our work is to provide answers to the aforementioned questions by means of PeRF-mesh, the analytic tool we implemented, helpful in defining measures and indexes of performance for large scale RF-mesh based smart meter communication systems.

The document at hand is structured as follows: Section 2 contains a short literature review centered on the performance analysis in wireless mesh networks, with a particular focus on smart grid systems; Section 3 presents the modeling of the system under consideration; Section 4 describes PeRF-Mesh, the analytic tool for performance evaluation; in Section 5 some numerical results are shown and in Section 6 the conclusions of the present work are summarized.

2 State of the art

A great deal of research effort is currently being expended on the performance study of RF-mesh networks. The importance of this theme is derived from the increasing interest in new smart grid applications. The main approaches that have been followed in literature can be grouped in two sub-categories: stochastic simulations [1, 2, 3, 4] and real-field measurements [5, 6].

Both approaches have some strong points as well as some shortcomings. As a matter of fact, a well configured simulator can perform significant performance studies with great savings, and can be helpful in designing and testing new and not yet implemented features and solutions for existing systems. On the other hand, real-field measurements permit analyses of actual systems and not of a modeled version of these. Also, testing systems in a real environment can give deeper insights on their characteristics: some features (e.g. realistic propagating conditions) are very difficult to predict and model, and real field tests can cast light on inconsistencies of the model, which a simulator could hardly discover because of the ideal environment it works within.

A third approach, which we decided to follow, is totally analytic: known properties of wireless networks are used to find mathematical equations that allow to analyze the system's performance. The analytic methodology can reduce the computational burden typical of simulations and can be easily extended to different scenarios and technologies.

The wireless interference problem is well explained in [7], where several protocols to model interference are presented. One of the most used, which we chose to adopt, is the *protocol-interference model*. In this model, first presented in [8], all the nodes at a certain distance from a node j are considered possible interferers in a communication directed to node j.

In a large scale network with thousands of users that share the same bandwidth, the performance is clearly affected by the choice of the MAC layer protocol: one of the most widespread in RF-mesh systems is the slotted ALOHA. An extensive research focusing on ALOHA performance has been carried out since its first presentation in 1971 by Norman Abramson [9]. The pioneer works of [10, 11, 12] laid the foundations of the analytic performance study of slotted ALOHA systems, focusing on single-hop systems only. [13] tried to analyze multi-hop systems with simple and regular topology (e.g. loop and bus). We took inspiration from the extensive work on ALOHA performance analysis models in order to find a mathematical equation for the collision probability in a RF-mesh system. To the best of our knowledge, a comprehensive analytic study of the combined effect of ALOHA and FHSS protocols on network performance is not available in literature.

3 RF-mesh system architecture and main features

One of the main difficulties in modeling AMIs is the fact that these are proprietary systems and many of their features are undisclosed. For this work, features of the RF-mesh smart meter communication network are derived from publicly available data about a RF-mesh system already installed in Québec [14].

The system under study has a three-layers architecture, as shown in Figure 1: the first is the Home Area Network (HAN), that consists of sensors, smart meters, appliances and all the other devices within the domestic area; the second is the Neighborhood Area Network (NAN), whose main scope is to connect smart meters (and consequently the HAN) to data collectors in a mesh topology that also includes routers; data

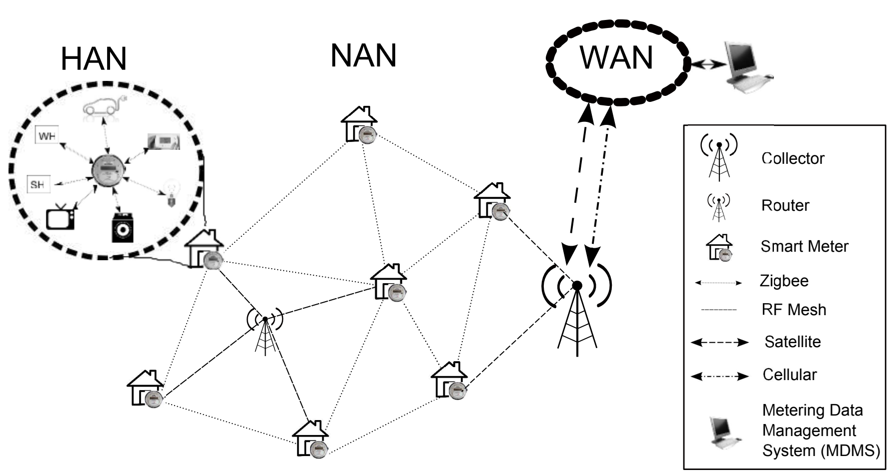

Figure 1: Architecture of the whole communication system.

collectors are used as gateway to the third layer of the architecture, the Wide Area Network, an IP backbone connected to the power utility Metering Data Management System (MDMS).

The first and the third layers of the architecture implement well-known technologies and protocols: the HAN adopts Zigbee short range links, while the WAN uses IP over satellite or cellular connections. On the other hand, the NAN is characterized by wireless links in the ISM band of $902-928$ MHz: this technology is called RF-mesh. The performance of the HAN and the WAN are well defined and a good branch of research involves analysis of Zigbee, satellite or cellular networks. Thus, in the rest of this work, we will focus on analyzing the performance of the RF-mesh NAN, not yet well defined and standardized.

In the currently deployed multi-hop wireless NANs, there is one data collector per several thousands of smart meters. The number of routers depends on the scenario: it is higher in rural networks with respect to urban environments, in order to ensure the connectivity in a more extended area.

The RF-mesh system adopts the FHSS protocol, which is a technique helpful in reducing co-channel interference, generated by the transmission of multiple devices using the same frequency band, either within the same NAN or in different networks.[1]

The frequency spectrum of the RF-mesh system under study is subdivided in $n = 80$ channels of 300 kHz bandwidth each [15]. A predetermined sequence of hops, schematized in Figure 2, is known to all the nodes in the network. Each device uses the same sequence to determine the frequency channel which its receiving antenna must be tuned to: the sequence is conveniently shifted in time in order to avoid that all the devices use the same channels simultaneously. Any node is able to determine the receiving frequency channel of its neighbors at any time; therefore, before transmitting a packet to a neighbor node j, node i can tune its antenna to the frequency channel of node j.

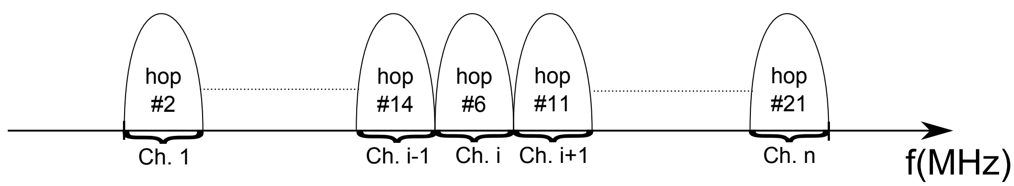

Figure 2: Example of frequency hopping sequence.

The access to the medium is controlled by means of the synchronous ALOHA protocol with time slots of duration $\tau = 0.7$ s. Devices synchronization is achieved through the Network Time Protocol (NTP): collectors are equipped with high precision clocks (e.g. iridium) and provide a reference time for the other nodes. NTP can ideally yield good results in terms of synchronization of extended networks: unavoidable errors in synchronization are tackled by restricting the portion of time in which it is possible to transmit to only 400 ms out of the available 700 ms, thus leaving the remaining 300 ms intentionally idle as a safety margin [14].

3.1 Interference and probability of collision

Interference is one of the main limits of wireless communications: the radio channel is shared among multiple users that can interfere with each other. Therefore, any wireless technology has to consider interference and reduce its effect on performance.

In RF-mesh systems, the access to the medium is regulated by ALOHA, a simple random access protocol conceived for networks with very low data-rates. When two or more interfering users attempt to transmit a packet, a collision is experienced and the involved packets are to be re-transmitted. An analytic expression to calculate the probability of collision in a multi-hop system, valid when a Poisson distribution of traffic

[1]The ISM band are used, among the others, by some microwave ovens, car key remote controllers, ZigBee and RFID

generation is assumed, was presented in [16]:

$$p_i = P(X_{I_i} > 0) = 1 - P(X_{I_i} = 0) = 1 - e^{-\tau \sum_{j \in I_i} \frac{\lambda_j}{1-p_j}} \quad (1)$$

where I_i is the list of interferers of node i, X_I is the number of transmitting nodes in set I, λ_i the mean transmission rate of node i and τ the time slot duration.

The numerical results in [16] were obtained using equation (1), without considering FHSS. As discussed in that paper, the results highlighted the necessity of integrating the FHSS protocol in the performance analysis of large scale RF-mesh systems.

A first step in the integration of FHSS was taken in [16] with the analytic formula:

$$\begin{aligned} p_i &= \sum_{g=1}^{+\infty} P(X_{I_i} = g) p^{(g)} = \\ &= \sum_{g=1}^{+\infty} \left(1 - \left(1 - \frac{1}{Q}\right)^g\right) \frac{\left(\tau \sum_{j \in I_i} \frac{\lambda_j}{1-p_j}\right)^g}{g!} e^{-\tau \sum_{j \in I_i} \frac{\lambda_j}{1-p_j}} \end{aligned} \quad (2)$$

In equation (2), Q is the number of non-overlapping channels used by FHSS and $p^{(k)}$ is the probability of having at least two nodes out of k using the same frequency channel among the Q available:

$$p^{(k)} = 1 - \left(1 - \frac{1}{Q}\right)^k \quad (3)$$

Equation (2) is used in PeRF-mesh tool to calculate the delay and define other important performance indexes, as explained in Section 4.

4 PeRF-mesh

4.1 Inputs

PeRF-mesh is the analytic tool we developed to analyze the performance of a large scale RF-mesh system with FHSS. Its structure is displayed in Figure 3. The tool needs the preliminary definition of some inputs: topology, routing and traffic.

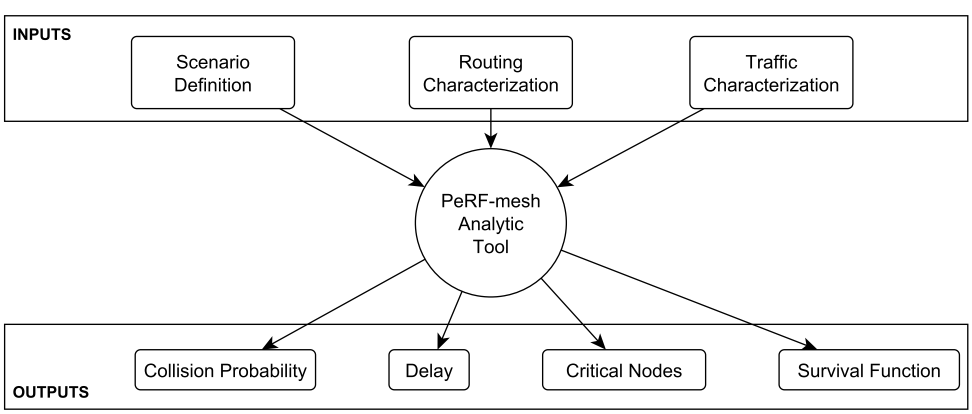

Figure 3: Block diagram of PeRF-mesh analytic tool.

The characterization of the topology consists of two phases: nodes placement and links definition. We decided to create our topology starting from publicly available data about a pilot installation of smart meters in Québec. Data about the position of routers and collectors were extracted by means of Google Earth, starting from a map published in a report to the *Régie de l'énergie*[2] of Québec [14]. Since the number of smart meters in the reference topology is greater than 3000, it was not possible to acquire information about their positions from the map included in the report. Therefore, in order to find their position, we developed a Python script to obtain from *Bing Maps* the GPS coordinates of residential buildings present in the pilot project areas. The assumption of one smart meter per building was used: this assumption works well in rural areas where there is a majority of one-family buildings; in urban areas, the assumption needs to be modified in order to account for buildings with many apartments. The links were defined in a static way: two nodes are assumed to communicate with each other if and only if their distance is lower than a fixed covering ray. The variable propagating conditions of radio signals are taken into account by employing different covering rays in different scenarios. For example, propagating conditions tend to be more convenient in rural areas with respect to urban environments, because less obstacles are present on average; when studying a rural area scenario, larger covering rays will be used.

The routing mechanism adopted in the tool is based on shortest paths, using distance as metrics. Nevertheless, this static assumption might neglect some important dynamic aspects of RF-mesh systems: other routing mechanisms (e.g. layer-based, AODV, geographical) are currently being investigated and will be integrated into the tool in the near future.

The traffic characterization is taken from [14]. We consider two different traffic streams: uplink, from smart meters to the data collector, and downlink, in the opposite direction. Routers do not generate any packet, they simply forward packets transmitted by other devices. The packet generation rate is assumed to be Poisson-distributed in both directions with mean parameters λ_{up} and λ_{down} for uplink and downlink respectively.

λ_i is the rate of packet transmission of node i: it includes packets generated by node i and also packets for which i is an intermediate node between source and destination. In [16] an analytic expression for λ_i was found:

$$\lambda_i = \begin{cases} \xi_i(\lambda_{up} + \lambda_{down}) + \lambda_{up}, & \text{if } i \text{ is a smart meter} \\ \xi_i(\lambda_{up} + \lambda_{down}), & \text{if } i \text{ is a router} \\ |M|\lambda_{down}, & \text{if } i \text{ is a collector} \end{cases} \tag{4}$$

where ξ_i is the number of shortest paths that contain node i and $|M|$ is the total number of smart meters.

4.2 Mathematical modeling

Once all inputs are defined, the probability of collision needs to be calculated.

For every node of the communication system, an equation (2) that links its collision probability to the collision probability of its neighbors can be written. The $|V|$ equations, V being the set of nodes in the network, form a *fixed-point* system of equations.

The following least-squares optimization model ([16]) is used to find numerical values of p_i (for $i = 1 \dots |V|$):

$$\min_{\boldsymbol{p}} \|f(\boldsymbol{p})\|_2^2 \tag{5}$$

$$s.t.: \begin{cases} p_i \geq 0 & \forall p_i \in \boldsymbol{p} \\ p_i < 1 & \forall p_i \in \boldsymbol{p} \end{cases} \tag{6}$$

[2] An economic regulation agency of the energy market.

where:

$$\boldsymbol{p} = \begin{bmatrix} p_1 \\ \vdots \\ p_{|V|} \end{bmatrix} \quad f(\boldsymbol{p}) = \begin{bmatrix} f_1(\boldsymbol{p}) \\ \vdots \\ f_{|V|}(\boldsymbol{p}) \end{bmatrix}$$

$$f_i(\boldsymbol{p}) = \sum_{g=1}^{+\infty} \left(1 - \left(1 - \frac{1}{Q}\right)^g\right) \frac{\left(\tau \sum_{j \in I_i} \frac{\lambda_j}{1-p_j}\right)^g}{g!} e^{-\tau \sum_{j \in I_i} \frac{\lambda_j}{1-p_j}} - p_i$$

It is important to remark that equations (1) and (2) are consistent with each other: in fact, (2) is equivalent to (1) when the number of available channels is one.[3]

4.3 Delay

The delay is one of the most important parameters in a communication system. Several types of delay are present in a communication network, but a common practice in time-slotted systems with small size packets is to consider the time slot duration to prevail over propagation, processing and queuing delay. These delay components are neglected in the current model but we are evaluating the possibility to include some of them, namely the queuing delay, in a Markov-modulated model, in course of development at the time of writing.

In an ideal system with no interference, only one transmission would be required for a single hop in a path; in reality, the presence of interference entails collisions, and each collision implies a re-transmission of the packet. Therefore, the average number of time slots necessary to transmit a packet in a single hop is:

$$N_{ij} = \frac{1}{1 - p_i}$$

As a result, the overall delay in a single hop corresponds to the time slot duration τ, multiplied by the average number of re-transmissions:

$$d_{ij} = \tau \sum_{(uw) \in \rho_{ij}} N_{uw} \tag{7}$$

where ρ_{ij} is the set of links forming the shortest path from i to j. In this work, we consider the delay in a multi-hop path from node i to node j to be the sum of the delays in each hop. Two delay quantities, d_i^u and d_i^d, are defined, related to uplink and downlink streams of communications, respectively.

4.4 Other outputs

As shown in Figure 3, PeRF-mesh provides two additional performance indexes, previously introduced in [16]: the critical nodes in the system and the so-called *survival function*.

A node is considered critical if and only if its collision probability is above a certain threshold. Such an analysis is very useful to discover eventual bottlenecks of the system.

The survival function is a mathematical function that represents the probability that a random variable is greater than a certain value. If applied to delay statistics, the survival function can provide interesting insight in the feasibility of generic smart grid applications, whose requirements are limited to a certain portion of nodes. An example of feasibility assessment using the survival function was provided in [16].

[3] This is due to the fact that $\sum_{n=1}^{+\infty} \frac{a^n}{n!} = e^a - 1$.

5 Numerical results

In this section, some numerical results obtained with PeRF-mesh analytic tool are presented.

We chose to test our methodology using data related to Mansonville, a rural area in Québec and one of three zones involved in the aforementioned pilot installation of smart meters [14], in 2011. The area is extended over 240 km^2 and includes 3415 devices (1 data collector, 114 routers and 3300 smart meters).

We assumed the same packet generation rate in uplink (λ_{up}) for all the smart meters and also the same packet generation rate (λ_{down}) from the collector to every smart meter. In multiple runs, we let the mean packet generation times ($1/\lambda_{up}$ and $1/\lambda_{down}$) vary in the interval between 0.5 and 4 hours in order to highlight the performance of the system at different traffic loads, representative of different smart grid applications.

The system of equations (5)–(6) was solved by using MATLAB on a Intel(R) Quad Core(TM) $i7-3770$ CPU @ 3.40GHz processor. The average computational time was below 15 minutes.

5.1 Collision probability

In Figure 4 we reported the variation of the maxima (dashed line) and the averages (continuous line) of collision probabilities with respect to packet generation rates in uplink and downlink. In particular, we used fixed values of the mean generation time in downlink ($1/\lambda_{down} = 1, 2, 3, 4$ hours) and drew the variation of collision probability according to λ_{up}. This figure shows that the collision probabilities do not undergo large variations as the traffic generation rate changes. For instance, we found that the mean of the collision probability when $1/\lambda_{down} = 1$ hour is 0.22% at $1/\lambda_{up} = 4$ hour and 0.52% at $1/\lambda_{up} = 30$ minutes.

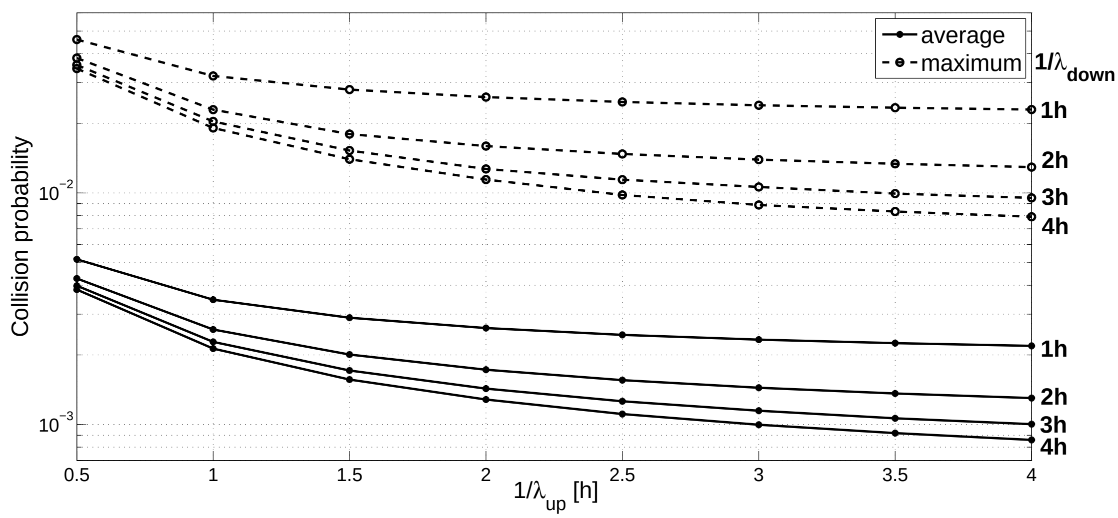

Figure 4: Analysis of the collision probability with FHSS according to λ_{up} with fixed values of λ_{down}.

5.2 Impact of FHSS

Numerical results on the collision probability in different traffic scenarios (reported in Table 1) were presented in [16]. In that paper it was shown that, for high traffic scenarios, the collision probabilities reached values close to one.

In order to highlight the impact of FHSS protocol on the performance analysis results, Figure 5 reports a comparison of the collision probabilities found with FHSS (in gray) against those presented in [16], without FHSS (in black). For the sake of clarity in the comparison, traffic scenarios IDs are used in this figure. A reduction of collision probability greater than an order of magnitude as found in all the scenarios; therefore we can safely state that FHSS has a key impact on the performance of large scale RF-mesh system.

Table 1: Traffic scenario ID according to λ_{up} and λ_{down}, taken from [16].

$\frac{1}{\lambda_{down}}$ [h]	$\frac{1}{\lambda_{up}}$ [h]							
	0.5	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**
1	1	5	9	13	17	21	25	29
2	2	6	10	14	18	22	26	30
3	3	7	11	15	19	23	27	31
4	4	8	12	16	20	24	28	32

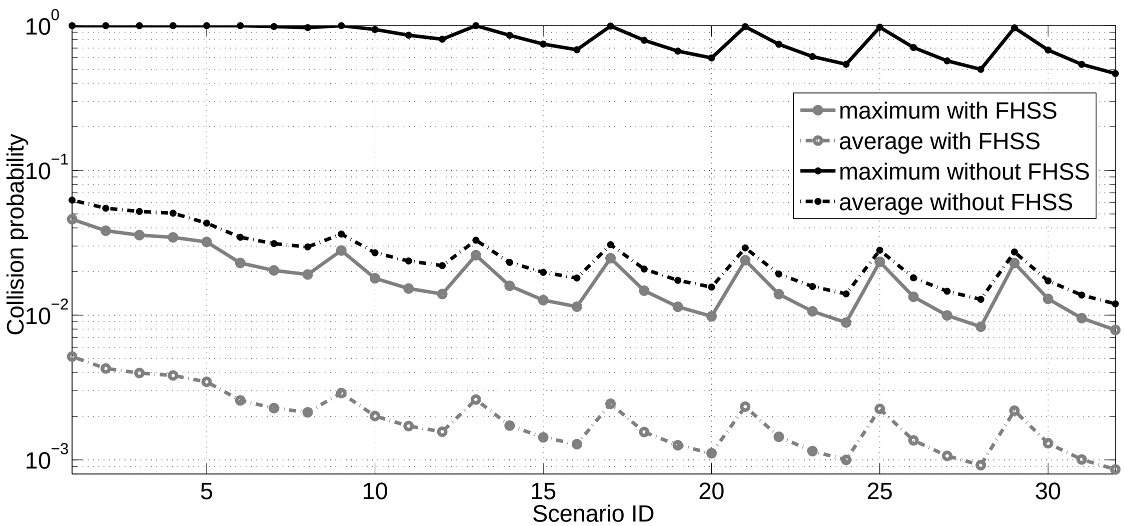

Figure 5: Comparison of collision probabilities with and without FHSS.

5.3 Delay

In Subsection 4.3, we explained how the delay is calculated from the probability of collision in PeRF-mesh.

In Figure 6, the variation of the delay in uplink is reported according to different values of traffic generation rate. In particular, we fixed the downlink mean generation time to 1 hour and let the $1/\lambda_{up}$ vary from 5 minutes to 4 hours.

On the left side of the curve, for lower mean generation times (and consequently higher traffic generation rates) there is a slight variation in the delay: we observe a mean value of 12.27 seconds with $\lambda_{up} = 5$ minutes and of 11.84 s with $\lambda_{up} = 10$ minutes, which results in a variation of -3.5%. On the other hand, the last two mean values of the delay are 11.5 and 11.49 seconds, with a variation of only -0.087%.

The flattening of the curve depends on the lower impact of collision probability on the delay as the traffic decreases. As the mean packet generation time increases, the value of the probability of collision is so low that it does not have an impact on the delay. In such cases, the delay of a packet from node i to node j, as showed in (7), tends to $\tau|\rho_{ij}|$ where $|\rho_{ij}|$ is the number of hops from node i to node j.

6 Conclusions and future steps

In this work we presented PeRF-mesh, an analytic tool to study the performance of large-scale RF-mesh systems with FHSS. To our knowledge, this is the first analytic tool to take into account the interaction of FHSS and ALOHA MAC access in a performance analysis study.

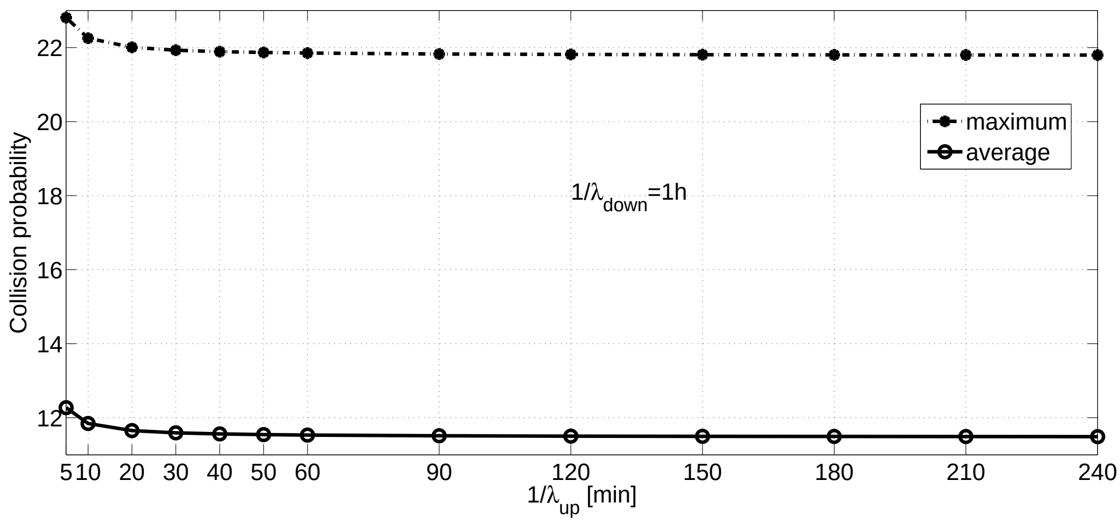

Figure 6: Variation of the delay according to λ_{up} with a fixed value of $\lambda_{down} = 1h$.

Performance analysis is key to assess the feasibility of real smart grid applications and it has some advantages with respect to stochastic simulations and real-field measurements.

PeRF-mesh allows thorough analysis of large-scale RF-mesh systems with a short computational time. Analysis of collision probability, delay and critical nodes can also allow to identify possible bottlenecks of the system in the design phase, resulting in high economical and resources savings.

The impact of the FHSS protocol was highlighted by a comparison of the numerical results obtained with PeRF-mesh against those obtained with a model without FHSS and available in [16]. A substantial improvement was observed, in terms of a reduction in the collision probability and the consequent decrease in the delay.

One of the future steps consists in the refinement of the analytic model, investigating the possible use of a Markov modulated system; in spite of increasing the model's complexity, this can represent additional features of real RF-mesh systems, not considered so far (e.g. probability of re-transmission). Other paths to explore are the integration of more complex propagation models and of more dynamic routing protocols. Finally, a combination of optimization and performance analysis is in the agenda: we are currently conceiving a model for the optimal placement of routers and data collectors.

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