Simulation and Analysis of a QoS multipath Routing Protocol for Smart Electricity Networks

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Abstract— **This paper presents several considerations that must be taken into account in the design of a QoS multipath routing protocol suitable for Smart Electricity Networks (SENs). The main goal is to analyze the routing requirements that will facilitate the future formal specification of a QoS-aware multipath routing algorithm for the coming SEN's data networks in the high voltage segment where long-distance mesh data networks will be a future challenge for engineering and research. In this paper, the study is focused on requirement specification regarding distance-vector routing algorithms that reduce the overall overhead of routing information needed in the network, thus preserving the scalability feature. In order to obtain a detailed study of the performance of these protocols, the proposal "Distributed path computation with Intermediate Variables" and several proposed improvements have been modeled using OPNET modeler in an aim to evaluate the performance of this protocol in different SEN domain-related situations.**

Keywords- Multipath routing; Quality of Service; Smart Electricity Networks.

I. INTRODUCTION

The future of the utilities walks hand in hand with Smart Electricity Networks (SENs) and its advantages [1][2]. SENs saves energy and can cope better with the unpredictable supply from renewable energies [3][4]. Actually, utilities require to be prepared to face the upgraded needs of its telecommunications infrastructure. Although it is known that this is a long term process and the prediction is that smart grids will be implanted in 2030.

One of the main challenges of SENs is to redesign its network architecture. Nowadays, a utility grid has been deployed according to a centralized scheme in which the different elements of the grid are logically and geographically located. This fact is due to the one-way power flow from the generation to dispersed loads. Current grid scheme is easy to operate but the SEN has an opposite point of view. The architecture is based on a decentralized scheme with elements logically identified but not geographically located. For example, the increment in renewable generators in the customer's premises will change the way the energy is generated. All customers will be able to generate energy, to consume it and finally to give the remaining part to the SEN. Because of this, communications must be upgraded and meet new goals [3][4] such as the necessity of several application protocols, the specification of new data models needed by the applications, the exploitation of the currently deployed communications infrastructure and the adoption of robust and QoS-aware routing protocols to satisfy the requirements of the network.

This paper presents and analyses a thorough study of the characteristics that must be considered in a QoS multipath distance-vector routing protocol, in the way to get a protocol that could be implemented in a SEN. In [1], authors have studied the issues on the design of a multipath protocol that could be implemented in a real smart grid. The first task of a QoS multipath routing protocol is to find several suitable loop-free paths from the source to the destination with the necessary available resources to meet the QoS requirements of the desired service. It has to take advantage of the topology of the utility network (partial mesh) by making the network resilient to failures. Moreover, the few requirements of bandwidth are another advantage of these protocols which allow to use the available bandwidth efficiently. There are a lot of implementations of multipath routing, for example: DASM [5], MDVA [6], MPDA [7], MPATH [8] or DIV [9]. These kind of protocols obtain the maximum redundancy of the network finding more than one path to a destination. All these protocols define the behavior of the algorithm but let undefined important aspects such as the routing metric or the load balancing method. These aspects must be defined in the final implementation of a routing protocol to operate properly.

The remainder of this paper is organized as follows: Section II describes the fundamental topics involved with the domain of Smart Electricity Networks. Characteristics and QoS requirements of SENs are presented and the need for a better communication architecture is also explained. Section III briefly details the proposed network model suitable for further formal specification of a QoS-aware multipath routing algorithm for SENs. Section IV introduces the fundamental topics involved in our analysis needed to understand the principles of multipath routing. Section V discusses the routing considerations and covers all the important design issues. Section VI presents the second part of the study with the implementation of a routing protocol based on the theoretical study done in [1]. This implementation has been done over the OPNET MODELER 12.0 simulator [10] and it allows to compare the results of some aspects defined in the theoretical study. Finally, in section VII, conclusions are outlined.

II. Smart Electricity Network's communication requirements

Current power grid is defined as a system made up of electrical generators, transformers, transmission and distribution lines used for delivering electricity power to final users. Monitoring and smart grid network control are very important features in order to provide continuity, QoS and security. Nevertheless, at the time, most of these functions are only carried out in high voltage and, sometimes, in the medium voltage grid. The future SEN must be distinguished by self-healing and automation taking into account that should support thousands of clients and all the energy providers. Actually, international organizations, governments, utilities and standardization organisms are becoming aware that the grid needs a modernization.

Many companies which belong to different sectors have seen a great business opportunity and are currently working to make themselves room in the SEN's market. The change towards the so-called Smart Grid or SEN promises to be a change in the whole business model involving utilities, regulation entities, service providers, technology suppliers and electricity consumers. In fact, this transformation towards an intelligent network is possible by importing the philosophy, concepts and technologies from the Internet ambit.

Nowadays, utility grid is used to transport energy from generators to end users. Currently, in most countries the grid is old and has several problems of inefficiencies and low robustness due to the lack of automation [11]. The grid could be improved to overcome these deficiencies by coordinating processes between Intelligent Electric Devices (IEDs). Thus, well-known problems such as those described in [11] could be avoided. SENs will manage lots of real-time information through a data network and they will collect information from established IEDs for the purpose of control. This kind of data networks is not exempt from the growing need of Quality of Service (QoS). SENs are expected to meet a drastic increasing demand of information, communication and miscellaneous data such as voice, data, image, video and multimedia communications, which can be accessed anywhere at any time.

SENs need to communicate many different types of devices, with different needs for QoS over different physical media. Availability is also crucial for the correct operation of the network. The elements of a SEN, the so-called IEDs, can have very different QoS necessities. For example, real-time communications are required in the case of fault detection, service restoration or quality monitoring; periodic communications are used in Automatic Meter Reading systems (AMR); bulk data transfers are useful to read logs and energy quality information. SENs would not be possible without the existence of the IEDs which can play as sensors and/or actuators. There exist many types of IEDs depending on the function carried out. The IEDs involved in these functions can be situated in different locations due to the pursued decentralized architecture. For example, electrical substation elements are connected to the substation's Ethernet network; sensors can be installed along electrical cables communicated through wireless standards. Communication from the control center to energy meters and between substations can be carried out via a high variety of technologies such as Power Line Communication (PLC) or WiMAX.

Due to these circumstances, SEN will be supported by data network with strict constraints of QoS. Therefore, one of the most important needed specifications for the SEN are those regarding its communications. A framework for management of end-to-end QoS for all communications in the grid will be a must in the future [12][13]. In fact, a suitable communications infrastructure allows increasing the efficiency of the electric system further than what is possible with automation without communication capacities.

Furthermore, automation of distributed generation requires new protections and supersedes the actual one way generation flow. The control and monitoring of these new flows could not be done with the same scheme used in the past, but can be done with the aid of a new and more flexible communication network.

Some of the new communication goals faced by SENs are listed below:

- New application protocols will be needed to meet the new network requirements.
- New data models will be required by the applications.
- It is essential to take full advantage of the communication infrastructure deployed.
- To adopt robust and quality aware protocols to satisfy the restrictive QoS requirements of the network.

III. Network model and notation

In this section, the network model and the used notation for the routing algebra and policies are described. This notation is used to formally define the routing protocol behavior and it is based on Sobrinho's routing algebra [14][15]. An algebraic approach is very useful for both understanding existing protocols and for exploring the design space of future Internet routing protocols.

A. Routing policy

The routing policy defines the elements used by the routing protocol to carry out the routing process. The routing policy is formed by [14][15]:

$$A = < \Sigma, \oplus, \mathrm{L}, \preccurlyeq > \quad (1)$$

Each element of this array (1) is defined in Table I. In addition to this, two logical operators are necessary: AND ($\wedge$) and OR ($\vee$) operators. In this paper, the following model of a cost computation based on [15] is used. It is outlined in Fig.1, where node j is the destination of the routing information and node v is the origin.

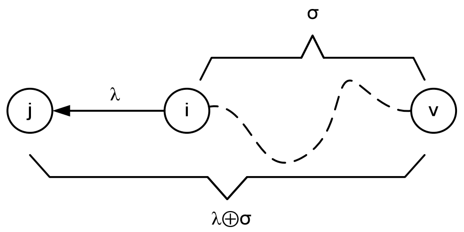

Figure 1. Example of the routing algebra where $(\lambda \in L) \wedge (\sigma \in \Sigma)$

TABLE I. ELEMENTS OF THE ROUTING POLICY

Element	Description
Σ	It is the cost associated to a path and it is known as the signature.
$\oplus$	It defines the way to add the cost of a link to a path and to calculate the total cost. It is known as the operator.
L	It represents the cost associated to a link and it is known as the label of the link.
$\preccurlyeq$	It is the precedence relationship and it is used to decide which path is the best one.

B. Representation of the routing information

In this section, it is described the proposed notation in order to define the information used and stored by the routing protocol. The objective is to avoid any confusion when different routing schemes and metrics will be explained. Actually, a routing protocol is an algebra together with a distribution mechanism (such as link-state or vector-distance) for computing routing solutions.

- *i*: It represents the origin node.
- *k*: It represents a neighbor of node *i*, which has sent a routing advertisement to node *i* ($k \in N_i$).
- *j*: It represents the advertised destination of the routing information received.
- λ_{ik}: It is the cost of the link from node *i* to node *k*.
- σ_{kj}: It is the cost of the path from node k to node *j* advertised by *k*.
- $\hat{\sigma}^{i}_{kj}$: It stands for the estimated cost of the path from node *k* to node *j* stored on the routing table of node *i*.
- $\hat{\sigma}^{i}_{ikj}$: It stands for the estimated cost of the path from node i to node j through the neighbor k stored in the routing table of node *i*.
- $\hat{\sigma}^{k}_{ij}$: It is the cost estimated of the path from node *i* to node *j* that node *i* guesses that is known by node *k*.
- S_{ij}: It is a set of all the neighbor nodes of the node *i* that are feasible successors to node *j*.
- N_i: It is a set of all the neighbor nodes of the node *i*.

A node can store two cost values from its neighbors: the actual values and the estimated values. Estimated values are the information received from the neighbors that can be potentially outdated due to network changes which have not been notified yet as the routing protocol has not converged.

IV. MULTIPATH ROUTING IN SENS

The number of nodes in a SEN can range from a few hundred to thousands depending on the deployment. SENs with thousands of nodes can become common in the future. Therefore, the routing algorithm needs to be distributed, decentralized and scalable.

Multipath routing can use disjoint paths or non disjoint paths. The problem with disjoint path is the dependence on the physical topology of the network and the difficulty in being allocated by the routing algorithm because any of the paths to a certain destination node can share any link [16]. For this reason, our study in this paper focuses on non disjoint path distance-vector multipath routing protocols.

Multipath routing let obtain some benefits for the network performance, such as: reduction of the average delay [7], more security against network attacks [8] or reduction in the overall convergence time when a link fails. The latter benefit introduces two extra advantages, the reduction of the communication overhead in the network and a convergence time close to 0 s. in some cases. On the other hand, the routing loops can exist with higher probability than in shortest-path routing.

A. Mechanisms for successors selection

Multipath routing algorithms maintain a group of vectors to the same destination called successors (S_{ij}). These neighbor nodes are used to route the packets to a certain destination. The most difficult problem that must be solved is the selection of these successors avoiding loops in the network. This problem has different solutions:

1) *Using loop-free paths with the same cost:*

This is the simplest multipath mechanism based on selecting the paths with the same cost than the shortest path to a certain destination. An example of a protocol that uses this type of multipath is OSPF.

$$S_{ij} = \left\{k \middle| \hat{\sigma}^{i}_{ikj} = \min \sigma_{ij} \ , \forall\, k \in N_i \right\} \quad (2)$$

The main advantage is the simplicity because it does not require modifying the baseline protocol behavior but it is pretty unlikely to find paths with the same cost.

2) *Using loop-free paths with a variation over the minimum:*

This mechanism is used, for example, by EIGRP. It is based on selecting the paths with a variance of γ in the shortest path.

$$S_{ij} = \left\{k \middle| \hat{\sigma}^{i}_{ikj} < (\min \sigma_{ij} \cdot \gamma), \forall\, k \in N_i \right\} \mid \gamma > 1 \quad (3)$$

The main disadvantages are that the probability of using a path with a loop depends on γ parameter and the inability to avoid bouncing effects due to a bad configuration of this parameter.

3) *Using loop-free paths in a pseudostationary network:*

This mechanism is based on the Loop Free Invariance (LFI) conditions [17] with the difference that multipath routing pursues a group of successors greater than one. The condition that must be satisfied in order to avoid loops is the following:

$$S_{ij} = \{k | \hat{\sigma}^i_{kj} < \sigma_{ij}, \forall k \in N_i\} \mid \sigma_{ij} = \min(\lambda_{iv} \oplus \hat{\sigma}^i_{vj}), \forall v \in N_i \quad (4)$$

If this condition is satisfied, it can be affirmed that there are no loops in the network when the routing protocol has converged. But during the convergence of the network it is possible that a loop is originated. To satisfy this condition even when the network is converging, it is necessary a synchronization mechanism.

4) *Using loop-free paths with second-to-last-hop information:*

This mechanism shares the information of the penultimate hop. With this information, the routing protocol knows all hops in the path and can calculate whether a new link added to a path is originating a loop or not. MPATH [8] is an example of this type of multipath routing protocol. Although this mechanism is robust, it also needs a synchronization mechanism to maintain the information updated on all nodes in the network.

B. Synchronization mechanism

LFIs can be used to avoid loops in a converged network but not during convergence time. The reason is the distributed nature of the distance-vector algorithms. This nature does not assure that the LFIs are accomplished by all the nodes in the network because each one maintains his own routing information and can make wrong decisions based on outdated routing information. For this reason, it is necessary a mechanism to state that the information is correct in all nodes of the network. This mechanism must update the routing information within a finite period of time and must have a beginning and an end. Moreover, it is necessary to bear in mind that only the metric's increasing needs to be synchronized because it is critical. A decrease in the metric cannot create a loop.

There are different methods of synchronization but most of them are based on the diffusing computations studied by Dijkstra [19]. The first multipath algorithm incorporating the diffusing computations was DASM [5], which uses a variant of the LFI used in the EIGRP's Diffusing-Update Algorithm (DUAL). This variant only initiates the synchronization when the Loop-free Routing Condition (LRC) is violated. LRC is a relaxed condition of the LFI and it reduces convergence time of DUAL and also the number of routing messages needed. The evolution of DASM is MDVA [6] which accelerates the diffusing computations.

The main problem of diffusing computations is the overhead and the delay needed in end to end synchronization. That is the reason why the synchronization proposed in MPDA [7] and MPATH [8] is only for a one hop scope. The advantage of this synchronization is that the originator of the update can receive an acknowledgement faster. DIV routing protocol [9] has been recently defined. This LFI-based protocol provides normal and alternate synchronization. Normal synchronization is similar to MDVA synchronization and alternate is similar to MPATH or MPDA synchronization. A difference in DIV is the treatment of a decrease in the cost metric. DIV produces a message that supersedes any increment process to the same destination and, thus, it can stop a diffusing computation that is taking place in the network. This difference, combined with the two possible synchronization mechanisms, gives more flexibility to the protocol. For these reasons, this protocol could be chosen for its use in SEN data networks.

C. Constraint- based protocols

The routing protocols based on constraints find one or more paths that satisfy a subset of QoS conditions imposed by the user. It is also necessary to define the QoS constraints scope. They can be applied to a single link or to the whole path [18]. The first problem solved was finding a path using two constraints, which is a NP-complete problem [18][20]. The problem with two constraints can be generalized to z constraints. MPOR routing protocol [20] is able to solve the Multiple Constraint Problem (MCP) over a group of z restrictions, furthermore this protocol uses an optimization function to select the path. The method applied to solve the problem is the limited path heuristic proposed in [21]. In order to avoid the loops, the algorithm uses LFIs with the synchronization mechanism proposed in DUAL. The disadvantage of this type of algorithms is the dependency on global parameters to solve the routing problems, thus limiting the possibilities of the algorithm. Moreover, the heuristic solution can fail to find the path even when this path exists.

V. CONSIDERATIONS IN THE DESIGN FOR A QOS MULTIPATH ROUTING PROTOCOL FOR SENS

The study from the different multipath algorithms, such as DASM, MDVA, MPDA, MPATH, MPOR or DIV among others has concluded that the most robust way to solve the multipath routing problem is applying a scheme based on the diffusing computations and use LFIs to avoid loops. Even though our initial studies were focused on solving the routing loops and bouncing problems using techniques such as split horizon, split horizon with poison reverse, triggered updates, hold down timers, the use of the second-to-last-hop information or legacy synchronization methods.

On the other hand, there are other aspects that must be defined to obtain an algorithm that could be implemented in a real SEN. Some of these aspects are: the detection of neighbors, the hierarchy of the network, the definition of which synchronization mechanism is used, the addressable elements in the network or the address scheme used by the protocol to identify the nodes in the network. Furthermore, if the protocol is oriented to provide QoS, additional aspects have to be defined, such as the QoS metric, the specification of the protocol to minimize the amount of bandwidth needed and the load balancing scheme. These aspects are treated in each of the following parts.

A. Neighbor detection

The neighbor detection has two primary objectives in a routing protocol: establish neighbor adjacencies and detect the failure/recovery of a direct connected link.

The distance-vector routing protocols do not need to establish adjacencies between neighbors, but the failure/recovery of a link is critical because it can force the synchronization of the routing algorithm which is crucial to maintain the stability of the network. In case of synchronization need, the most critical event is the increment in the metric because it can create a loop in the network. If the failure of a link is not detected quickly, all the packets routed across the failed link will be discarded decreasing the performance of a SEN. A failure in the detection could compromise the detection of the end of a diffusing computation and it is known as Stuck In Active process or SIA. The cause of a failure in the neighbor detection could be the physical medium. For example, Ethernet or PLC is a shared medium and it is not always possible to detect a neighbor failure if a switch or bridge is in the middle. This behavior is likely to be usual in the future SENs' PLC and wireless hybrid networks.

The solution to that problem is to implement a keep-alive mechanism controlled by the routing protocol, consequently incrementing the message overhead of the routing protocol. On the other hand, the possibility of using BFD protocol [22] could be very interesting for our purposes. BFD, which is a much more efficient solution, establishes a connection with neighbors through a three way-handshake and it monitors them with hello messages. In case of failure, it is immediately notified to the routing protocol.

B. *Hierarchy of the network*

The network hierarchy is the distribution in areas of the nodes in the network. Some examples of hierarchic protocols are OSPF or IS-IS which are link-state protocols. Hierarchy mechanism is applied to solve the scalability problem of the link-state protocols, although it can be used on distance-vector to reduce the amount of traffic inside an area.

The information maintained by a node in the network is updated depending on the number of changes in the network. The routing table size of flat networks increases linearly by limiting the scalability of the protocol due to the amount of information that is needed to be shared. When the routing protocol uses hierarchy techniques, a group of nodes are treated as a unique addressable entity from the top of the hierarchy (e.g., OSPF areas). An example of hierarchic routing protocol is HIPR [23] which is based on the Loop-free Path-finding Algorithm (LPA). The three most important advantages derived from this mechanism are the reduction in the number of routing messages needed to converge, the reduction of the size on the route table (reducing the memory needed by the node) and also the reduction of the convergence time.

When a hierarchic protocol is used, it is necessary to define the hierarchy scheme used because it settles for the direction of the information flow. For example, OSPF forces all areas to be in contact with the backbone area by addressing all the traffic through it. On the other hand, it is the ALVA algorithm [24], which implements a more flexible scheme.

C. *Algorithms based on sequence numbers*

The sequence numbers are introduced in the routing messages in order to allow the routing protocol to identify the updates. For example, DIV numbers the increment updates for identifying to which diffusing computation belongs to. This number also let identify out of order messages or detect duplicated messages.

An important issue that must be taken into account when sequence numbers are used is that they are part of a finite group of numbers. For this reason, it would be necessary to define the maximum possible value and the mechanism to synchronize them when that maximum is reached. Another aspect that must be defined is the scope of a sequence number, it can identify a local sequence number between two neighbors (this is the case of DIV) or it can be global to the entire network (this is the case of AODV [25]). The AODV's option is the most difficult to synchronize because the sequence number must be synchronized across the entire network [26]. The last topic that must be defined is the behavior of a new node in the network because it would not be synchronized with the network. It is related with the neighbor detection mechanism that must also synchronize new nodes reached in the network.

D. *QoS metrics*

Several routing protocols are oriented to provide QoS. All of them provide the QoS based on the metric used by the routing protocol, which give much more information than the number of hops. This is the reason why the metric chosen is an important parameter when a routing protocol is designed. The metric is the value used to select which path is the best one. Moreover, it is necessary to define the optimization functions which define the objective of the routing policy.

The metrics could be subdivided into two flavors: static and dynamic. Static metrics represent a stable vision of the network. The variation of these metrics is usually caused by disconnected links. On the other side, by using dynamic metrics, the stability of the network could be compromised depending on how frequently the metric is updated. Its main problem is that they can change frequently, making necessary to apply hysteresis cycles or the average of the metric value. In order to promote network stability, such metrics have been dismissed for SEN networks in this paper. A metric classification is depicted below.

1) *Single metrics*

These are the simplest ones and they only represent a single characteristic of a path. Examples of routing protocols that use these metrics are RIP or IS-IS, using the number of hops as a path metric. Another useful metric example for SENs is the Bandwidth-inversion Shortest Path (BSP) [27] or the Enhanced Bandwidth-inversion Shortest Path (EBSP) [28] with better performance in heterogeneous network (see Table II and Table III).

2) *Combined metrics*

These metrics also represent a characteristic of a link using one value. But this value is obtained from a combination of metrics by avoiding NP-complete problem [13]. The metric proposed in [29] is an example of a metric with a combination of bandwidth, delay and reliability of the link (Table IV).

3) *Multiple metrics*

This metric scheme represents a link with more than one cost value. The entire network exchanges this information and then the node could combine this information in order to decide the best path to the destination. The most known examples of this type of metrics are de Widest Shortest Path (WSP) [30] and the Shortest Widest Path (SWP) [29]. Other examples are [31] and [32]. The former divides bandwidth between numbers of hops and the latter divides delay between bandwidth. The main difference between them is how they prioritize the importance among all metrics to obtain the preferred path. Another example is the metric proposed on [33], whose metric scheme uses the number of hops, link bandwidth and total bandwidth of the path. It establishes a hierarchy to evaluate all the metrics, first it is evaluated the number of hops; if both paths have the same metric, the minimum bandwidth is evaluated and so on. It is known as lexicographic order [14] (Table V).

TABLE II. BSP METRIC

Σ	$\sigma \in R^+$
$\oplus$	$\lambda \oplus \sigma = \lambda + \sigma$
L	$\lambda \in R^+, \lambda = \frac{1}{BW}$
$\preccurlyeq$	$\leq$

TABLE III. EBSP METRIC

Σ	$\sigma \in R^+$
$\oplus$	$\lambda \oplus \sigma = \lambda + 2 \cdot \sigma$
L	$\lambda \in R^+, \lambda = \frac{1}{BW}$
$\preccurlyeq$	$\leq$

TABLE IV. EXAMPLE OF COMBINED METRIC

Σ	$\sigma \in R^+$
$\oplus$	$\lambda \oplus \sigma = \lambda + \sigma$
L	$\lambda \in R^+, \lambda = {bandwith}/{delay \cdot reliability}$
$\preccurlyeq$	$\leq$

TABLE V. EXAMPLE OF MULTIPLE METRIC (LEXICOGRAPHIC ORDER)

Σ	$\Sigma_{\text{hop}} \times \Sigma_{\text{BW}_{\text{link}}} \times \Sigma_{\text{BW}_{\text{total}}} : < \sigma_h, \sigma_{bl}, \sigma_{bt} >$
$\oplus$	$(\lambda_{bl}, \lambda_{bt}) \oplus (\sigma_h, \sigma_{bl}, \sigma_{bt}) = < \sigma_h + 1, \lambda_{bl} + \sigma_{bl}, \lambda_{bt} + \sigma_{bt} >$
L	$\lambda_{bl} \in R^+, \quad \lambda_{bl} = link\ bandwidth$ $\lambda_{bt} \in R^+, \quad \lambda_{bl} = total\ bandwidth$
$\preccurlyeq$	$(\sigma_h, \sigma_{bl}, \sigma_{bt}) \preccurlyeq (\sigma'_h, \sigma'_{bl}, \sigma'_{bt}) \quad iif$ $(\sigma_h < \sigma'_h) \vee (\sigma_h = \sigma'_h \wedge \sigma_{bl} < \sigma'_{bl}) \vee$ $(\sigma_h = \sigma'_h \wedge \sigma_{bl} = \sigma'_{bl} \wedge \sigma_{bt} \geq \sigma'_{bt})$

4) *Metrics based on constraints*

This metric strategy also represents the cost value of a link with many different values [34]. The difference resides in the way to select the best path. This selection is based on a subset of constraints that defines a range of values. If the metric of a path is between these values, it is considered as a feasible path. Therefore, this strategy does not have the objective to minimize or maximize a path metric to a destination. An issue to be solved is the method used to manage *n* constraints. There are situations in which this method cannot find a correct path [35] even though it exists.

E. Efficiency and routing overhead

A routing protocol has to miss the minimum bandwidth by reducing the communication overhead. If this requisite is not accomplished, the traffic of the SEN could be affected by the routing updates causing the failure of the QoS agreements. Communication overhead could be caused by too large periodic updates or due to too frequent updates (for example when dynamic metrics are used). One possible solution is to apply a hierarchical routing protocol to reduce the information advertised inside an area. The best solution could be the use of triggered updates instead of periodic updates, if the network topology does not change frequently and it is almost stable. In this case, periodic updates are a waste of bandwidth because there is no change to announce. On the other hand, in case of a frequently changing network, the use of triggered updates can result in a misleading operation. If a node generates a lot of triggered updates it can saturate the network because of the domino effect. This can be avoided applying a timer when the triggered updates are received; the expected behavior is the reduction of the overhead by waiting enough time to receive and retransmit subsequent updates.

Another solution is used, for example by EIGRP, by limiting the amount of bandwidth that can be used by the routing protocol. This approach is efficient but it can affect the performance of the routing protocol when more bandwidth than the assigned is needed and so leading some nodes to lose the connectivity with some destinations.

F. Load balancing schemes

A load balancing scheme is not a requisite of a routing protocol, but it is necessary to specify it when multipath routing protocol is used in order to take advantage of the multiple paths to a single destination. The efficiency of the load balancing scheme would rely partially on the metric used by the routing protocol because this information is used by some load balancing algorithms. Otherwise, if more than one path is used simultaneously, there is the possibility of introducing variable delays. This delay variation affects dramatically to transmissions based on TCP protocol, by activating the Fast-Retransmit method and wasting more bandwidth. This behavior could increase the number of lost packets thus reducing the actual throughput.

Load balancing could be carried out in a flow-based or packet-based strategy. The flow-based mechanism is based on information such as IP address or a hash of the information of the flow. The advantage of this approach is that the packet reordering is not needed because a single flow uses a unique path. Obviously, its main disadvantage is inefficiency using the bandwidth of the network. For example, an intensive flow can congest a single path whereas another data flow could be using a better uncongested path as the load balancing scheme cannot cope with this situation. When packet-based load balancing is used, the bandwidth of the network is efficiently allocated but reordering is needed in the destination.

VI. Multipath Routing Protocol Analysis Behavior

A. *Study groups for simulations*

In this section, DIVs behavior is defined and also a brief description of the random scenario used to run the simulations is given. Even though Distributed Bellman Ford (DBF) has been studied, the behavior of this protocol is not described in this section because it is a well-known protocol and is the base of a standard protocol (RIP).

The modeled routing protocol is based on DIV [9] which is the most evolved distance vector routing protocol studied in [1]. DIV has two types of synchronization mechanism, one called local and another called alternate. Both mechanisms have been modeled in this paper. The local method only synchronizes the routing information with one hop when an increase in the metrics is detected. On the other hand, there is the alternate method: this type of synchronization is a common synchronization method that notifies all nodes affected by the metric increment (L). The local method is the fastest one but the stability of the network could be compromised because it could happen that a node cannot reach another node in the network when the routing is converging. The alternate method is more robust because the old path affected by the metric increment is maintained until all the nodes have been informed of the metric increment and have made the correct changes.

In our approach, we have changed the addressing of the routing protocol to maintain a hierarchy of 16 SEN's areas with a maximum of 256 nodes per area. This hierarchy was applied to limit the routing information exchanged inside an area, improving the efficiency of the protocol in terms of bandwidth. The other decision that has to be taken is the metric used in order to implement a QoS-aware protocol: this metric has been EBSP. EBSP metric has a better response than BSP [27] and fits correctly in heterogeneous networks which are typical in SENs. Another advantage of this metric is its representation with a single value, reducing the amount of bandwidth needed to distribute the routing information.

To understand the model implemented in the simulator, we have represented the implementation with an activity diagram in UML. Fig. 2 represents the general behavior of the protocol.

This protocol has been implemented in the OPNET simulator and it has been generated a subset of scenarios to study the protocol. These scenarios were randomly generated according to two criteria:

- The average number of links per node.
- The number of nodes in the network.

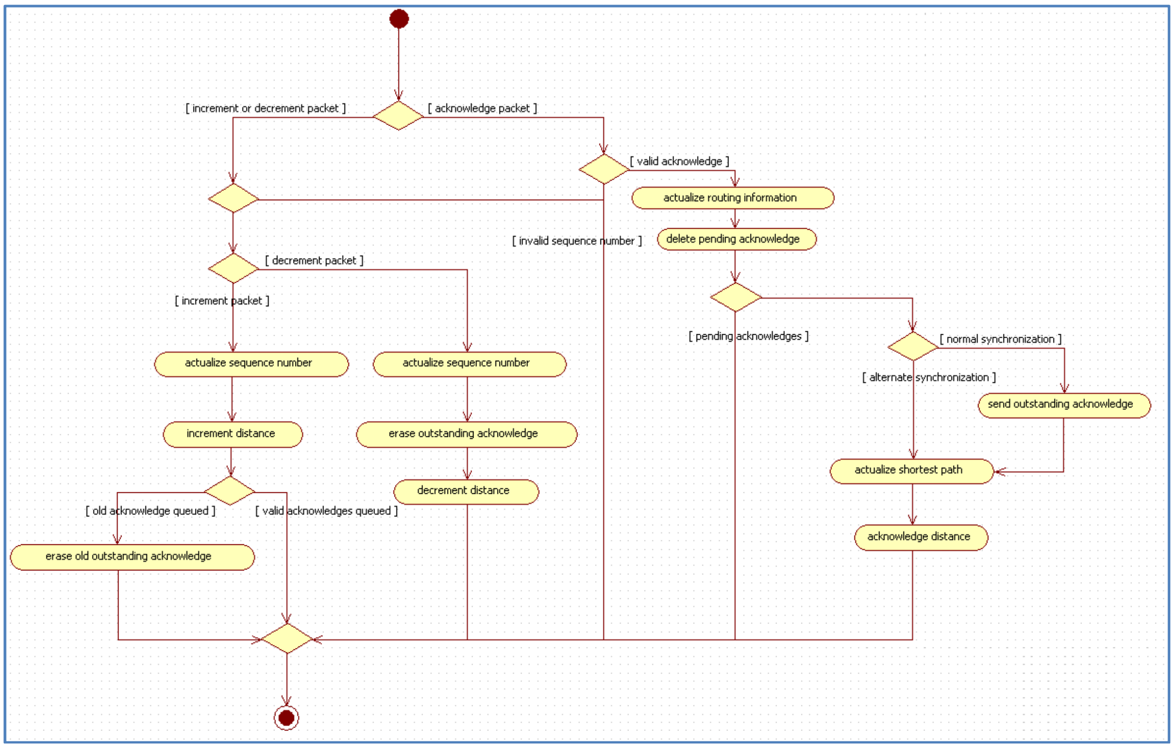

Figure 2. General behavior of the routing protocol [9]

For this study, 4 study groups of 5 scenarios have been generated. The average number of links per node for each study group is: 2 links for the study group number 1, 3 links for the study group number 2, 4 links for the study group number 3 and 5 links for the study group number 4. The number of nodes is 256 and this number is the same for each scenario.

B. OPNET simulator

The OPNET simulator [10] is an event oriented simulator. The language used to program a new node is a proto-C language specifically designed for this simulator. The behavior of the node is modeled through different phases. The first phase is the node model, which consists in designing the flows of information into the node. These flows are modeled among modules and each module contains processes. These processes are modeled in the second phase, which consists in specifying the Finite State Machine (FSM) that rules the behavior of the module. Finally, the third phase consists in programming the different states modeled into the FSM.

This section describes the two parts of the model done over OPNET modeler. The first part is the design of the node to implement the two variants studied in this paper: DBF and DIV. The second part introduces the automatic scenario generation tool created specifically for this study.

The node model designed is very simple. It contains sixteen transmitters and sixteen receivers, all connected to a simple queue module. The node has sixteen point-to-point receivers and transmitters because it is the maximum number of neighbors allowed in the design of the protocol. The module selected to interconnect all the transmitters and receivers was a queue because it can manage different queues and is easier to store, receive and transmit the messages. This queue contains the process model shown in Fig. 3.

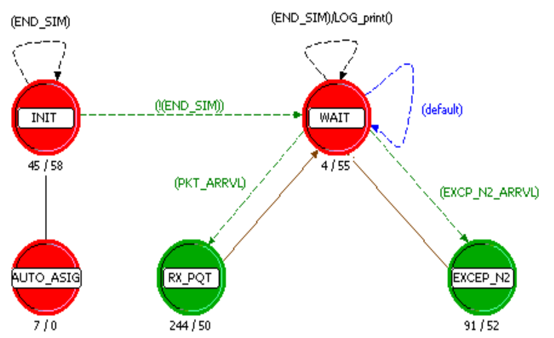

Figure 3. FSM of the models to study the protocols DBF and DIV in the OPNET simulator

The behavior of the machine state can be extracted from the UML diagram shown in Fig. 2. Nevertheless, the tasks done in each state of the finite state machine are briefly described.

- The AUTO_ASSIGN state assigns an address to the node and also initializes some variables used in the INIT state.
- The INIT state focuses on the initialization of all the variables used by the node including all the variables used by the routing protocol.
- The WAIT state waits for the arrival of a packet or the disconnection of the lower level which means that a failure of the link or the node has taken place.
- The RX_PQT is the main state of the process model. It processes all types of packets that can be received: metric increment, metric decrement or acknowledge. In this state is where all the actions derived from a metric increment or decrement are programmed (Fig. 4-6).
- The EXCEP_N2 state is a simple state to detect if the failure is from a link or from a node and initialize the variables according to the type of failure and send the corresponding messages of metric decrement or increment to the rest of the neighbors.

The advantage of this design is the generic states, which allow to model different behaviors with the same FSM and reduce the time wasted to implement the DBF and DIV algorithms.

C. Automatic scenario generation

One of the objectives of the study done in this paper is to analyze a range of similar scenarios to extract the correct results which allow to support the conclusions over them. The scenario is characterized with two parameters: the number of nodes and the average number of interconnections per node. Nevertheless, the automatic scenario generation tool within OPNET does not allow creating a scenario only based on these two parameters. OPNET has a powerful automatic scenario generator which allows creating full-mesh, partial-mesh, tree or bus topologies, but none of these topologies fit in our goal.

For this reason, an application that generates an *xml* file which can be imported into OPNET with the designed scenarios has been created. The main found problem when programming the application was to find out how to write an *xml* file to import it into the OPNET simulator. The second problem was the type of topology, which must connect physically all the nodes in the same network, without any isolated node. The other point of the generated network is the average of interconnections. The number of interconnections cannot exceed the maximum specified to the application.

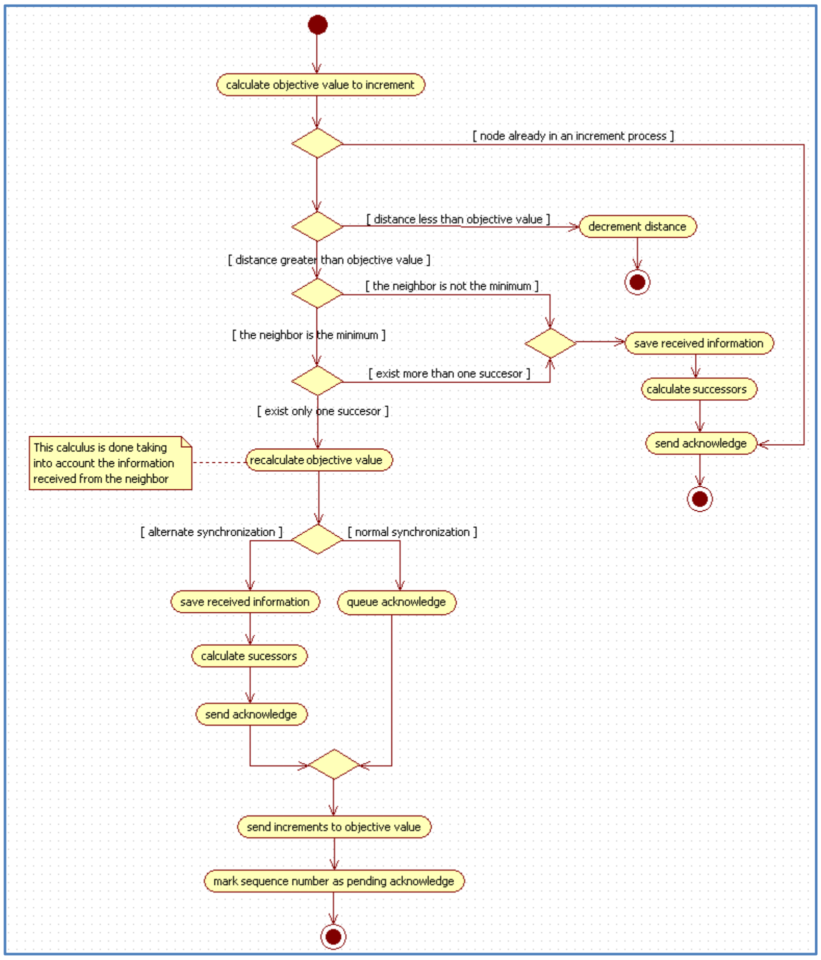

Figure 4. Metric incrementation algorithm

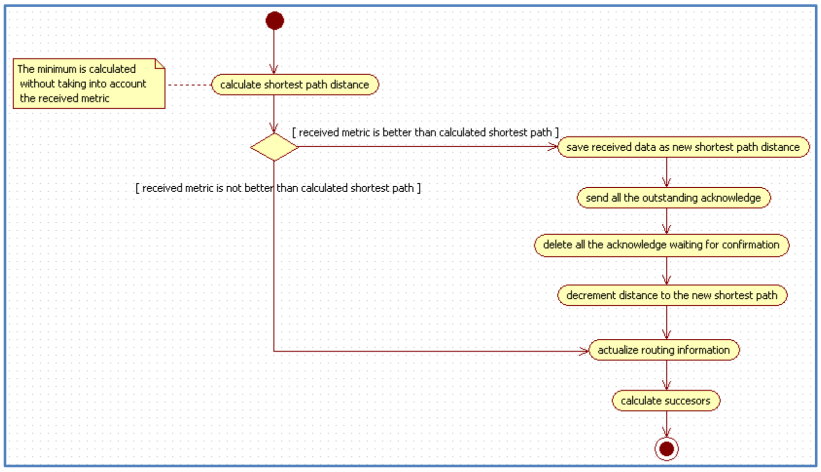

Figure 5. Metric decrementation algorithm

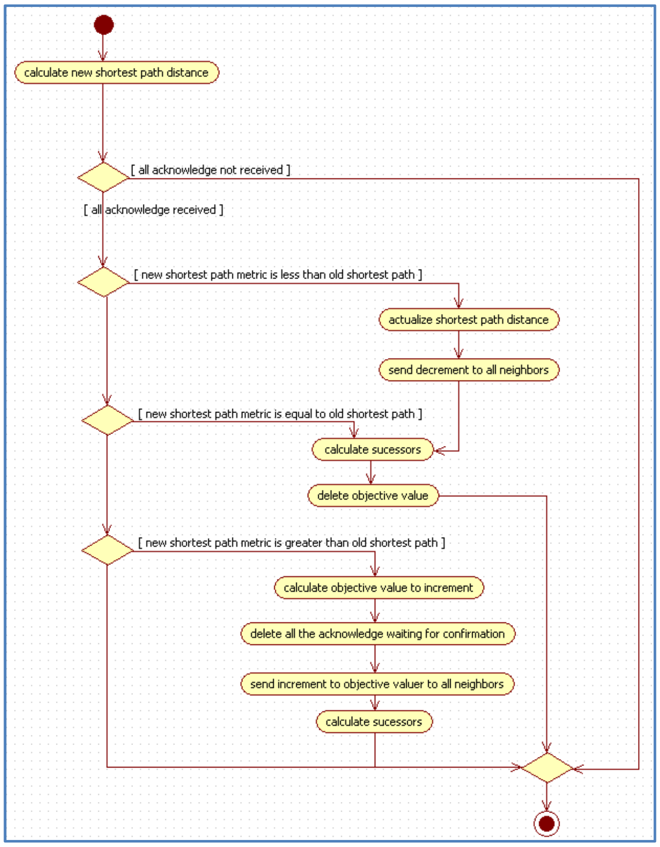

Figure 6. Acknowledgment process

Finally, the most relevant point of the automatic generated network by the simulator tool is the random interconnection of the nodes, which allows to generate five scenarios with the same specifications but with completely different physical interconnections among the nodes. This is the main advantage of this application, the possibility of generating a variety of scenarios with the same definition (number of nodes and average number of interconnections). This variety of scenarios gives the possibility of studying different physical topologies similar to those provided by SENs with the two implementations of the analyzed routing protocols.

D. Simulations and analysis

First of all, it is described the study on the number of found paths in the four groups of simulated scenarios (study groups), which depends on the average number of links in each scenario. Fig. 7 shows the number of paths found by the routing protocol where the x-axis represents the number of found paths and the y-axis represents the percentage of nodes with this number of paths to the destination. In Fig. 7, it can be seen that all nodes in the network find a minimum of one path to its destination, moreover, the scenario with an average of two links per node have a 10% of nodes with 2 paths which is the maximum in the network. When the number of links per node is increased to an average of five links, the 50% of the nodes in the network has more than two paths. This behavior gives a lot of stability to the protocol because a node has an alternative path to the destination if the primary fails.

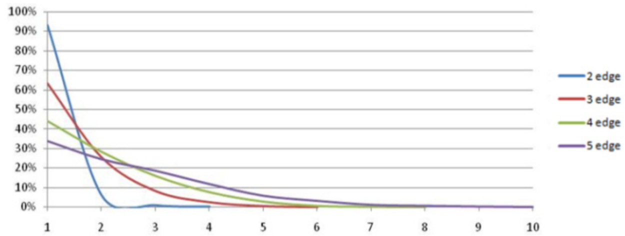

Figure 7. Number of paths found

The second topic that must be analyzed is the delay of an IP packet when there is traffic in the network. To simulate this, the same traffic pattern in all the nodes in the network has been configured. The configured pattern transmits 510 packets per node, which is enough to compare the delay in the network with 2, 3, 4 and 5 links per node. Each packet is transmitted to a different destination in the network and each node has 255 destinations configured, this makes two packets per destination.

This study presents the performance of DBF, which is a basic implementation of a Bellman Ford algorithm based on a hop count metric. In addition to this, in order to evaluate the performance of the multipath routing, DIV has been modeled with a limitation in the number of feasible shortest paths used to route the traffic. This limitation allows us to study the improvement introduced when multiple found paths for the protocol are used.

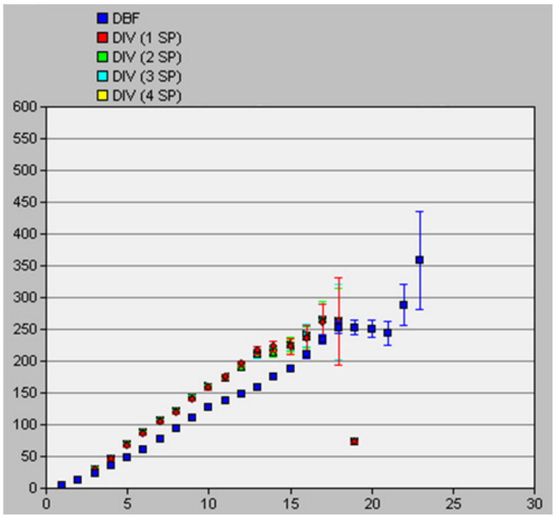

Figure 8. Delay vs. Hop count in the scenario with an average of 2 links per node

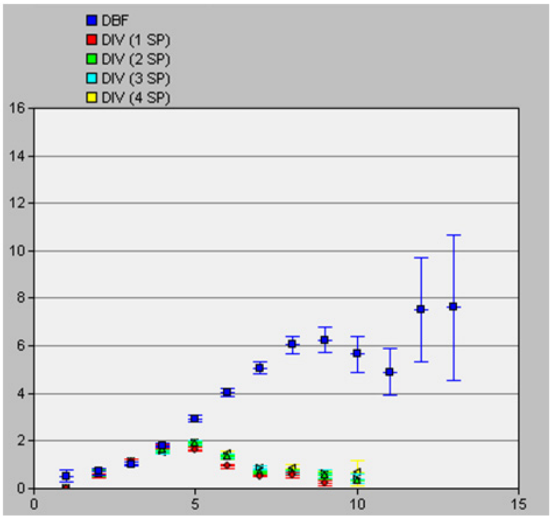

Figure 9. Delay vs. Hop count in the scenario with an average of 5 links per node

Fig. 8 and Fig. 9 show the results of the delay with a confidence interval of 98%. The implementations shown are DBF and DIV with limitations of 1, 2, 3 or 4 feasible shortest paths. Fig. 8 shows the delay (y-axis) according to the hop count (x-axis). The graph presents the results in the 2-link per node scenario where the x-axis represents the number of hops done by the analyzed IP packets and the y-axis represents the delay of IP packets. Fig. 9 presents the results in the 5-link per node scenario where the x-axis represents the number of hops done by the analyzed IP packets and the y-axis represents the delay of IP packets.

The results exposed in Fig. 8 and Fig. 9 show an interesting conclusion: when the scenario has 2 links per node, the best result is obtained by DBF with a metric of hop count; whereas the DIV implementation in the scenario with 5 links per node, which is supposed to be more prone to multipath routing, can take advantage of the network topology by reducing the overall delay of the packets.

When the difference between using 1, 2, 3 or 4 feasible shortest paths on DIV is evaluated, there is no much difference, the only conclusion is that the more paths are used, the more delay is introduced; but this delay is very low.

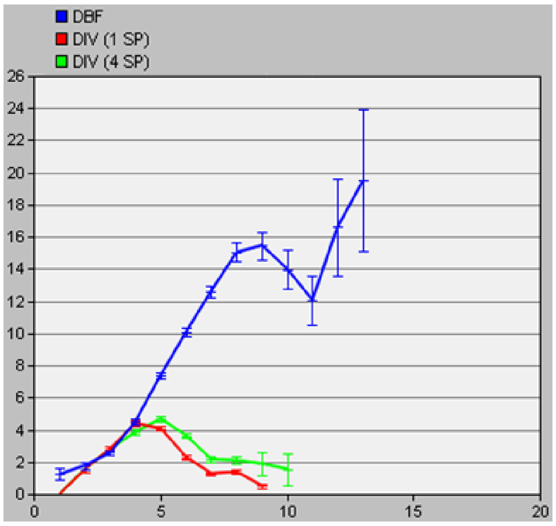

Figure 10. Packet delay vs. Hop count in the scenario with 5 data packets generated per node

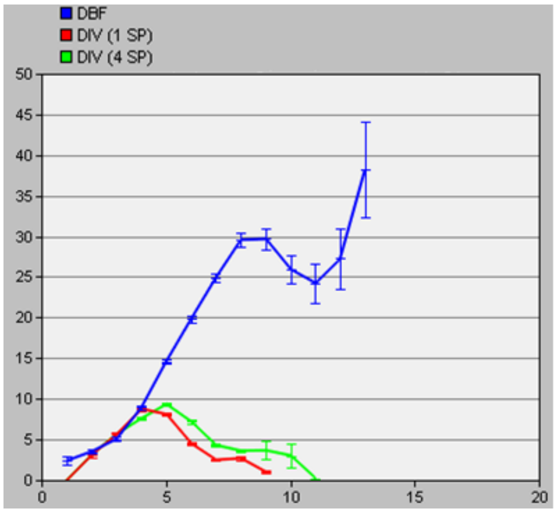

Figure 11. Packet delay vs. Hop count in the scenario with 10 data packets generated per node

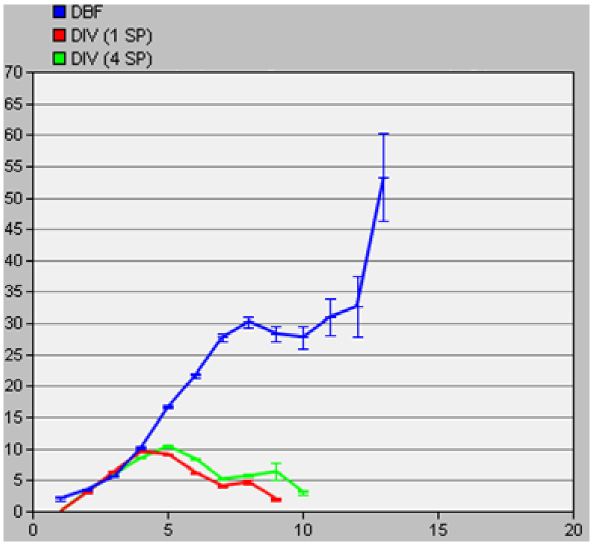

Figure 12. Packet delay vs. Hop count in the scenario with 20 data packets generated per node

The last study done is about the behavior of the routing protocol when the network is congested. The traffic pattern used to congest the network was slightly different. This new pattern configures the transmission of 2, 3, 5, 10 and 20 data packets per node and per destination. Again, the study is focused on the implementations of DBF and DIV, but in the case of DIV the study focuses only on the limitation of 1 and 4 feasible shortest paths. The results obtained with the pattern of 5, 10 and 20 packets are shown in Fig. 10-12 with 98% confidence interval. For example, Fig. 10 shows the average packet delay (y-axis) in function of the hop count metric of the path (x-axis). This graph presents the pattern with 5 packets per node.

The results obtained show that DBF has a very bad performance, whereas DIV can take advantage of the multipath routing. It is, in this situation of congestion, when a protocol oriented to provide QoS must react better and this is the case of DIV.

VII. CONCLUSION

Multipath routing protocols based on distance-vector have emerged as the evolution of its predecessor (shortest-path routing protocols). The study has concluded that these enhanced protocols improve a lot of aspects such as the increment of the network capacity and they improve the redundancy. The main advantage is the increment of the network efficiency, increasing the practicable bandwidth with the same resources and minimizing the delay of the packets.

The design of a multipath protocol is more demanding than a shortest-path routing protocol. The reason is the increase in the number of usable paths. That increase is proportional to the potential loop problems. On the other hand, the amount of routing information to transmit is greater and the mechanism to synchronize all this information is harder to design. All the mechanisms applied on shortest-path such as poison reverse, hold down timers and triggered updates do not fit enough multipath routing. The mechanism with better performance is the use of LFI in order to avoid loops and to synchronize the routing information. From our point of view, DIV-based routing algorithm is the best protocol to use as a baseline in the design of a multipath routing protocol for SENs.

A correct metric must be selected if it is needed to focus the design on QoS providing. Avoiding combined metrics and metrics based on constraints seems to be a good practice, although the last one is a widespread practice to provide QoS-aware routing. Another aspect that the metric must accomplish is to have the enough granularity to find multiple paths, this is the case of the metric used in EBSP which effortlessly finds multiple paths easier than other metrics strategy.

The OPNET simulator is a powerful tool to model a protocol from scratch, giving the possibility of customizing the node behavior. From the point of view of an implementation, it brings the possibility to test the feasibility of a design and study its performance. The practical study has shown that the multipath protocol can find more paths even when there are only two links per node. The increase in paths allows to reduce the overall delay in a transmission and allows to orient the protocol to provide QoS as well. To sum up, the protocol studied in generated scenarios (e.g., Fig. 13) together with the EBSP metric are a good option to implement a QoS-aware routing protocol for SENs.

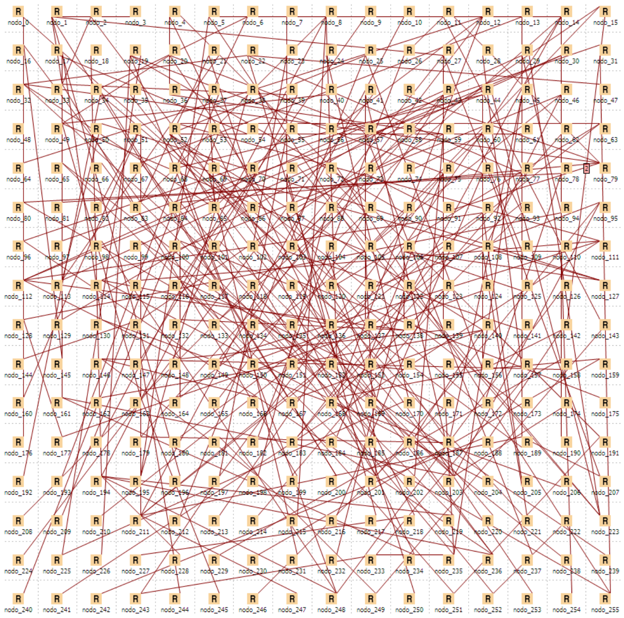

Figure 13. Example of an automatic generated scenario

Finally, an important conclusion is the relevance of the load balancing scheme. This scheme is not usually a part of the routing protocol but there exist different possible implementations that can take more advantage of the multiple paths found by the routing protocol.

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