A centrality-based topology control protocol for wireless mesh networks

Andrés Vázquez-Rodas*, Luis J. de la Cruz Llopis

Department of Telematics Engineering, Universitat Politècnica de Catalunya (UPC)
C. Jordi Girona 1-3, 08034 Barcelona, Spain

Abstract

Nodes in wireless multi-hop networks establish links with their neighbors, which are used for data transmission. In general, in this kind of networks every node has the possibility of acting as a router, forwarding the received packets when they are not the final destination of the carried data. Due to the routing protocol procedures, when the network is quite dense the overload added by the routing management packets can be very high. To reduce the effects of this overload a topology control mechanism can be used, which can be implemented using different techniques. One of these techniques consists of enabling or disabling the routing functionality in every node. Many advantages result from selecting just a subset of nodes for routing tasks: reduction of collisions, protocol overhead, interference and energy consumption, better network organization and scalability. In this paper, a new protocol for topology control in wireless mesh networks is proposed. The protocol is based on the centrality metrics developed by social network analysts. Our target network is a wireless mesh network created by user hand-held devices. For this kind of networks, we aim to construct a connected dominating set that includes the most central nodes. The resulting performance using the three most common centrality measures (degree, closeness and betweenness) is evaluated. As we are working with dynamic and decentralized networks, a distributed implementation is also proposed and evaluated. Some simulations have been carried out to analyze the benefits of the proposed mechanism when reactive or proactive routing protocols are used. The results confirm that the use of the topology control contributes to a better network performance.

Keywords: Topology control, wireless mesh networks, social network analysis, centrality metrics, connected dominating set

1. Introduction

Smart environments, smart devices, smart interaction, computing anytime and anywhere, ..., the accelerated development of information technologies and mobile devices results in people and/or "things" increasingly dependent on the online services offered through the Internet. In such scenario, Wireless Mesh Networks (WMNs) have evolved as a cost effective possible solution for user uninterrupted access to networking facilities. Valued features like robustness, reliability, easy deployment and maintenance, self-forming and self-configuration, make WMNs an important alternative to achieve an always-on connectivity. Among the three typical architectures of WMNs [1], the present work focus on the client meshing one. In this case, the end-user devices are able to simultaneously provide application interface, routing and network configuration capabilities. Nowadays, the most common hand-held device used by an increasing number of people is the smart phone. The evolution of such mobile devices with their variety of embedded sensors results now in a not only communication equipment, but a complete sensing system [2]. Numerous applications are emerging in many fields like health, traffic, human behavior, environment monitoring, social networking and

*Corresponding author. Tel.: +34 93 401 7027.
Email addresses: andres.vazquez@entel.upc.edu (Andrés Vázquez-Rodas), luis.delacruz@entel.upc.edu (Luis J. de la Cruz Llopis)

commerce [2]. With this perspective it is entirely feasible to consider a WMN composed by mobile phone users moving around a city as a cost-effective complement to commercial cellular networks. One of the major concerns in this kind of devices is related to their energy consumption. Therefore, optimization techniques that aim to reduce it are always required [3].

Topology control techniques have been developed to improve the energy efficiency and the battery lifetime of a variety of networks. It also aims to reduce collisions, protocol overhead, and interference by means of a better control over the network connections and redundancy [4]. In general, there are three main types of topology control approaches [4]. First, power control techniques [5, 6], adjust the communication range of the wireless nodes by means of the transmission power of their transceivers. This way, nodes are able to better manage their neighborhood size, interference level, power consumption and connectivity. Secondly, power mode mechanisms [7, 8] control the active or sleep operation modes of the nodes to dispense with redundant stations and still achieve the desired connectivity. Finally, hierarchical clustering approaches [9, 10, 11] aim to construct an efficient virtual backbone for data forwarding by the selection of a connected dominating set (CDS). From graph theory, a CDS of a graph is a connected subset in which all the nodes that does not pertain at that subset have at least one adjacent neighbor inside the subset. Due to the reduced number of nodes developing routing task, the main advantages of this CDS-based topology control are: collisions, protocol overhead and energy consumption reduction, efficient network organization and scalability improvement. In this work we evaluate an alternative method for this last category of topology control based on social network analysis metrics.

In this context, thanks to the increasing availability of network maps which depicts the behavior of complex systems and the universality of their characteristics [12], network science appears as the renewed study of the structure and the dynamic behavior of a variety of networked systems [13]. Accordingly, social network analysts have developed an important set of measures and metrics which allow understanding the behavior and quantify the topology features of a diversity of networks [14]. Specifically, in this work we focus on centrality metrics developed to identify the most important actors (nodes) in a network by means of graph theory definitions and concepts.

In summary, the purpose of this work is to present and evaluate an alternative topology control mechanism based on centrality measures borrowed from social network analysis. This topology optimization has been applied to a client wireless mesh network formed with user hand-held devices.

The rest of the paper is organized as follows. In Section 2 we report and analyze the related work. Section 3 provides a background on centrality metrics. Section 4 presents and evaluates the proposed topology control mechanism. A performance evaluation has been carried out by means of simulations, taking into account both reactive and proactive routing protocols. The results are presented in Section 5. Finally, the conclusions and future works are summarized in Section 6.

2. Related work

Nowadays, the application of complex networks techniques and social network analysis concepts to improve the performance of wireless ad hoc networks is growing as a fertile research area [15]. Some recent works are summarized in the following. [16, 17, 18] apply the small world phenomena, re-popularized by [19], to reduce the average path length of the network. The basic idea of these proposals is to modify the physical topology of the network based on the social features of the underlying graph. The small world property (or low average path length) could be achieved either by the aggregation of long-ranged links [17] or by a combination of rewiring, deletion and/or addition of links/nodes [16]. Authors in [18] combine centrality measures with directional beamforming to create long-range links between more central nodes. The same authors extend their study to sparse highly partitioned networks in [20].

SimBet [21] is a routing protocol designed for delay-tolerant MANETs. It uses two social network analysis metrics (centrality and similarity) for message forwarding decisions. Betweenness centrality is selected to identify more suitable bridge nodes, and the similarity measure is used to find nodes that are closer to the destination neighborhood. A utility function combines the similarity and the betweenness utilities and allows adjusting the relative importance of them. For performance evaluation both utilities has been assigned the same importance. For their part, authors in [22] apply social network analysis metrics to detect critical nodes in a WMN. They show how network reliability substantially degrades when coordinated attacks are directed to highest centrality nodes. Simulations evince that nodes with high betweenness centrality exhibit a greater impact than nodes with high degree or closeness centrality. Authors also propose a socially-aware TDMA channel access scheduling algorithm. The main idea is to give higher priority (assigning more time slots) to nodes with high closeness centrality values. Simulations show important throughput improvements at the expense of increased delay.

The time-evolution of the topological characteristics of vehicular networks from the perspective of graph theory and social network analysis is the subject addressed in [23]. It is confirmed that relevant and useful information about the behavior of the VANETs could be inferred from the centrality metrics. The importance of nodes with high centrality values on the design of more efficient VANET protocols is also discussed.

A topology control algorithm for WSN based in edge betweenness centrality [24] is proposed in [25]. This metric is used to identify most relevant edges or links between nodes, regarding energy consumption. For each node, the aim of the proposal is to select a set of logical neighbors that minimize energy consumption and fulfill QoS requirements. Simulation results show better performance of this proposal in comparison with traditional topology control methods in terms of number of logical neighbors, energy consumption, latency and hit-ratio (percentage of served queries).

Authors in [26] propose a routing protocol based on a connected dominating set (CDS). A simple marking process is used to establish the initial CDS: a node is designed as gateway if it has at least two unconnected neighbors. This initial CDS is reduced by the application of rules based on the node IDs. An extension of the selective removal rules are presented in [9]. In this case the degree and the energy level of the nodes are considered to reduce the CDS and to achieve balanced energy consumption. In [27] Connected Dominating Sets with bounded diameters are taken into account. To construct these DS with the smallest size, authors propose and evaluate two centralized algorithms and one distributed version. On the other hand, given the fact that the transmission ranges of all network nodes are not necessarily equal, authors in [28] model the network by means of a Directed Graph and propose two different solutions for the case in which all the network links are bidirectional. A recent and extensive survey on energy-aware distributed topology control algorithms is presented in [4].

Many topology control mechanisms are intended to sensor networks in which the dominant data flow traditionally goes from the sensor nodes to the sink. In this work we focus on mesh networks in which it is more common that every node may be origin or destination of the data flow. On the other hand, we evaluate the use of centrality metrics which are calculated both in a centralized or a distributed way. Besides, we propose and evaluate a distributed implementation of the router selection mechanism, as well as different possibilities to achieve total network connectivity.

3. Background on centrality

Centrality is one of the most useful mathematical measures developed by social network analysts to capture the structural properties of social relationships. It aims to identify the most important actors/vertices within a graph that represents any physical network. Centrality metrics could be based mainly on the degree of a vertex (number of edges connected to it [14]) or on the geodesic distances between them [15]. In the following we present a summary of the three most useful centrality metrics.

Degree Centrality is the simplest centrality metric. It is defined as the number of edges (links) attached to a vertex (node) [29]. In a WMN the degree centrality of a mesh station can be viewed as the number of one-hop neighbors with which it has been established a peer link. This centrality is generally scaled by the number of nodes N in order to be a measure independent of the network size. Then, the degree centrality Dc_i for the node i is computed as:

$$Dc_i = \frac{\sum_{j=1}^{N} x_{ij}}{N-1} \tag{1}$$

where $x_{ij} = 1$ if there is a link between node i and node j and $x_{ij} = 0$ otherwise. In some networks, it could result logical to think that a node which has links to many others (high degree centrality) has greater impact in the network than nodes with few links.

Closeness Centrality aims to identify nodes that spread messages in shorter time [29]. For that, this metric uses the concept of geodesic path, which is the path with the shortest distance between two nodes. The closeness centrality Cc_i for node i is computed as:

$$Cc_i = \frac{N-1}{\sum\limits_{j=1}^{N} d_{ij}} \tag{2}$$

where $i \neq j$ and d_{ij} is the geodesic distance between nodes i and j. In social networks, actors with high closeness centrality can communicate their ideas faster than actors with lower closeness centrality [14].

Betweenness Centrality measures the proportion of shortest paths between any pair of nodes passing through a specific node [30]. The control over communications, connections and information flows could be dominated by nodes with high betweenness centrality. The betweenness centrality Bc_i for node i is computed as:

$$Bc_i = \sum_{j=1}^{N} \sum_{k=1}^{j-1} \frac{g_{jk(i)}}{g_{jk}} \tag{3}$$

where $i \neq j \neq k$, g_{jk} is the total number of geodesic paths between node j and k, and $g_{jk(i)}$ is the number of geodesic paths between node j and k that pass through node i.

4. Topology control mechanism and centrality evaluation

In this section we propose and evaluate a topology control mechanism based on centrality metrics. We start with a description of the dynamic wireless mesh network subject to analysis. Then, a centralized implementation and evaluation is presented in order to identify the most appropriate centrality metric for our purpose. At this point, different considerations are done for a practical distributed implementation. Finally, the practical implementation of the protocol is presented.

4.1. Scenario under consideration

For the experimental evaluation we have considered a dynamic wireless mesh network generated by the ns-3 network simulator [31]. The mesh stations (nodes) are based on the IEEE 802.11s amendment which is currently incorporated in the IEEE 802.11-2012 standard [32]. The simulation scenario consists of 100 mesh stations uniformly distributed in a 1040 x 520 m area. According to [33] these values guarantee minimal quality criteria for stringent protocol evaluation. Specifically, the average shortest-path hop count is greater than four hops (to avoid that most of the data packets be interchanged just among one or two-hop neighbors) and the average network partitioning is lesser than 5% (to avoid an excessive number of isolated nodes). The nodes move according to a random walk 2D mobility model inside the rectangular bounds. Each node moves with a speed chosen randomly between 2 and 4 m/s. The direction and speed of the nodes are updated after they have moved 100 m. These values are selected with the assumption that the mobile nodes are transported by people moving around a segment of a city. The initial node positions and their trajectories are shown in Fig. 1. For the wireless channel, the log-distance propagation loss model has been considered.

According to [32], before the transmission of data frames, mesh stations must create and maintain a logical topology using the mesh peering management protocol. Every mesh station discovers its mesh neighbors (peers) by means of beacon frames which are periodically sent. When a new neighbor has been discovered, the mesh station starts a peer link open handshake. It begins with a Peering Open management frame that contains mesh configuration parameters. If the target station agrees with such parameters, it responds with a Peering Confirm frame. The same procedure is executed in the opposite direction to ensure bidirectional links. Only if the complete handshake procedure is successfully executed, a peer link is established between two mesh stations. Standard does not specify why or when a peer link must be closed. The ns-3 mesh networking implementation [34] triggers a close peer link procedure when the number of

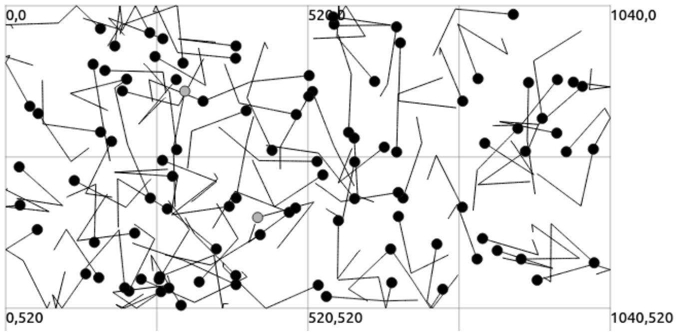


Figure 1: Initial node positions and their trajectories.

successive lost beacons achieves a maximum configurable value. By default this threshold is set to 5. If there is an active data flow, the ns-3 mesh model also executes a close procedure when a station is unable to transmit to a peer a number of successive frames. This value is also set by default to 5.

4.2. Centralized implementation

Based on the presented scenario, first of all we have analyzed several snapshots of the mesh network dataset taken every 5 s. For each snapshot and for each node inside the network we compute its degree, closeness and betweenness centrality metrics. ORA [35] and UCINET [36] software have been used to centrality calculations, while network graphics are done with ORA. With the centrality values, we are able to rank and identify the most central nodes from those three points of view. Fig. 2 shows this ranking for one specific snapshot (at time=5 s) and for the three metrics. Blue nodes represent the most central stations and the red ones the least. As expected, Fig. 2 confirms that different nodes are selected as most central ones for each different metric. This is because each metric evaluates a very different parameter and there is no relationship among them.

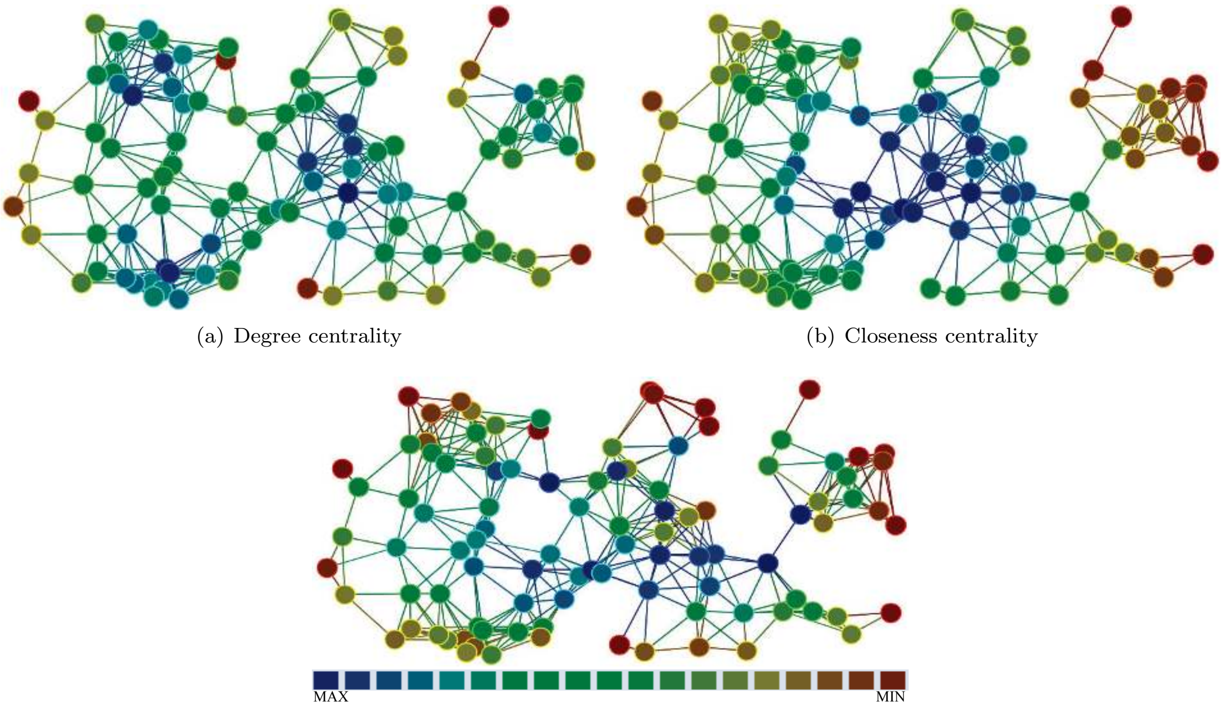
As previously said, to reduce the complexity, communication overhead and energy consumption of the network, we want to find a subset of mesh stations that forms a connected dominating set. So, instead of allowing each node to perform routing tasks, we choose only the most central stations to do it. In a roughly first approach, we limit the number of routers to the forty (40%) most central nodes for each network dataset and for each centrality metric. We virtually remove all the links between non-router stations and keep all the other. If a non-router station has a link with more than one router, we keep all these links in order to preserve network resilience and to enable future load balancing and fair energy consumption improvements. Fig. 3 shows the resulting virtual topology for each centrality metric and for the same snapshot considered in Fig. 2. Blue nodes represent the selected routers, the green are the mesh stations that have a link with at least one router and the red represents the isolated nodes.

To determine which of the centrality metrics is the most suitable for our topology control application, we compare (for all the network datasets and for the three centrality metrics) the resulting network fragmentation F, that is, the proportion of nodes in a network that are disconnected from each other. It can be computed in an efficient way through the following equation [37]:

$$F = 1 - \frac{\sum_k s_k \left(s_k - 1\right)}{N \left(N - 1\right)} \tag{4}$$

where s_k is the number of nodes of the k^{th} component of the graph that represents the network.

Fig. 4 shows the time-evolution of the network fragmentation for the three centralities and for two different percentages of selected routers. As can be seen, the values for the betweenness centrality are considerably lesser than for the other two centrality metrics. And as expected, for all the centralities the fragmentation decreases when a greater percentage of nodes are selected as routers. Besides, Table 1 summarizes the average, the standard deviation and the maximum values for this measure. As can be observed, the mean and maximum fragmentation using the betweenness centrality are much lesser than with the other two options. Furthermore, the betweenness-based selection exhibits a more stable (confident)

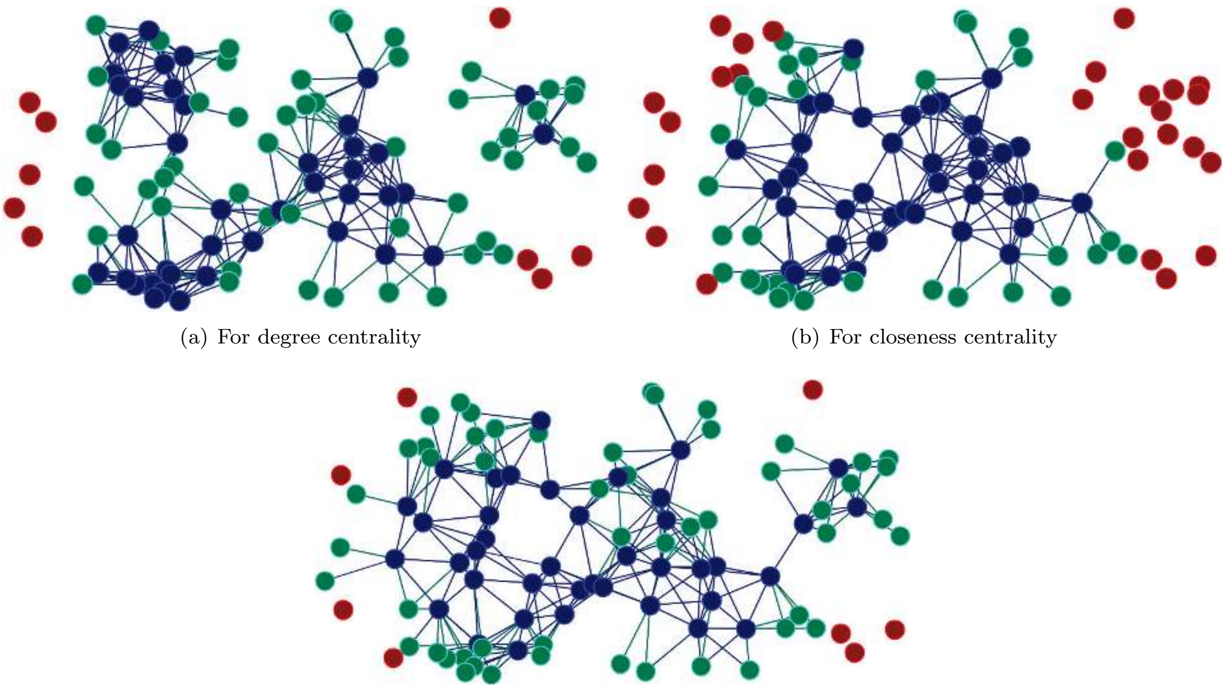


(a) Degree centrality

(b) Closeness centrality

(c) Betweenness centrality

Figure 2: Centrality metrics for one of the WMN snapshots.



(a) For degree centrality

(b) For closeness centrality

(c) For betweenness centrality

Figure 3: Resulting topology with the 40% most central nodes as routers.

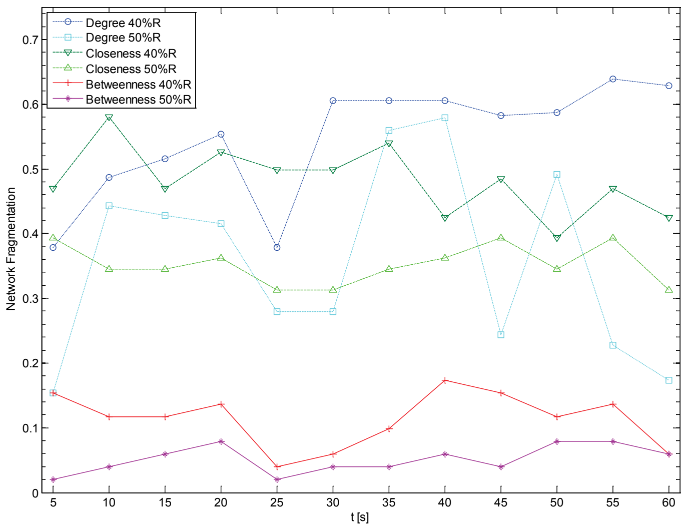


Figure 4: Time evolution of the network fragmentation for the three centrality metrics and for 40 and 50% selected routers.

Table 1: Summary of the resulting network fragmentation and the number of links per connected node values.

Centrality	**%R**	**Network Fragmentation**			**Links per connected node**		
		Mean	SD	Max	Mean	SD	Max
Degree	40	0.547	0.090	0.639	7.405	0.839	8.635
	50	0.356	0.148	0.579	7.226	0.424	8.158
Closeness	40	0.481	0.053	0.580	6.511	0.371	7.205
	50	0.352	0.030	0.393	6.796	0.362	7.395
Betweenness	40	0.113	0.042	0.173	5.430	0.212	5.691
	50	0.051	0.021	0.079	6.123	0.299	6.573

behavior since its standard deviation is the least among the three options. Another metric that we use to compare the three different centralities is the average number of links which remain active after router selection per connected node. Again, betweenness centrality exhibits better performance since on average it requires lesser number of links for each node that remains connected. The maximum and the standard deviation of this metric are also the least among the analyzed options. Other centrality metrics like hub, authority, and bridging have also been evaluated and for all the cases the betweenness centrality exhibits better outcomes. Based on this, we can conclude that by far the betweenness centrality is the metric that better identifies the subset of nodes that should be considered as routers.

4.3. Distributed implementation

In this work, we are dealing with a totally dynamic network, in which the links among mesh stations continuously change due to their movements and channel conditions. This is done in an autonomous and distributed way through the mesh peering management protocol. Accordingly, our topology control algorithm must be implemented in a fully distributed manner. Mesh stations must be able to decide which nodes act as routers based only on their local information, and without the need of any central controller. In the previous section we determined that betweenness centrality is the best choice for our purpose. Therefore, we must use the egocentric version of betweenness centrality [38]. This version requires only the first order (one-hop) neighborhood information of each node instead of the complete network topology. Moreover, this information is available in each mesh station since they keep an updated record of their peer links.

An efficient algorithm to compute the egocentric betweenness is presented in [39]. Each node represents its ego network (one-hop neighbors) by means of the adjacency matrix **A**. The elements of this matrix are

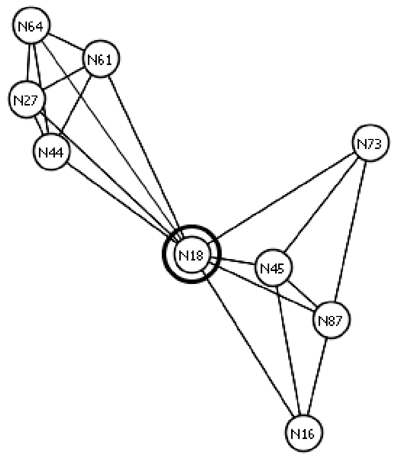


Figure 5: Egocentric network structure from the perspective of the node N_{18}.

given by:

$$A_{ij} = \begin{cases} 1 & \text{if there is a peer link between nodes } i \text{ and } j \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

As an example, Fig. 5 shows the egocentric network structure from the perspective of the node N_{18} at a given time instant.

The adjacency matrix for this ego network is given by:

	N_{18}	N_{16}	N_{27}	N_{44}	N_{45}	N_{61}	N_{64}	N_{73}	N_{87}
N_{18}	0	1	1	1	1	1	1	1	1
N_{16}	1	0	0	0	1	0	0	0	1
N_{27}	1	0	0	1	0	1	1	0	0
N_{44}	1	0	1	0	0	1	1	0	0
N_{45}	1	1	0	0	0	0	0	1	1
N_{61}	1	0	1	1	0	0	1	0	0
N_{64}	1	0	1	1	0	1	0	0	0
N_{73}	1	0	0	0	1	0	0	0	1
N_{87}	1	1	0	0	1	0	0	1	0

Observe in Fig. 5 that all the shortest paths between non-adjacent stations that pass through the ego (the station who is calculating its egocentric betweenness) have a length of two hops. Therefore, when $i \neq j$, and being $\mathbf{1}$ the matrix with all its elements equal to 1, the expression $\mathbf{A}^2[\mathbf{1} - \mathbf{A}]_{i,j}$ gives the number of shortest paths with length 2 that links stations i and j. Thus, the egocentric betweenness is the sum of the reciprocal of the resulting non-cero elements [39].

Note that the peering management protocol guarantees that all the links are bidirectional, and then the matrices are symmetric and only the elements above the main diagonal must be taken into account. For the node N_{18} this results in:

	N_{18}	N_{16}	N_{27}	N_{44}	N_{45}	N_{61}	N_{64}	N_{73}	N_{87}
N_{18}	*	0	0	0	0	0	0	0	0
N_{16}	*	*	1	1	0	1	1	3	0
N_{27}	*	*	*	0	1	0	0	1	1
N_{44}	*	*	*	*	1	0	0	1	1
N_{45}	*	*	*	*	*	1	1	0	0
N_{61}	*	*	*	*	*	*	0	1	1
N_{64}	*	*	*	*	*	*	*	1	1
N_{73}	*	*	*	*	*	*	*	*	0
N_{87}	*	*	*	*	*	*	*	*	*

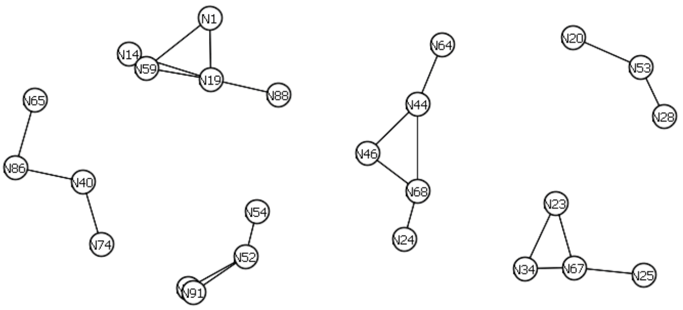


Figure 6: Routers selection using 1-hop egocentric betweenness.

Therefore, the egocentric betweenness for the node N_{18} is equal to 16.333. This way, whit just local information, every node is able to calculate its egocentric betweenness value. This value should be updated every time a station establishes a new peer link or it closes a previously established one. In a practical implementation, the nodes will refresh this value at predetermined time intervals.

Once selected a distributed way to obtain the centrality values, we also need a distributed way to select the nodes that will act as routers. Note that in this case there is not a central control with all the information needed to select the nodes with higher centralities. Our proposal here is that every node selects as router the node (or nodes) with higher egocentric betweenness in its neighborhood. Note that with this way of proceeding, the same node can be selected as the router for different neighborhoods. This way, the total number of routers is reduced, and this number is determined by the procedure itself. Of course, this simple method guaranties that every station is connected to a router, but it does not assure that all the routers are interconnected between them. Therefore, some further actions will be needed. On the other hand, the main advantage is that it is a very simple and implementable method.

With this background, the procedure to select the mesh stations that will develop routing tasks can be summarized as follows: first, each station calculates and broadcasts its egocentric betweenness centrality value, and second, in its respective ego network, each station selects the neighbor (or neighbors) with the highest betweenness to be used as routers. The details and practical implementation of the protocol are exposed in Section 4.4.

In the following we present the evaluation of this topology control algorithm for the network dataset previously described. We analyze different alternatives to create a connected dominating set in a distributed way. In first place, we consider that each station computes its egocentric betweenness with the first-order (one-hop) neighborhood information and selects as router just the one with the highest egocentric betweenness. As expected due to the distributed router selection, instead of a connected backbone, this procedure generates a set of isolated clusters that have no common routers among them. Fig. 6 presents the worst case obtained in the simulations, that is, the time instant with the higher number of isolated clusters. For this specific case, 25 percent of stations have been selected as routers. Although this is the worst case, it is worth to mention that the 8.33 percent of the network snapshots analyzed construct a fully connected backbone with this most simple procedure, and with 30 percent of stations selected as routers on average.

To improve the connectivity among the selected routers, in the following some different approaches are proposed and evaluated.

4.3.1. K-hops egocentric betweenness centrality

The first possibility is to consider a higher number of hops when computing the egocentric centrality. For instance, we can assess the case in which the stations compute it taking into consideration the two-hop neighborhood information. Again, only the most central station is selected as router in every neighborhood. Fig. 7 shows a significant connectivity improvement for the same network snapshot shown in Fig. 6. Nevertheless, there are still two unconnected clusters. In this case, 31 percent of stations have been selected as routers.

The theoretical limit for this approximation is the case in which the stations compute the sociocentric instead of the egocentric betweenness centrality. Namely, each station needs to know the complete network

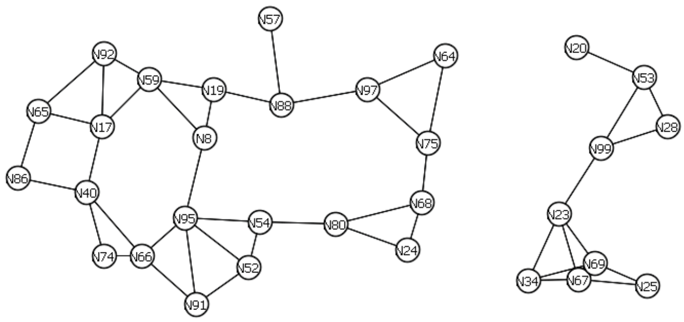


Figure 7: Routers selection using 2-hop egocentric betweenness.

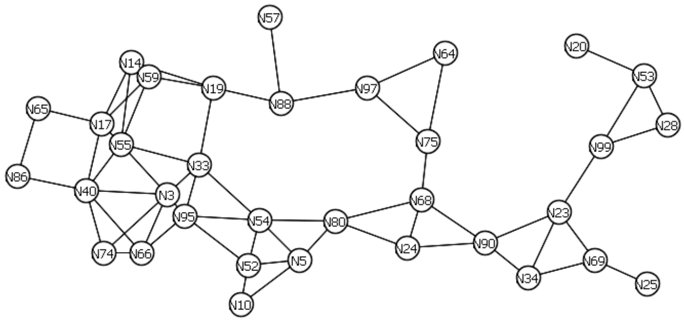


Figure 8: Routers selection using the sociocentric betweenness.

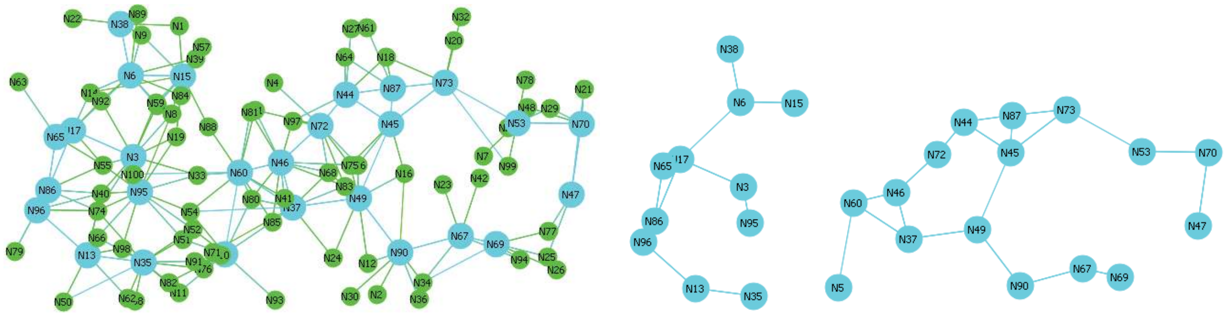
topology information, which is not a practical consideration for dynamic WMNs. Fig. 8 shows that this procedure creates a complete backbone with 34 percent of stations selected as routers. However this total connectivity among all the selected routers is not achieved for all the network snapshots that have been evaluated. Then, this procedure does not guarantee the creation of a CDS.

4.3.2. Probe packets

In the following, we describe another possible solution which guaranties that all the selected routers create a single connected backbone at the expense of increasing the signaling overhead. After a first router selection round, based on egocentric betweenness, the non-router stations virtually linked to at least two routers verify the connectivity between them. If there is no path between any two routers connected to a non-router station, that station must be marked as router. To this end, the station transmits a probe message through one (and only one) of its links. This special message must be retransmitted by the routers and, if connectivity exists, it will be received by the sending station through the other links. If the message is not received before a predetermined time, the station marks itself as router and communicates this decision to its neighborhood. To illustrate this, Fig. 9(a) shows a different network snapshot. The cyan bigger nodes represent the stations that have been selected as routers based on one-hop egocentric betweenness and a selection with just one router per station. As it can be seen, selected routers forms two components (Fig. 9(b)) that can be linked through either of stations N_{88}, N_{33}, N_{54}, N_{52}, N_{51}, N_{91}, N_{82} and N_{11}. These nodes will be marked as routers according to the proposed procedure.

4.3.3. Higher number of routers per neighborhood

We have evaluated another procedure in which the stations, instead of selecting only the most central node, mark as routers the two nodes with the higher one-hop ego betweenness values in each neighborhood. Fig. 10 shows the resultant backbone for the same mesh network dataset. In this case, 43 percent of stations have been selected as routers. This process generates a fully connected backbone for the 83.33 percent of the network snapshots tested. The increase in the number of redundant routers can be exploited by load balancing techniques, and it is also valuable from a network resilience perspective. Due to the fact that this approach is the one with a lower amount of overload, we have chosen it to propose a practical implementation



(a) Complete topology (b) Selected routers

Figure 9: Connectivity achieved with the probe packets approach.

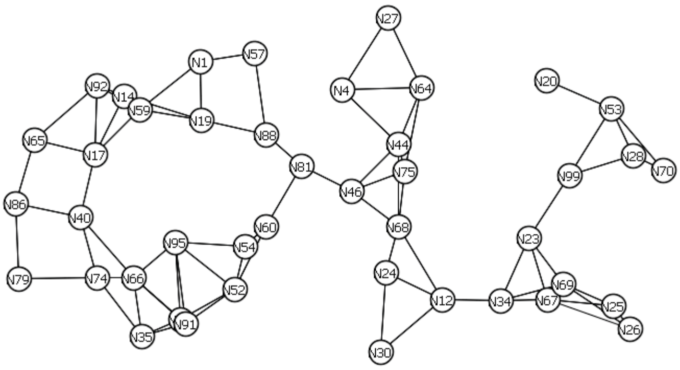


Figure 10: Resulting backbone selecting two routers per neighborhood.

in the next section. Obviously, incrementing the number of routers selected by each station will ensure a fully complete backbone for all the scenarios at the expense of a higher router redundancy. As a future line of work we will study the minimum number of routers per neighborhood needed to guaranty a desired connectivity (expressed as a percentage of the total connectivity).

4.4. Practical implementation

Energy efficiency and fair energy consumption are consider for the practical implementation of the protocol. It is carried out in three steps:

- Step 1: Every node broadcast its own neighbors list by means of a Neighborhood Advertising Frame (NAF). This is a special management frame where every neighbor is identified by its MAC address.

- Step 2: Every node receives the NAFs from its neighbors. With this information, they are able to compute their own egocentric value. Once computed, they broadcast that value in the Egocentric Advertising Frame (EAF). In order to allow fair energy consumption in the network, the nodes remaining energy is also included in the frame.

- Step 3: Every node receives the egocentric value of all of its neighbors and selects the one with the higher value as its router. If different options are available (i.e., different neighbors with the same centrality value), the node with the higher value of remaining energy is chosen. A multi-metric protocol, assigning different weights to the centrality and energy remaining values, is one of the targets of a future work. The decision is communicated to the new router with the Router Selection Frame (RSF). When the new router receives the RSF, it switches to the router mode (or router state) and activates its routing functionality. As said in the previous section, in order to guarantee obtaining a connected topology, a bigger number of routers can be chosen by every node.

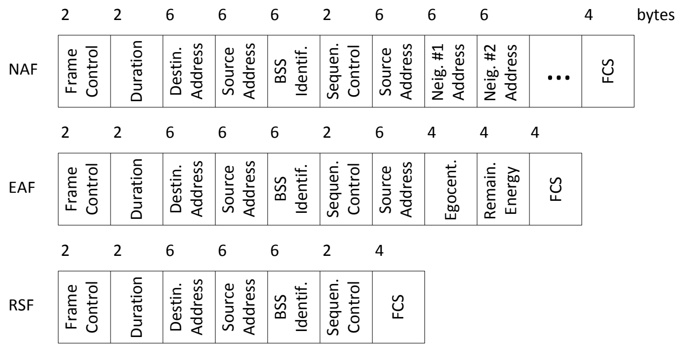


Figure 11: Frames format.

Due to the network variability, this three steps procedure must be repeated every certain interval time, called the Topology Updating Time (TUT). Besides, the router state must be seen as a soft state. That is, to keep the routing functionality activated, a node must receive at least a RSF every TUT seconds. Otherwise the node understands that its routing functionality is not needed anymore and switches it off.

Fig. 11 shows the specific frame format for the new three management frames needed by this protocol. The NAF and EAF frames can be included into the mesh-specific management frames. They are broadcast frames and therefore they do not need to be acknowledged by the receiver. The RSF frame is also a mesh-specific management frame but in this case it is a unicast frame and therefore it must be acknowledged by the receiver. The three frames can be identified by the sub-type code in the Frame Control field.

Calling N_T the total number of nodes in the network and N_R the number of routers that every node selects, the total number of bytes transmitted by this protocol procedure is:

$$N_T\left[\text{size}\left(NAF\right)+\text{size}\left(EAF\right)+N_R\left[\text{size}\left(RSF\right)+\text{size}\left(ACK\right)\right]\right] \quad \text{bytes} \tag{6}$$

where size(X) stands for the size in bytes of the frame X.

As it can be seen in the Fig. 11, the size of the NAF depends on the number of neighbors. Calling N_N to the average value of this number, the average size of these frames is $34 + 6N_N$ bytes. The size of EAF and RSF frames are 42 and 28 bytes respectively. Substituting these values in Eq. 6 we obtain:

$$N_T\left(34+6N_N+42+42N_R\right)=N_T\left(76+6N_N+42N_R\right) \quad \text{bytes} \tag{7}$$

This amount of bytes is sent by the protocol every TUT seconds. Therefore, the bit rate added by the topology control protocol to the network, R_{TC}, is:

$$R_{TC}=\frac{8N_T\left(76+6N_N+42N_R\right)}{TUT} \quad \text{bps} \tag{8}$$

Obviously, R_{TC} grows linearly with N_T, N_N, N_R, and $(1/TUT)$. These dependencies are shown in Fig. 12 for several values of the involved parameters. It is important to remark that the lifetime of a network topology must be greater than or at least equal to the lifetime of a routing path. In the figure two typical values have been considered (one of them, 5.12 s, is the standard default value). The resulting protocol bit rate will affect the node energy consumption and the network load, and will be taken into account later in the performance evaluation.

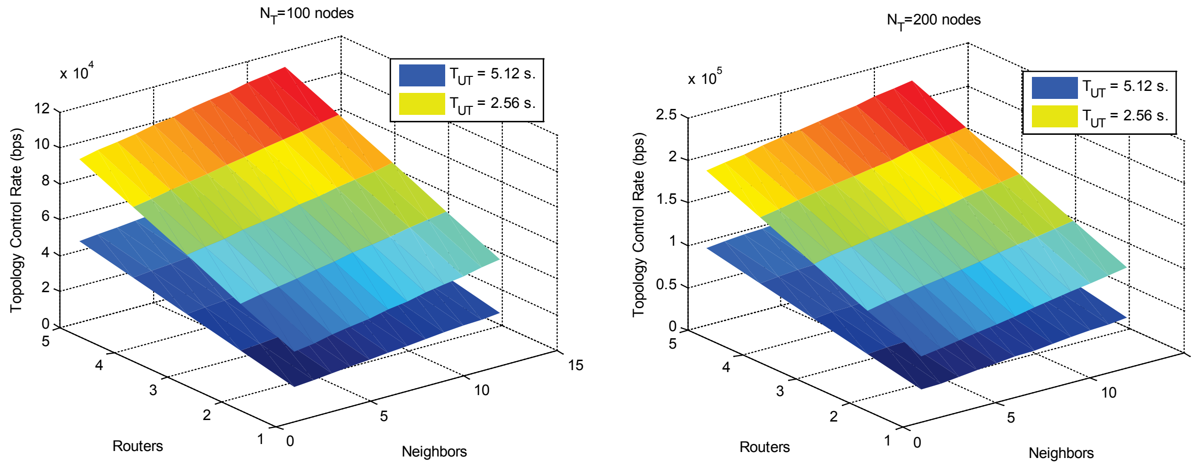
5. Performance evaluation

In this section, extensive simulations have been carried out to evaluate the performance of WMNs with the proposed centrality based topology control mechanism. For the evaluation, we consider the following metrics and parameters:

– The rate of routing management messages.

– The total number of forwardings per successfully received packet.

– The network efficiency in terms of packet delivery ratio.



(a) 100-nodes mesh network

(b) 200-nodes mesh network

Figure 12: Topology control protocol bit rate for different N_T and TUT values.

– The energy consumed on a node by node basis.

– The end-to-end packet delay.

– The transmission bit-rate savings taking into account the overload added by the topology control protocol.

We take into account the two routing modes of the hybrid wireless mesh protocol (HWMP). In the reactive on-demand mode, a source mesh station starts a path discovery procedure only when it has a data packet to send to any destination. This operation mode is more suitable for peer to peer communication inside the mesh network. On the other hand, proactive mode is more appropriate when a single or a few mesh stations are configured as gateways for external communications and therefore they are the targets of most of data connections. In this mode, a single or few mesh stations are configured to be path tree roots, and they periodically initiate path selection procedures.

All simulations are done with the ns-3 network simulator. To model the mesh network, we have used one of the network snapshots described in Section 4.2. It consists of 100 IEEE 802.11s-based mesh stations randomly distributed in a 1040 x 520 m rectangular area. For all the experiments, we compare the performance of the mesh network when all the station are configured as routers with the case that only 40 most central nodes are selected as routers (from now they will be called the All R and Top 40R topologies for convenience). All the simulations are 500 s long and we have carried out 100 statistically independent runs for every experiment. The average of these runs with 95% confidence interval is shown for all the results. In the following, we present and discuss the simulation results for different mesh network conditions and configurations.

5.1. Reactive mode. Impact of traffic load

The aim of this part is to evaluate the impact of the traffic load on the network performance when peer-to-peer communications are more relevant and then, mesh stations are operating in the reactive mode. We vary the number of simultaneously active UDP data flows from 5 to 40. The source and the destination nodes are randomly selected for each independent run and for each flow. All the UDP flows are configured with an exponential distribution for the interarrival time with mean value of 20 ms. For the packet length we use an exponential distribution with mean of 512 bytes that has been truncated to a minimum of 12 bytes (header size), and a maximum of 1500 bytes. Mesh stations are configured with the default value of 5.12 s for the lifetime of reactive routing information.

First of all, Fig. 13 shows the evolution of the mean rate of routing management messages as a function of the number of data flows. Evidently, since mesh stations are using the on-demand path selection mode,

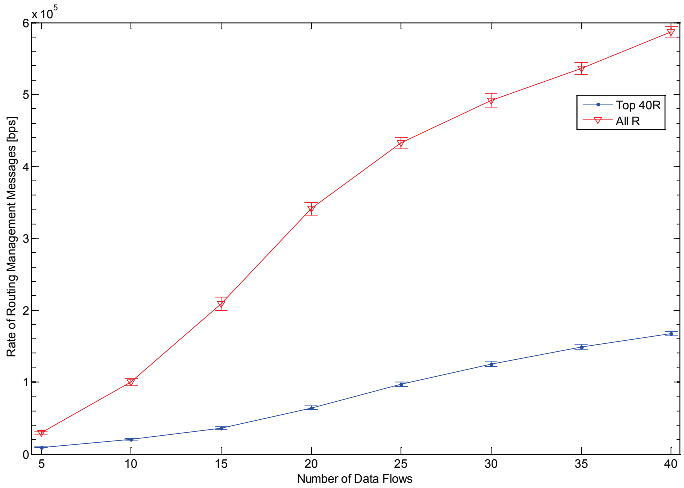


Figure 13: Rate of routing management messages as a function of the number of active flows.

a greater number of sources demand a greater number of path selection procedures. Therefore, the rate of routing management messages increases when the number of data flows increases. As expected because of the lower number of mesh stations with path selection functionality, a significant reduction occurs (76.14% on average) when the mesh network operates with the topology control mechanism. Observe that this reduction directly impacts on the total energy consumed by the network.

The next parameter that we consider is the total number of unicast data packets forwarded by all the stations in the network (Fig. 14). We can clearly identify two different trends of this parameter. For low traffic loads, up to 15 concurrent flows for the network without topology control and up to 20 flows when topology control is applied, the data forwardings growth linearly with the number of flows. Beyond these values the network starts to exhibit a saturated behavior and then the growth becomes less significant. This is also verified when we study the total number of successfully received packets (Fig. 15). This figure confirms that the network is saturated beyond 15 data flows for the All R topology and beyond 20 flows for the Top 40R case. Over these values, although there are more sources generating data packets, there is practically no increase in the number of successfully received data packets. The topology control mechanism produces a savings of the total data forwardings of 32.77% on the average. This is another important reduction of the total amount of energy consumed by the network. It is important to remark that this is not in detriment of the number of received packets. In fact, when the topology control is applied, the stations get on average 2.3% more data packets than without topology control. Precisely, to better analyze this relation we compute the total number of data forwardings per successfully received packet. Fig. 16 shows the evolution of this measure and it can be observed that for all the cases the network with topology control is more efficient. Namely, the number of forwardings is reduced a 33.43% on average. We also verify that an increase of traffic sources causes more collisions and therefore a greater number of retransmissions and forwardings are required to deliver each data packet. This growing trend continues until the network reaches the saturated state.

The next parameter that has been evaluated is the network efficiency in terms of packet delivery ratio. Fig. 17 shows that the network with the topology control becomes more efficient when the number of sources is equal or greater than 20. This is because the impact of the signaling required for path selection is not so important when a few number of stations are generating data traffic. Nevertheless, in more practical situations, the routing overhead is more relevant and then the advantage of reducing the number of stations involved in routing is evident. Within the interval of this experiment, although this is not our main objective, the average improvement of the network efficiency is about 3.7% when the topology control is applied.

This small improvement in the efficiency comes together with a significant reduction of the global energy consumption inside the network, which is in fact the main goal of this proposal. To evaluate this, we consider the total amount of energy dissipated by each node for all the transmissions and receptions during

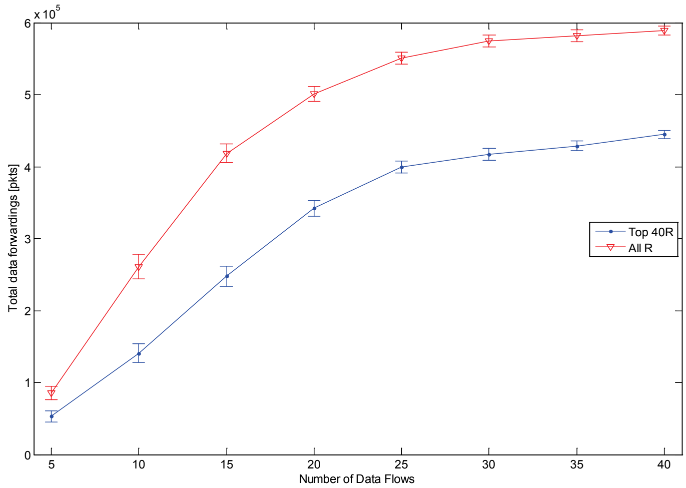


Figure 14: Total data forwarding as a function of the number of active flows.

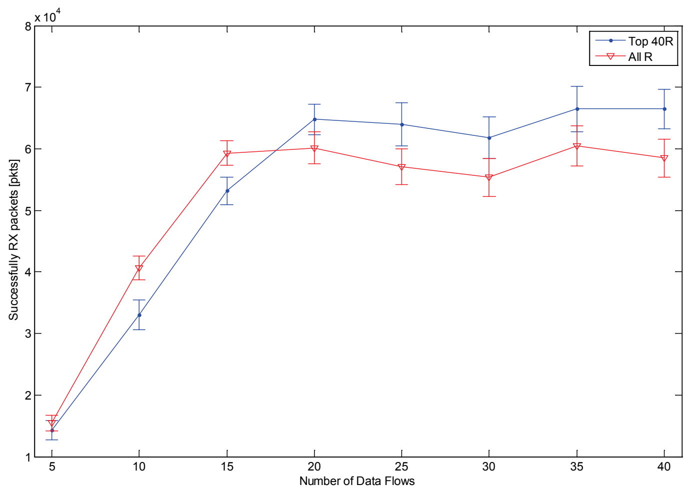


Figure 15: Total number of successfully received data packets.

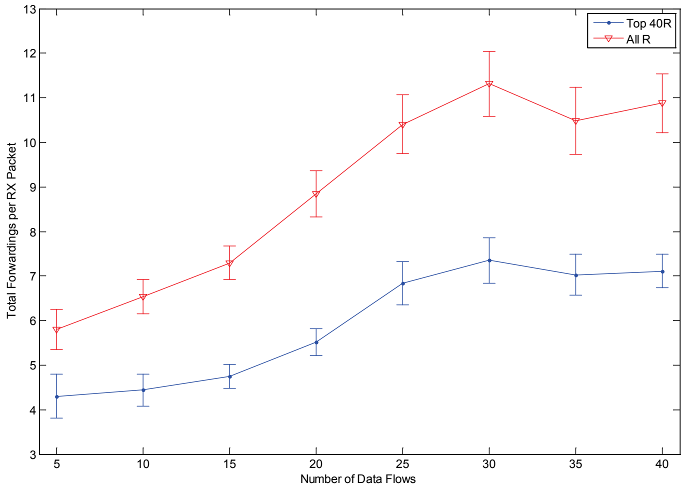


Figure 16: Total data forwardings per successfully received packet.

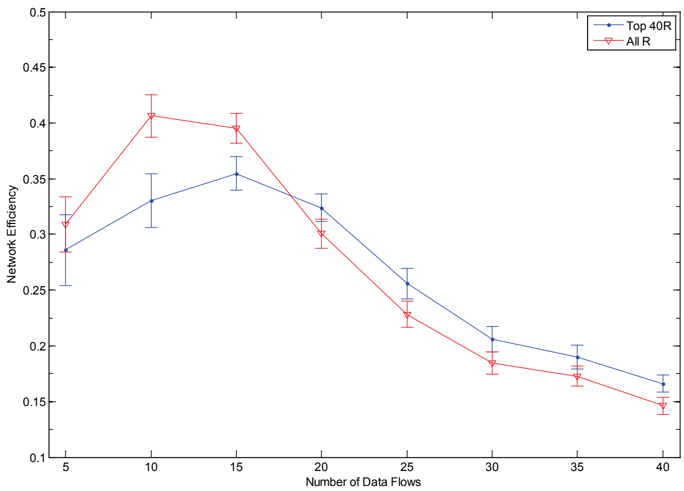


Figure 17: Network efficiency in terms of packet delivery ratio as a function of the traffic load.

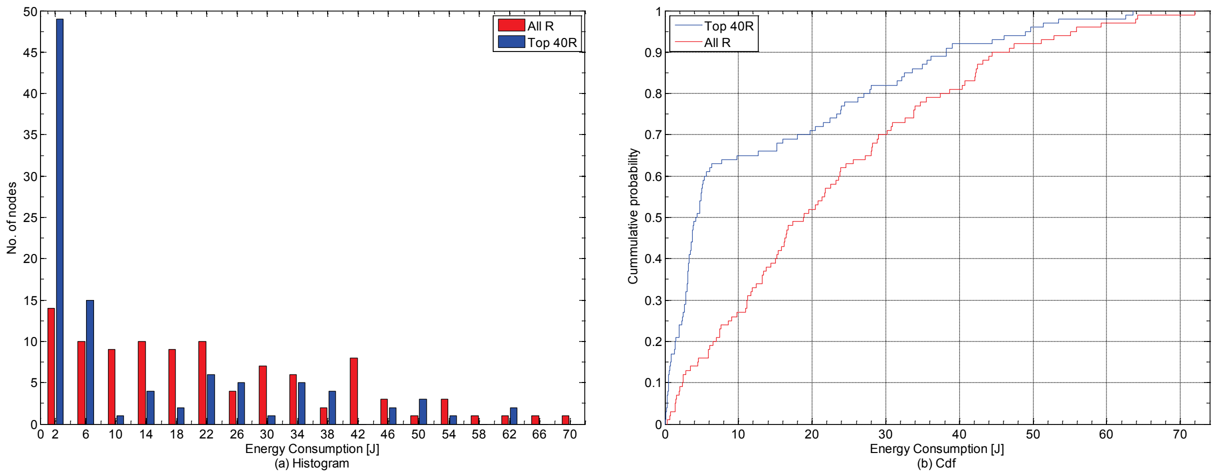


Figure 18: Energy consumption statistics for the 15-flows reactive mode case.

the entire simulation time. The energy model presented in [40] has been considered for all the reported cases. Fig. 18(a) shows the histogram of the energy consumed by the nodes for the 15-active flows case (which corresponds to a non-saturated situation). As can be observed, the maximum energy dissipated by a node has been reduced from 72 to 63.6 J when topology control is applied. The total energy consumed by the network has been reduced around a 41% (from 2247.4 to 1324.4 J). Besides, the cumulative distribution function of the energy consumption (Fig. 18(b)) shows also the better behavior achieved with the topology control. For instance, it can be observed that around 27% of nodes dissipate less than 10 J for the All R case, and that this figure is increased to 65% for the Top 40R case.

Finally, Fig. 19 shows the cumulative distribution function of data packets end-to-end delay. As expected, a greater number of data sources increases the contention for channel access and also the path selection messages overhead. This implies that path selection requests require more time to be resolved and then the end-to-end delay of data packets grows with the number of traffic sources. For all the cases the delay whit the Top 40R is lower than with the All R topology. The difference is more significant for low traffic loads (Figs. 19a–b) and is reduced when the network is saturated (Figs. 19c–f).

5.2. Reactive mode. Impact of reactive routing information lifetime

The aim of this set of experiments is to analyze how dynamic a network could be. Mesh stations continue working in reactive mode and 20 simultaneous peer-to-peer data flows are established between randomly selected sources and destinations. A more dynamic and variable network requires a more frequent activation of the mesh path selection mechanism in order to keep the paths updated. As stated in the IEEE 802.11-2012 standard [32], we can control the time for which mesh stations consider the forwarding information to be valid by means of the *dot11MeshHWMPactivePathTimeout* control variable. Therefore, in this section we evaluate the performance of the network when this lifetime varies from 5.12 to 1 second. The evolution of the mean rate of routing management messages is shown in Fig. 20. Of course we can observe that, although the traffic load is equivalent for all the cases, the rate of path selection related messages grows as lifetime of reactive routing information decreases. As expected, topology control produces an important reduction of around 83.43% because of the reduced number of mesh stations involved in routing. This directly corresponds to the same significantly energy consumption savings due to the lower amount of routing messages exchanged by the mesh stations. We verify that the limitation in the number of routers has no negative impact in the total number of successfully received packets. In fact, as can be seen in Fig. 21, topology control produces an average increase of around 8.75% in the number of successfully received packets with regard to the All R configuration. The decreasing behavior is explained as follows: lower duration of established paths implies a greater number of path discovery messages which in turn increases the collisions and the contention inside the network. Thus, data packets have less transmissions opportunities and then there are less successfully received packets.

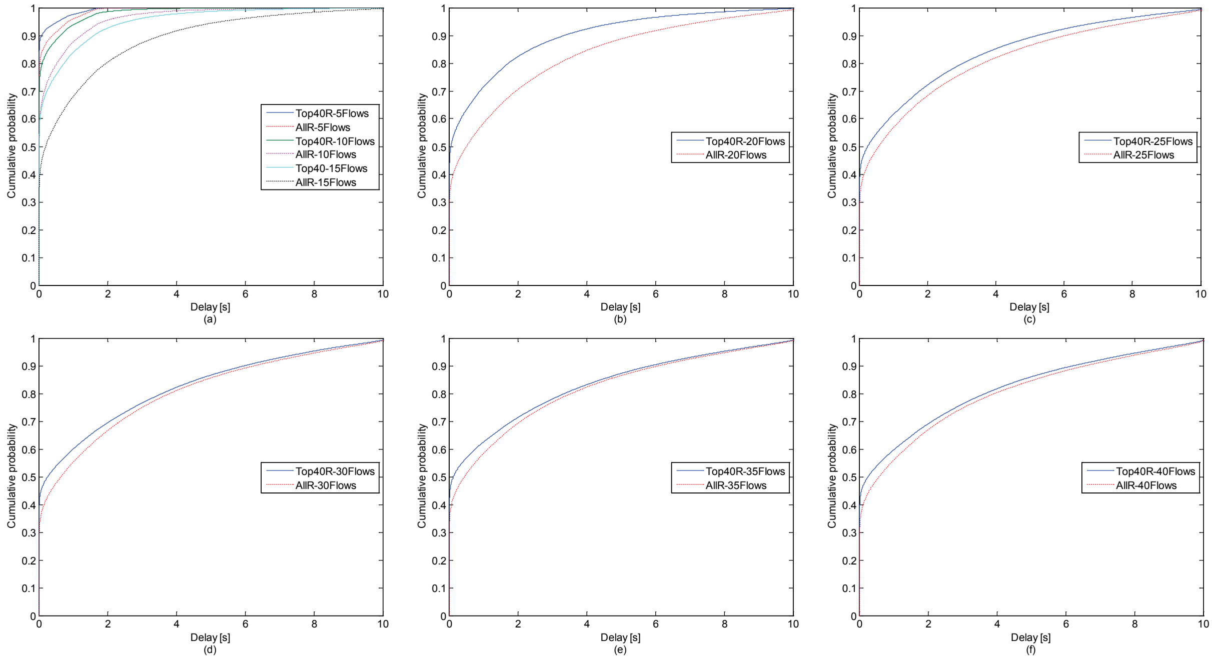


Figure 19: Cumulative distribution function of data packets end-to-end delay.

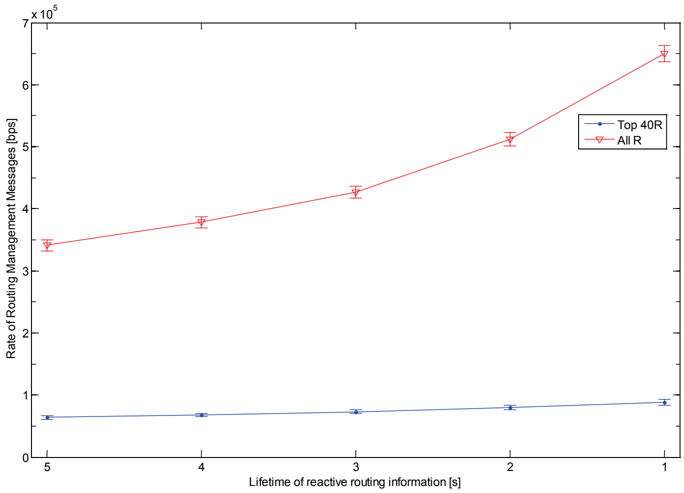


Figure 20: Rate of routing management messages as a function of the reactive path lifetime.

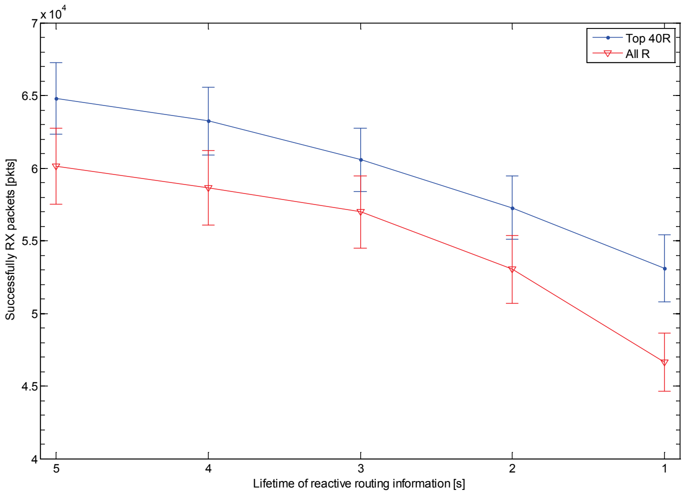


Figure 21: Total number of successfully received packets as a function of reactive path lifetime.

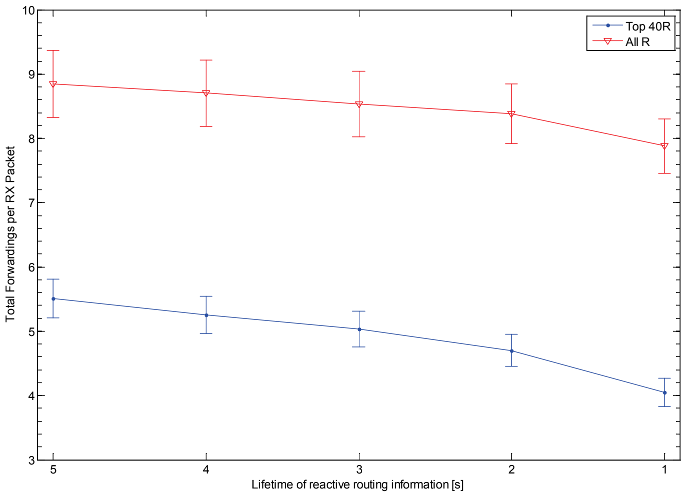


Figure 22: Total data forwardings per successfully received packet as a function of reactive path lifetime.

This behavior is also confirmed when we analyze the total number of data forwardings per successfully received packet (Fig. 22). We can observe that, although the traffic load remains equivalent for all the cases and even the increasing number of collisions requires more data packet retransmissions, the high network contention caused by the routing messages overhead reduces the transmission opportunities of data packets and then the number of forwardings decreases instead of remain constant or grow due to collisions. Nevertheless, it is important to remark that the topology control contributes with an average reduction in the number of data forwardings of about 42.19%. This represents again a considerably energy consumption savings.

The network efficiency in terms of packet delivery ratio also exhibits a decreasing tendency when the lifetime or reactive routing information decreases (Fig. 23). As previously said, this is due to the big amount of routing management messages overhead required for a faster update of the established paths. An important observation is that, for a given network efficiency value, the topology control allows almost twice routing information updates compared with the network operating with all routers. For example, the efficiency reached by the All R network with the default active path timeout value of 5.12 s could be achieved with the Top 40R topology even if the path updates are done approximately every 2.7 s. In summary, topology control also improves the scalability when more dynamism and variability is required.

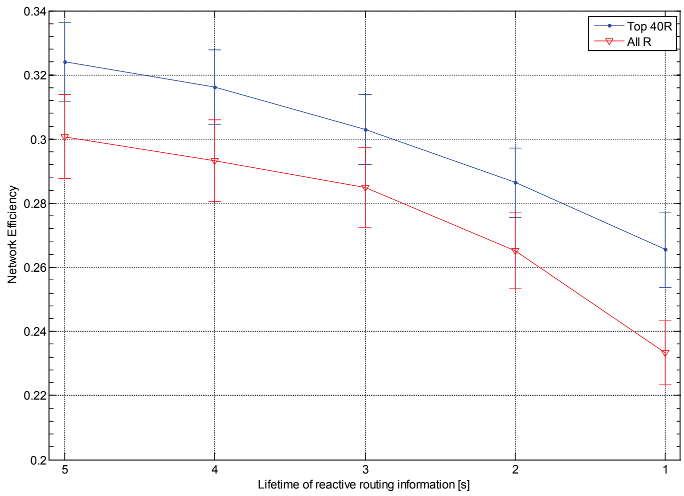


Figure 23: Network efficiency as a function of reactive path lifetime.

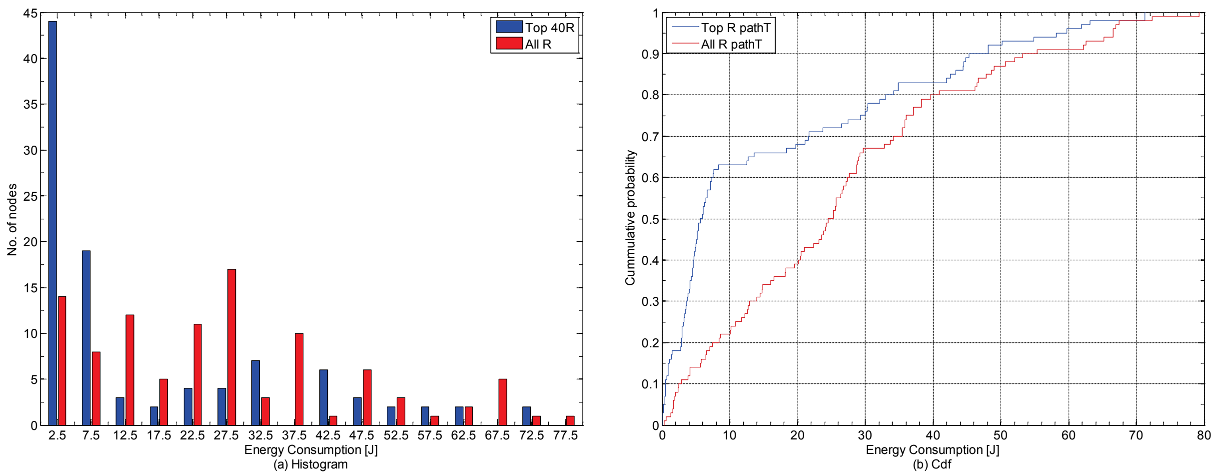


Figure 24: Energy consumption statistics for the nodes working with the reactive mode, 20 peer-to -peer data flows and reactive routing information lifetime of 3 s.

With the same criteria of the previous section, Fig. 24 shows the energy consumption statistics for the network configured with a reactive path lifetime of 3 s. The histogram (Fig. 24(a)) shows that the maximum energy dissipated by a node in the network reduces from 79.3 to 71.3 J when topology control is applied. The total energy dissipated in the network reduces around a 38.44% (From 2655.8 to 1635 J). The cdf (Fig. 24(b)) shows that while only 23% of nodes consumes less than 10 J in the All R configuration, this percentage increases to 67 in the Top 40R network.

The data packets end-to-end delay analysis (Fig. 25) reveals that the delay decreases when the path updates are more frequents. This is due to the fact that the network reacts earlier to link failures and to paths that should no longer be valid for data forwarding. But it is also because there is a lesser number of data packets forwarded by intermediate stations and a lesser number of successfully received packets. When the level of routing overhead increases, most of the packets that finally arrives to the destination are those that traverse a few number of intermediate nodes. Therefore, those packets arrives in shorter time. On the other hand, it is important to remark that the application of topology control improves the performance of the network regarding end-to-end delay for all the simulation cases. Even the worst case results for the network with topology control (Lifetime = 5.12 s) are better than the results for network with all routers

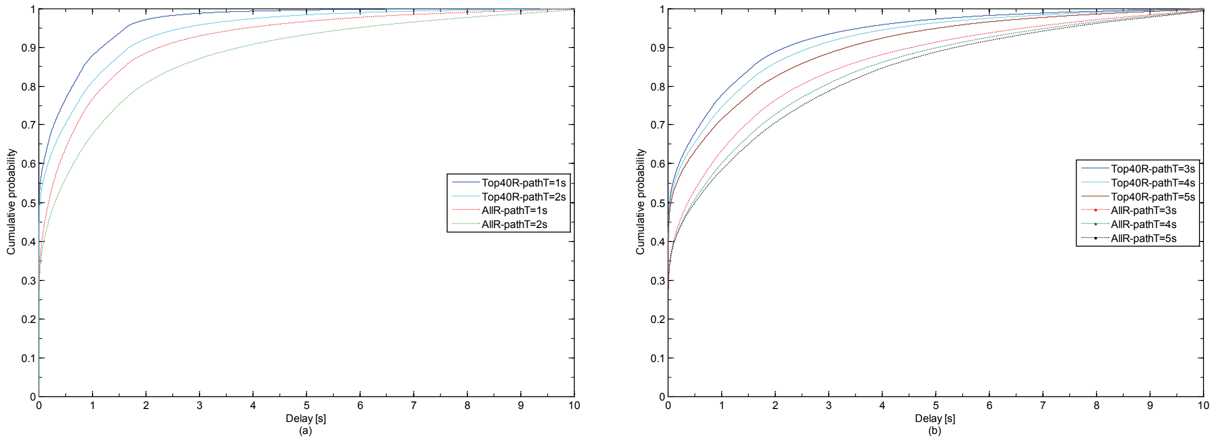


Figure 25: Cumulative distribution function of data packets end-to-end delay for different reactive path lifetimes.

and lifetime greater than or equal to 2 s. The reason for this is that the paths are established faster when a lesser number of stations are involved in the path discovery procedure.

5.3. Proactive mode. Impact of proactive routing information lifetime

Proactive mode of HWMP protocol is more suitable when the target of data communications is mainly outside of the mesh basic service set. The most common use cases are mesh stations accessing to Internet or the internetworking with other network technologies. In these cases, one or more mesh stations are configured to be the root mesh station(s) and they play the role of gateways. Each root periodically sends path request (PREQ) messages in order to build a proactive tree, and thus, create paths from all the mesh stations to the root.

As in the previous section, we begin evaluating how fast proactive data forwarding paths could be updated. A faster route update is required by more dynamic networks in which stations continuously vary their established peer links. Obviously, this implies a greater path selection management messages overhead. As stated in the IEEE 802.11-2012 standard [32], the lifetime of the proactive routing information is configured by the *dot11MeshHWMPactivePathToRootTimeout* control variable. This variable should be greater than *dot11MeshHWMProotInterval* which in turn controls the frequency of proactive PREQ frames sent by the root. For the evaluation we configure one station as the root and then we vary the values of these pair of variables from 20.48 to 0.64 s for the active path to root timeout and from 8.192 to 0.256 s for the root interval. As it can be seen, we maintain constant the default ratio between these variables in all the reported cases. For each independent run, the traffic load consists of 25 simultaneously active data flows, five uploads from randomly selected mesh stations to the root and 20 downloads from the root to randomly selected stations. The expected growth of routing management messages rate as the lifetime of routing information decreases is verified in Fig. 26. We also confirm that proactive routing overhead is greater than the reactive one. For instance, when the default routing lifetime values are used and for the 25 flows case, the routing management rate increases from around 432 Kbps (Fig. 13) to 1.1 Mbps for the All R configuration, and from around 97 Kbps to 190 Kbps for the network with topology control. The application of topology control produces an average reduction of around 78.87% in the routing management messages overhead.

The increase of routing overhead due to faster path updates causes more collisions and then data packets need to be retransmitted a greater number of times. This is verified in Fig. 27 which shows the evolution of total data forwardings per successfully received packet as a function of routing information lifetime. It can be seen that, although the traffic load remains equivalent for all the cases, the average number of forwandings required to successfully transmit each data packet increases as the lifetime decreases. The average reduction achieved with the application of topology control for this parameter is around 51.75%.

The growing routing overhead makes increasingly difficult to successfully transmit data packets and then the network efficiency gradually reduces (Fig. 28). As previously said, although this is not the main objective

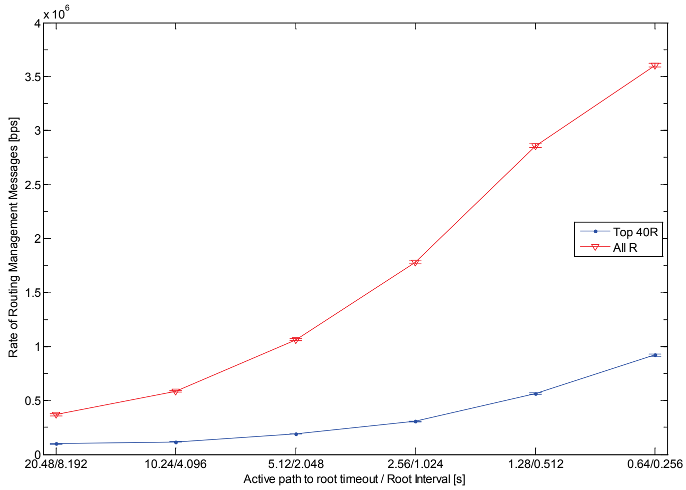


Figure 26: Rate of proactive routing management messages for different update times.

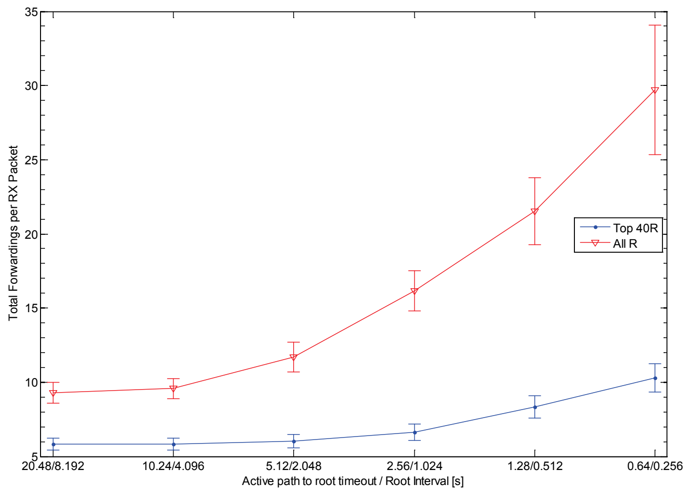


Figure 27: Total data forwardings per successfully received packet for different proactive path lifetimes.

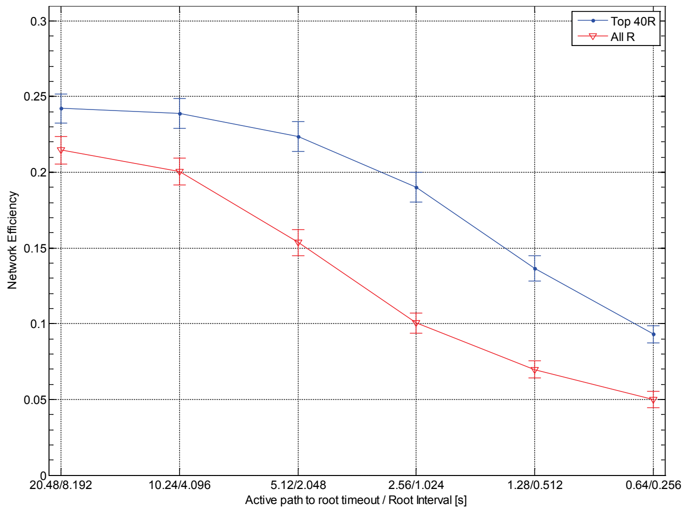


Figure 28: Network efficiency for different proactive path lifetimes.

of the topology control mechanism, the network efficiency significantly improves when only the most central stations are involved in the path selection algorithm. The average improvement achieved in the presented range is about 58.17%. This improvement is much more significant than in the reactive mode case in which the path selection overhead level is lower. Fig. 28 also shows that, for a given network efficiency, the mesh network with topology control supports almost four times faster path selection updates.

The energy consumption statistics for all the nodes in the network, including the root mesh station configured with the default values for the routing information lifetime (i.e. the active path to root is 5.12 s and the root interval is 2.048 s) are shown in Fig. 29. As expected, the station configured as root dissipates significantly more energy than non-root stations since all the traffic (data and routing) starts and ends in that node. For the root station, the energy dissipation reduction achieved with the topology control is around 14.79% (from 775.1 to 660.5 J). The total energy dissipated in the network reduces around 30.4% (from 3233.1 to 2250.2 J). These higher energy dissipation values also confirm the greater overhead of the proactive mode regarding to the reactive one. The cdf of Fig. 29(b) shows that 52% of nodes dissipates less than 20 J for the All R configuration and this value increases to 73% in the Top 40R network. On the other hand, since the root is a special type of station, Fig. 30 shows the energy consumption statistics for only non-root stations. The histogram and the cdf in Fig. 30 identifies a drawback of the proposed topology control mechanism: three nodes selected as routers are overloaded regarding the All R configuration. This fact also confirms that the remaining energy of nodes must be included in the router selection process as stated in Section 4.4.

The end-to-end delay cdf (Fig. 31) also confirms that each successfully received data packet had to be retransmitted a greater number of times. It can be observed that faster proactive path updates increases the data packet delays. This behavior holds for both network configurations, with or without topology control. Nevertheless, delays are smaller when topology control is applied due to the lower channel access contention.

5.4. Proactive mode with more than one root station

A way to improve the network efficiency is to distribute the root or gateway functionality to a greater number of mesh stations. This section evaluates the effect of adding one or two roots to the previous configuration. For the reported simulations, the proactive path lifetime remains constant in its default values ($activePathToRootTimeout = 5.12$ s and $rootInterval = 2.048$ s). In the first set of experiments, the traffic load also remains constant (for each independent run there are 25 continuously active data flows: five uploads from randomly selected mesh stations to the roots and 20 downloads from the roots to randomly selected stations). Fig. 32(a) shows the rate of routing management messages as a function of the number of

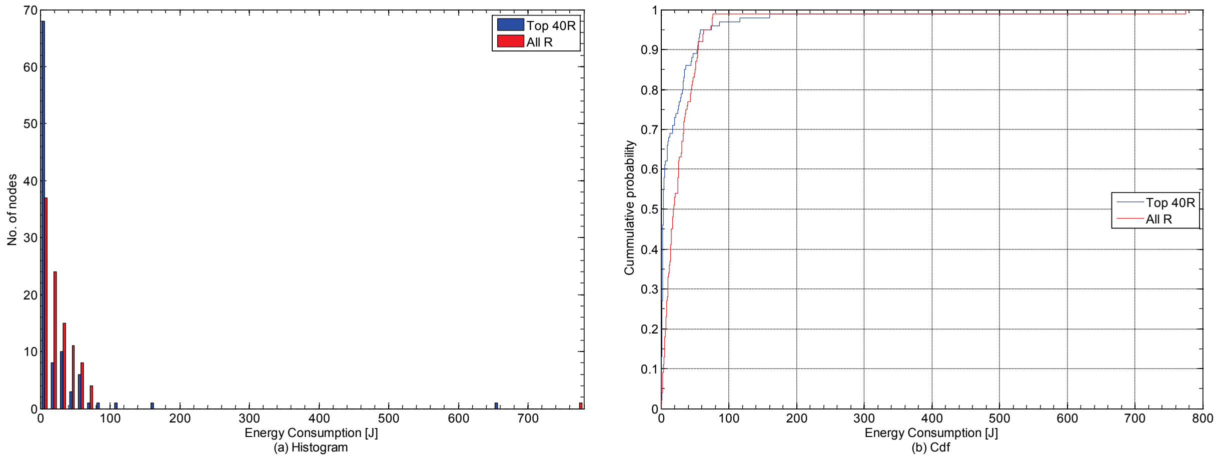


Figure 29: Energy consumption statistics for the network working in the proactive mode with one root station. The root node is included and the proactive routing information lifetime is set to the default value of 5.12 s.

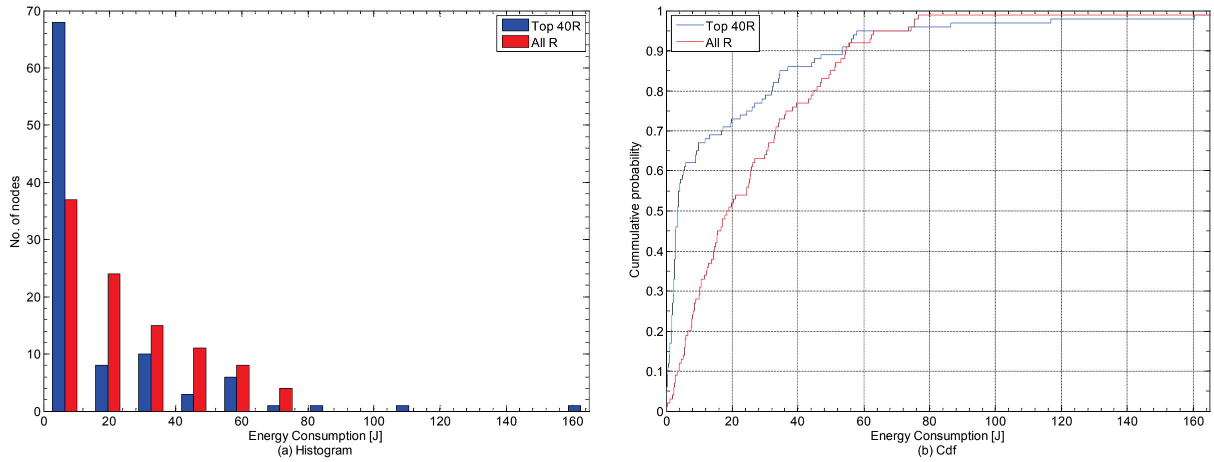


Figure 30: Energy consumption statistics for the network working in the proactive mode with one root station. Only common mesh nodes are included and the proactive routing information lifetime is set to the default value of 5.12 s.

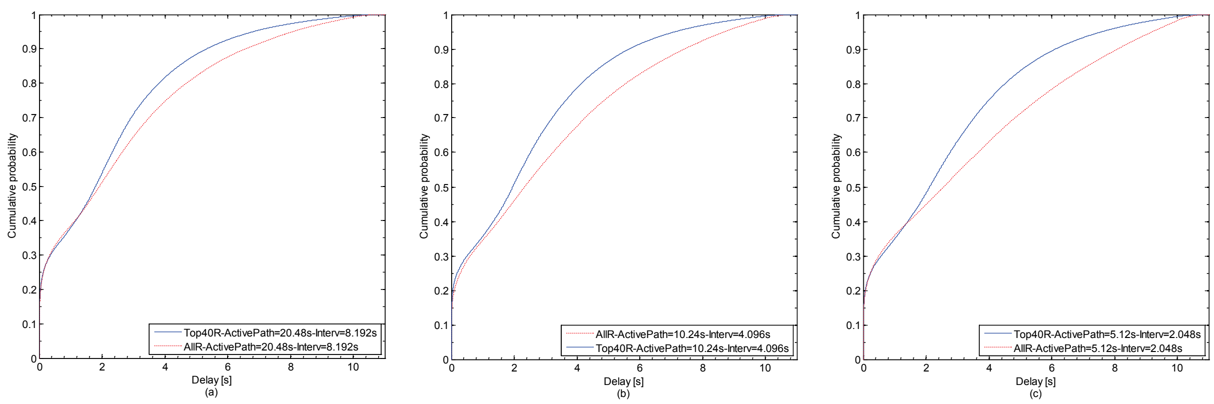


Figure 31: Cumulative distribution function of data packets end-to-end delay for different proactive path lifetimes.

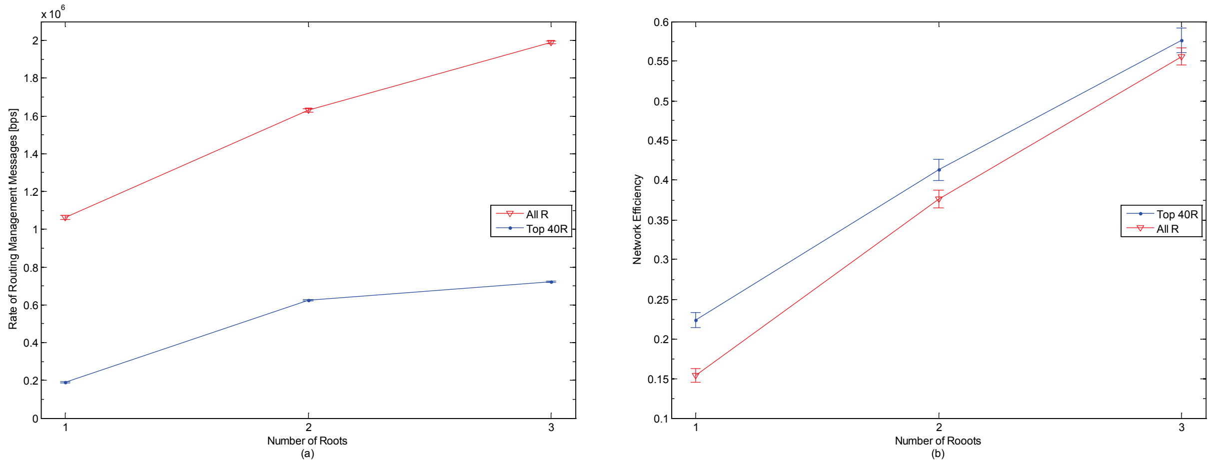


Figure 32: Proactive mode, variable number of root stations and constant traffic load; (a) rate of routing management messages; (b) network efficiency.

root stations. Obviously, since proactive mode is used, this rate increases when there are a greater number of roots independently of the traffic load. It is important to observe that the growth is not linear because of, while each root sends periodic PREQs, the non-root stations just response with a PREP to the root with the best path metric. The average path selection overhead reduction achieved with the application of the topology control in this case is around 69.14%.

The evident improvement of the network efficiency in terms of packet delivery ratio due to the distribution of the load in a greater number of roots can be verified in Fig. 32(b). On the other hand, the reduction of path selection overhead decreases the collisions probability and thus a greater number of data packets successfully arrives to the target stations when topology control is applied. The average value of the improvement due to topology control is around 19.71% for the reported experiments. The improvement is more significant when the level of congestion around the root(s) is greater (i.e. the one root case).

Finally, we evaluate the situation in which the number of roots and the traffic load increases at the same time. Namely, for the single root network data traffic consist of 25 flows, for the network with two roots there are 50 flows, and for three roots there are 75 active flows. For all the cases, downloads represents the 80% traffic and uploads the remaining 20%. The results for this set of simulations are shown in Fig. 33. As expected, since proactive mode is used, the rate of routing management messages (Fig. 33(a)) is pretty similar to the constant traffic results. There is a slight difference, a bit more noticeable for the network with tree roots and all stations as routers (around 145 Kbps), due to the higher level of channel contention produced by the 75 data flows. This higher contention reduces the transmission opportunities of routing messages and therefore its rate is lower than in the 25 flows case. This does not happen when the topology control is applied since the path selection overhead has been reduced a 68.2% on average.

Although the traffic load is increased, the distribution of root functionality to a greater number of roots still improves the network efficiency (Fig. 33(b)) of the network configured with all stations as routers. The reduction of the number of mesh stations involved in routing implies the availability of fewer alternative paths, and causes a decrease by 2% of the network efficiency with topology control and two roots with respect to the one root case. This does not hold for the three roots case, which achieves around a 6% of improvement in comparison with the one root network because of a better distribution of the traffic load. Nevertheless, for all the cases, the efficiency of the network with topology control is better than the all routers network even though consuming less energy. The average improvement is about 19.54%.

The energy consumption statistics for the three roots and 75 active flows configuration are shown in Fig. 34 for all the nodes in the network and in Fig. 35 for only non-root stations. Again, the three root stations can be easily identified. Although the global energy dissipation is reduced around a 10.25% (from 5782.9 to 5190.3 J) with the topology control, we can recognize, as in the previous section, four overloaded

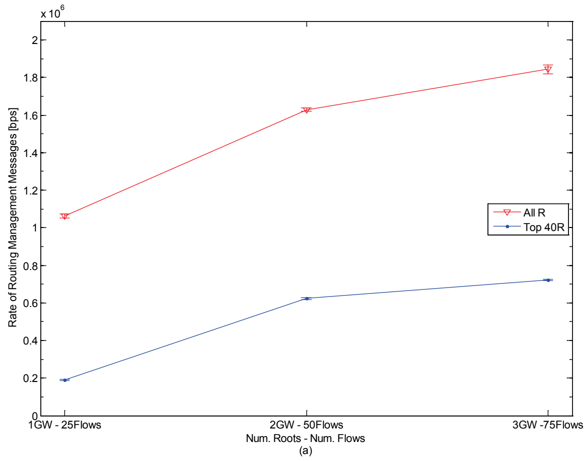


Figure 33: Proactive mode, variable number of root stations and traffic load; (a) rate of routing management messages; (b) network efficiency.

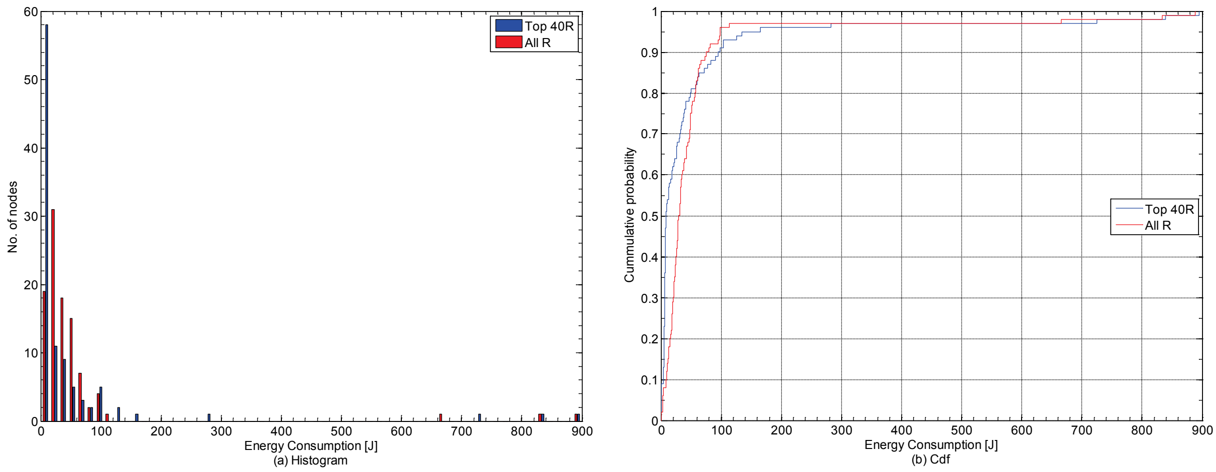


Figure 34: Energy consumption statistics for the network working in the proactive mode with three root stations and 75 active flows. The root nodes are included and the proactive routing information lifetime is set to the default value of 5.12 s.

non-root stations regarding the All R network. However, the nodes that dissipate less than 20 J increases from 30 to 64% in the Top 40R case.

5.5. Total bit rate savings for the distributed implementation

This section includes a first approximation to the evaluation of the proposed distributed implementation. We analyze the total bit-rate savings achieved with the application of the topology control mechanism. The computations include the reduction of data forwardings, the reduction of path selection related messages and also the cost of the router selection protocol (Eq. 8). For all the reported cases, in order to compute the bit rate added by the topology control we make the following considerations: $N_T = 100$ nodes, $N_N = 8$ (i.e. N_N equal to the average degree of all the nodes in the network), $N_R = 2$ which results on average in around 40% of nodes selected as routers, and the periodicity (TUT) of the required topology control related messages is the same that the routing information lifetime. Remember from Section 4.4 that TUT $\geq$ *dot11MeshHWMPactivePathTimeout*.

For the first set of experiments, reported in Section 5.1, Fig. 36 shows the total bit-rate savings achieved with the topology control application as a function of the number of data flows. In this case TUT= 5.12 s and remains constant for all the different traffic loads. An average savings of 1.24 Mbps is reached with the topology control and the previously mentioned network saturation is also verified in this figure. It

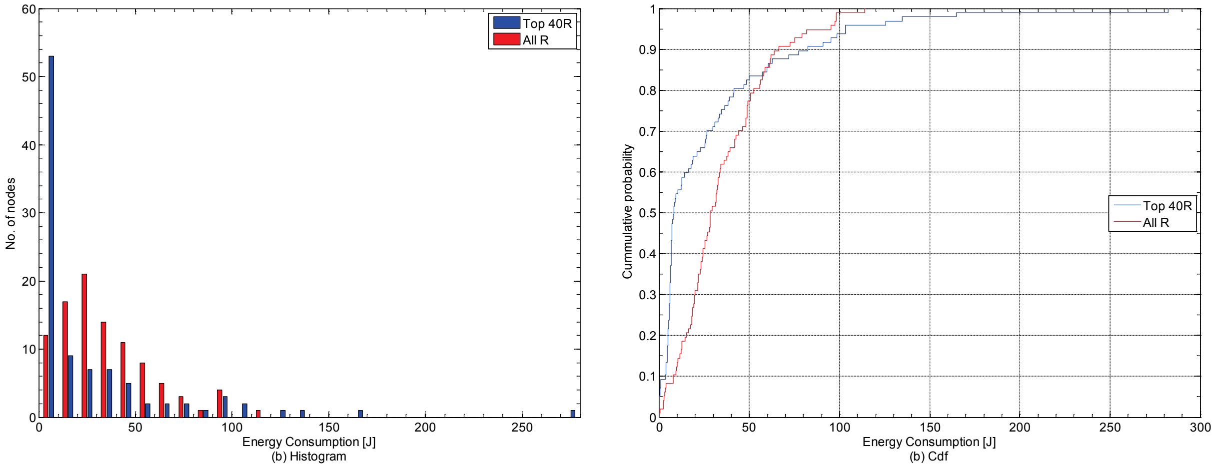


Figure 35: Energy consumption statistics for the network working in the proactive mode with three roots and 75 active flows. Only the non-root stations are included and the proactive routing information lifetime is set to the default value of 5.12 s.

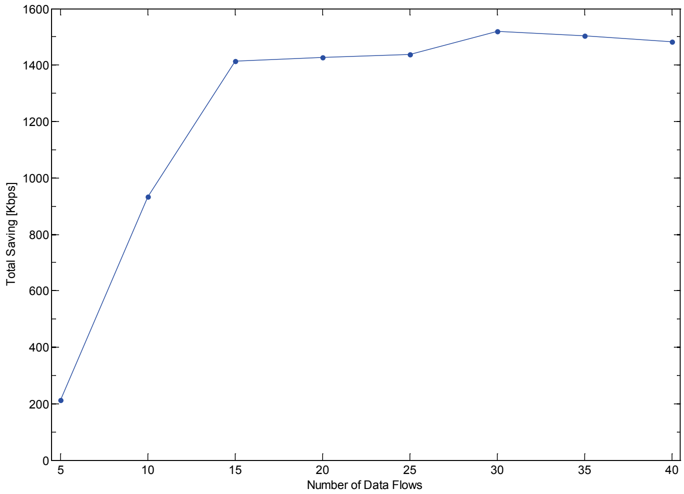


Figure 36: Global bit-rate savings as a function of traffic load.

is important to remark that the transmission/reception energy savings of the mesh stations is directly proportional to this reported quantity.

On the other hand, Fig. 37 shows the evolution of this global traffic reduction as a function of the lifetime of the reactive routing information (experiments reported in Section 5.2). As previously justified, in these experiments the periodicity of topology control updates is again the same than the path lifetime. The average reduction for the reported cases is around 1.46 Mbps.

Finally, the global bit-rate reduction for the proactive one-root case (experiments reported in Section 5.3) is shown in Fig. 38. The average value of the savings is around 1.86 Mbps and as it was expected this is greater than in the reactive mode configuration.

6. Conclusions

In this paper we have evaluated the feasibility of using the centrality metrics from social network analysis to create a topology control mechanism based on a connected dominating set. Specifically, for a dynamic wireless mesh network formed by user hand-held devices, we have proposed and evaluated some mechanisms to select which of those devices must act as routers, forwarding the packets received from other hand-held to their destination. The mechanism implementation has been proposed in two ways, centralized and

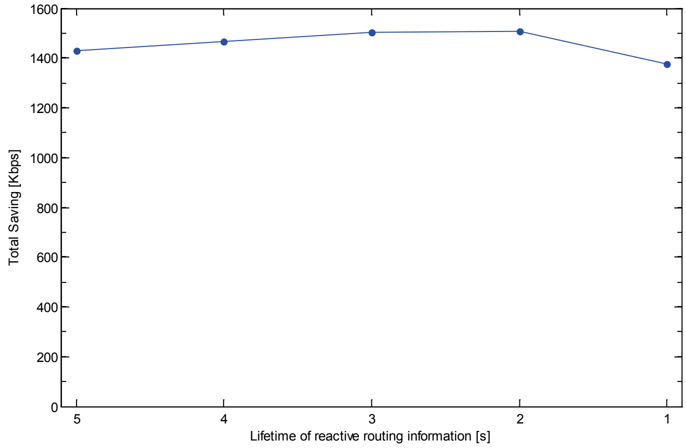


Figure 37: Global bit-rate savings as a function of reactive path lifetime.

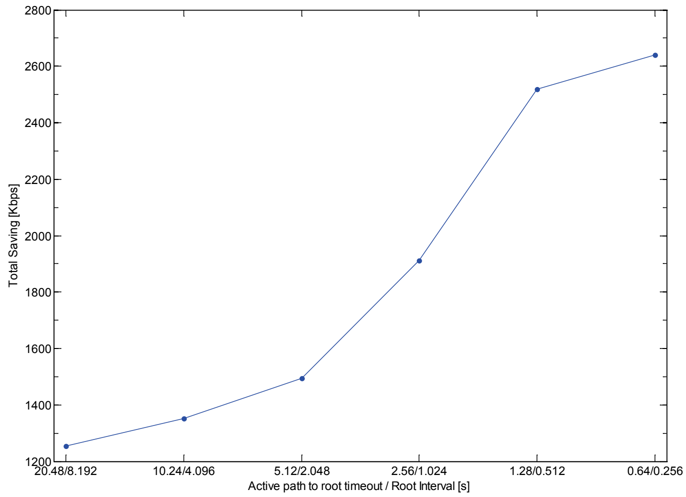


Figure 38: Global bit-rate savings as a function of proactive path lifetimes.

distributed. For the centralized approach, we have evaluated the three most common centrality measures: degree, closeness and betweenness centrality. In all those cases, the more central nodes have been selected to form the backbone. The experimental analysis has shown that the network fragmentation using the betweenness centrality is considerably lesser than the resultant with degree or closeness centralities. Thus, it is possible to conclude that by far the betweenness centrality is the metric that better identifies the stations that should be considered for routing tasks. In the second place, taking into consideration that a centralized implementation could be unfeasible in most scenarios, a distributed implementation has been proposed. In this case only the betweenness centrality has been considered. To distribute the responsibility, the concept of the egocentric network perspective of each station is needed. That is, every station computes its own centrality knowing only its own established links (neighbors). Besides, due to the dynamic and time evolving nature of the network with which we are dealing, we also discuss and evaluate different distributed mechanisms to select the central stations that will act as routers. First of all, every station selects the node in its neighborhood with the highest centrality. This mechanism works well in most cases if a minimum density of nodes exists. Then again, the complete connectivity is not assured. To guarantee that connectivity, some approaches have been proposed and compared in terms of overload and effectiveness. As a future line of work, the minimum number of routers per neighborhood needed to guaranty a desired connectivity in the distributed implementation will be studied.

The effectiveness of this centrality-aware topology control protocol has been verified through extensive simulations. The evaluation has been carried out for both reactive and proactive path selection modes. For all the studied cases the efficiency of the network was improved or at least remain equal but always with a considerably lower amount of transmission/reception energy consumption. Another common factor in all the simulation results is the reduction of the packet end-to-end delays. This is a direct consequence of the global bit-rate savings which implies lower channel contention. The reduction of the number of mesh stations involved in the path selection procedure also improves the scalability when the variability of the network demands faster path updates. Finally, we confirm that greater energy savings are obtained in the proactive path selection case because of the greater overhead present with this operation mode.

As current and future lines of work we are carrying out performance evaluations considering human mobility models. Besides, we are designing and evaluating a multi-metric protocol which assigns different weights to the egocentric betweenness centrality and the node remaining energy values.

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