Analyzing the Small World Effect in Wireless Multi-hop Networks

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Abstract

Wireless Multi-hop Networks (WMNs) represent a challenging communication paradigm, raising great interest in the research community. A great limit for a massive usage of WMNs is the low scalability of the communication layer due to lack of a centralized control and limited bandwidth of the wireless channels. To overcome these issues, the concept of Small World (SW) can be applied in order to reduce the average distance between any two nodes in the network. However, a SW configuration affects the behavior of the communication system at different layers. In this paper we investigate how to evaluate the impact of a SW configuration in a real WMNs by using both network simulation and graph theory tools. In particular, we present a new analysis environment, where a tool for graph analysis, igraph, is included in a well-known simulator, Omnet++. This new evaluation approach shows very interesting and unexpected results in the evaluation of the SW model in WMNs.

1 Introduction

Simulation analysis is a standardized, mature, and flexible modeling tool to study the behavior of WMNs. Working conditions (e.g., node mobility, transmission range, etc...) can be modified by simply tuning simulation parameters, so that a large spectrum of network scenarios can be evaluated. Performance of specific network configurations and protocols are easily drawn by analyzing changes in the results of simulations according to the initial settings. Simulation tools are useful to develop and test networking services, but they do not provide a rigorous analytical treatment of node connection effects.

To make an analysis of a network topology structure, a valid support is provided by the graph theory. In fact, WMNs can be modeled as spatial graphs, where edges among nodes correspond to wireless links in the networks. So, node i and node j have an edge e_{ij} if j is within the radio coverage range of i. In our idea, a meaningful analysis of WMNs should be based on both simulative and graph theory-based approaches, in order to evaluate how interconnections among nodes impact the behavior of the whole communication system. However, it is not a usual practice to apply graph-based modeling tools to develop efficient networking solution, nor to design new networking solutions by using a rigorous application of graph theory. We have implemented a new evaluation tool, which integrate the properties of a well-known network simulation environment, that is *Omnet++*[1], with the functionalities of a software package for graph theory, that is *igraph*[2][3]. It is a very flexible tool useful in many networking scenario, since it allows to analyze both wired and wireless networks, in both static and mobile conditions.

In this paper we show the validity of our new modeling tool dealing with a very interesting research field, that is the applicability of the Small World (SW) model to WMNs. The term "small world" was coined to describe social networks as very large systems with short paths among the elements inside. The SW model does not fit just social networks, but it can be applied in many fields, such as biological, economic and med-

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ical. Interesting applications have also been exploited in the computer networking area, for example in World Wide Web [4] and Peer-to-Peer systems [5]. In such environments, the SW phenomena can be observed if the average hop-count between nodes does not strongly depend on the network size. In this way, there is a high probability to find a short path between any two nodes, despite the great number of nodes composing the network. Some research works have explored benefits of SW configurations also in WMNs. However, a SW configuration affects the behavior of the communication system at different layers. Thus, a solid analysis approach is necessary to investigate such issues.

We have evaluated the impact of a SW configuration in a real WMNs. Our evaluation results are surprising. In fact, we would expect that when the network topology is organized according to the SW model, the reduction in the network diameter means, at the network layer, a reduction in the routing path length. However, our simulation results show that the improvement of routing performance is very limited and far away from our expectations.

In this paper we present our experimental results. As first step, we discuss the applicability of the SW model in WMNs, with particular attention to the physical meaning of *short-cuts*. In fact, wireless networks are characterized by broadcast communications and it is important to specify how to implement long-range connections among nodes. As second step, we analyze how performance of a real WMN change when short-cuts are introduced in the topology. Then, we compare theoretical results drawn from the graph theory with experimental results, in order to evaluate advantages and drawbacks of SW configurations.

The paper is organized as follows: in Section 2 we formally characterize a SW model and in Section 3 we present the state of the art on the application of SW models in wireless networks. In Section 4 we discuss the applicability of SW models in WMNs. In Section 5 we present our new evaluation tool based on the integration of igraph into the Omnet++ framework. Then, we start our analysis on SW configurations in WMNs. In particular, Section 6 describes our investigation scenario and shows experimental results. Section 7 provides our conclusions and guidelines for future advances.

2 The Small World model

The SW concept comes from a series of social experiments conducted by Milgram [6]. He observed that, on average, "six degrees of separation" exist between any pair of persons in the world. Afterwards, SWs were also observed in many other contexts and also in the Internet and the world wide web.

To understand network structures that exhibit low degrees of separation, Watts and Strogatz conducted a set of experiments on graphs [7] analyzing characteristics of regular and random graphs. In particular, they looked at two properties of graphs: 1) the average path length L and 2) the average clustering coefficient C. L provides information on the distance between nodes in terms of number of connections. C is a measurements of the degree of interconnection among nodes in a specific area. Given a graph $G = (V, E)$ with V nodes and E edges, an edge e_{ij} connects node i to node j. The neighborhood N of a node i is the set of nodes it is connected to:

$$N_i = \{j \in V : e_{ij} \in E\} \tag{1}$$

The degree k_i of a node i is the number of nodes in its neighborhood N_i, that is $|N_i|$. A path from a node i to a node j is a sequence of consecutive edges in the graph $G = (V, E)$ and the length of the path L_{ij} is the number of edges traversed. The average path length L of the graph is the median of the means of the shortest path length connecting each node $i \in V$ to all the others. The local clustering coefficient C_i for a node i is then given by the proportion of links between the nodes within its neighborhood divided by the number of links that could possibly exist between them. For a directed graph, e_{ij} is distinct from e_{ji}, and, therefore, there are $k_i(k_i - 1)$ links that could exist among the nodes within the neighborhood for i. Thus, the local clustering coefficient for node i is given as:

$$C_i = \frac{|\{e_{jk}\}|}{k_i(k_i - 1)} : j, k \in N_i, e_{jk} \in E \tag{2}$$

The degree k_i of a node i is the number of nodes, $|N_i|$, in its neighborhood N_i. The clustering coefficient for the whole network used by Watts and Strogatz is the average of the local clustering coefficients of all the nodes i:

$$\bar{C} = \frac{1}{n} \sum_{i=1}^{n} C_i \tag{3}$$

So, C reflects local properties of a network while L expresses global characteristics.

Regular graphs (e.g. square grid networks) have a high values of C, since nodes have many mutual neighbors, but large L and, also L scales with the system size. On the contrary, random networks have a small L, but exhibit very little C. Watts and Strogatz observed that by re-wiring a few random links in regular graphs, L was reduced drastically (approaching that of random graphs), while C remains almost constant (similar to that of regular graphs). This class of graphs was termed SW graphs, and it emphasizes the importance of random links acting as short-cuts that contract the average path length of the graph without modifying the clustering degree of the system. In particular, a SW network is defined to be a network where the distance P_l (in terms on number of hops) between two randomly chosen nodes grows proportionally to the logarithm of the number of nodes N in the network [7], that is:

$$P_l \propto log(N) \tag{4}$$

3 Related Works on SW in WMNs

Usually, studies on SW effects in wireless multi-hop networks face up the problem following two different approaches: 1) graph theory based approach, to analyze the properties of the system according to the connectivity features and 2) protocol based approach, focused on the development of specific networking services.

However, depending on the different analysis approaches provided by simulators and graph-theory tools, researches have to limit the investigation of their proposed solutions to specific aspects. Graph theory is useful to analyze SW effects in a communication scenario by considering connections among nodes in the network. Helmy [8] analyzes how L and C change with short-cuts established by link addition or link rewiring (even if it is not specified how link addition or rewiring can be physically achieved in wireless networks). Results show that significant reduction of L is possible with a very small number of short-cuts (about 1% of the nodes in the network) and that its maximum reduction is when the lenght of short-cuts is about 30-40% the network diameter. Similar results have been discussed in [9]. Rothkuge et al. [9] have modeled WMNs as transitional networks, that is a combination between spatial and relational networks, and they have proved that adding short-cuts (called bypass) the number of average hops can be reduced to around 67%. Authors in [10] present a solution to create a sensor network with SW features, where the end-points of shortcuts are nodes with more powerful hardware. They take into account the data communication flow to create network shortcuts toward the sink node in a way that the communication between the sink and the sensor nodes is optimized. The authors assume that endpoint nodes of shortcuts should operate in two frequency types, one for communication among them and another one for communication with the other sensor nodes.

A protocol based approach is useful to develop networking services based on the SW model, such as routing protocols, information discovery services and so on. In [11], the architecture called CARD for resource discovery and routing in large-scale wireless ad hoc networks is presented. In CARD resources within the proximity of a node are discovered using a proactive scheme. To discover far away resources, each node keeps information on few distant nodes called contacts, which work as short-cuts in the network and provide an efficient way to query for distant resources. In [12], Latvakoski presents a hierarchical routing protocol, where an overlay logical routing mechanism is executed on top of the network routing layer. In the neighbor discovery process, the overlay protocol detects the logical neighbors which are able to communicate directly without any intermediate nodes. Then the direct physical link is established between the logical overlay nodes. In [13], the authors propose a clustering scheme to maintain coverage and to minimize interference based on the SW model. The presented scheme allows to choose a cluster head with high degree to shorten the number of hops between source and destination and then it limits power level of cluster members to reduce interference and to increase space reuse.

4 Applicability of the SW model in WMNs

Due to the implicit locality of communication links, topologies of homogeneous WMNs, where nodes have uniform distribution in the space, are regular graphs. Especially in large networks, if we introduce in the network topology few random short-cuts among sensor nodes according to the Watts and Strogatz model, we can obtain a considerable reduction of L, which becomes almost independent from the size of the network [8][9][14]. To apply the SW model in WMNs, it is necessary to clarify how short-cuts among nodes can be established by considering the broadcasting nature of wireless communications. Some works in this research area assume hybrid WMNs, where short-cuts are set up through wired connection [15][16]. These solutions are usually designed for Sensor Networks, but they are not useful in WMNs, which assume the absence of whichever fixed infrastructure. If this assumption is disappointed, the main goal of anywhere and anytime communications fails. Different solutions set short-cuts by using multiple wireless interfaces that work on different channels [14][17][10]. These solutions allow to keep the system free from wired infrastructures, but they impose hard requirements for devices equipment. Also, making a SW through several network interfaces, especially assuming different technologies, implies a design of a software infrastructure able to manage the physical complexity of the system. We believe that a more strategic approach to set short-cuts is based on Topology Control (TC) strategies, which represent a very flexible way to optimize resource usage according to the characteristics of the communication system. To implement shortcuts in the network, some nodes are elected as Leaders. Leaders increase their transmitting power in order to establish long-range connections. Increasing the transmitting power of Leaders means establishing unidirectional links in the communication system. Under the assumption of bidirectional communications, links between Leaders work as shortcuts. In fact, Leader are fully connected each other, but most of the nodes are able to receive packets from Leaders but not to send them to Leaders, as shown in Figure 1. Leaders $L1$ and $L2$ are in the communication range of each other. Thus they are connected with a bidirectional link. Also node $N1$ is in the communication range of $L1$ and $L2$, but its transmissions cover just $L1$. Thus, the link between $L1$ and $N1$ is bidirectional, but the link between $L2$ and $N1$ is unidirectional and will not be used for communications. Similar considerations can be done for node $N2$, characterized by an unidirectional link with $L1$ and a bidirectional link with $L2$. So, if H is the number of Leaders in the network, the number of shortcuts is at most $H(H-1)/2$.

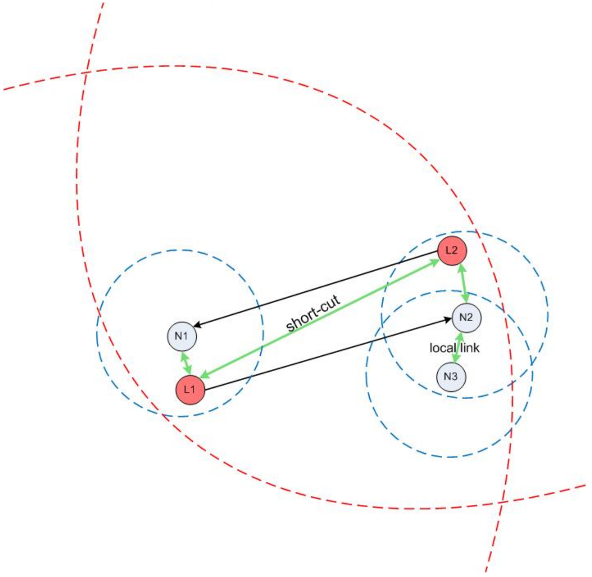


Figure 1: Unidirectional and bidirectional links

In this paper we investigate the behavior of the network when some nodes increase their transmission power. At this stage of the work, we assume that nodes set their communication interfaces statically before the network starts. Since the purpose of this paper is to evaluate the benefits brought by a reconfiguration of nodes connections according to the SW model, we postpone to a future work the development of a software infrastructure for the automatic configuration of the communication devices and the application of Topology Control (TC) schemes to improve network performance. The introduction of short-cuts in the communication infrastructure poses new challenges to be investigated:

- short-cuts can be bottlenecks in communications;
- wide coverage range of Leaders can increase interference and error rate in local communications;
- energy consumption of nodes involved in shortcuts can reduce the mean lifetime of the network;
- mobility of nodes can drastically reduce benefits of SW configurations.

In the remaining part of the paper, we present our new evaluation tool and investigate some of the above problems by using its additional features.

5 A New Investigation Approach

The importance of simulation tools for WMNs is proved by the large number of simulators which have been developed for wireless networks (SWANS, OpenWNS, Omnest,...) or which implement models to analyze wireless systems (Omnet++, NS2, Matlab,...). Simulations allow to perform an experimental analysis of the system, but they do not provide information on system properties, such as link structure in the communication system, interconnection degree among nodes and a reference model for the network topology. Such information can be useful to design efficient networking protocols and to test them, since they allow to capture specific features at the base of the system behavior. For example, in designing a computer communication network, it is desirable to provide good connectivity among all sites at reasonable cost. To make an analysis of the network topology structure, a valid support is provided by the graph theory. In fact, WMNs can be modeled as spatial graphs, where edges among nodes correspond to wireless links in the networks. Through the application of graph theory, research outcomes in many areas will benefit, including routing, scheduling, mobility management, dimensioning, interference control, energy management and localization.

Omnet++ is an open-source object-oriented event-driven network simulator. Its optional *INET Framework* module supports simulations of wireless and mobile networks within Omnet++, implementing models for wireless communications, nodes mobility, wireless multi-hop routing protocols.

igraph is an open-source library for the creation and manipulation of direct and indirect graphs. It includes algorithms to solve the classical problems of graph theory, such as the minimum path between two nodes, mean distance among nodes, size of connected components and so on.

Our main goal in this work is to integrate the functionalities of the igraph library in Omnet++, thus to have a full-scale tool for the evaluation of networking systems, providing also new methods for network analysis (see Figure 2). This new tool contains functions for both generating and manipulating graphs, providing algorithms for the analysis of graph properties, such as graph girth, diameter and connectivity, which are all accessible from the simulation environment.

The Omnet++ framework has a modular structure, logically organized in three main elements, as shown in Figure 2: Engine, Model Component Library (MCL) and User Interface (UI).

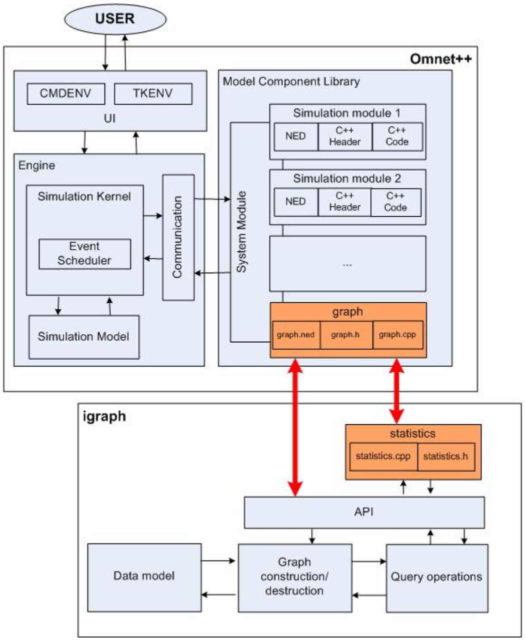


Figure 2: Software architecture of our new evaluation tool

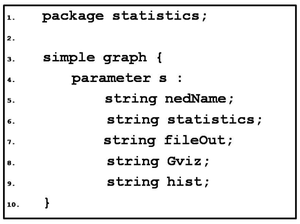
The Engine models events and packets through *message* objects and all the modules in the simulation framework communicate with message passing. The MCL collects the code of compiled simple and compound modules, which are instantiated by the simulation kernel at the beginning of the simulation execution. The structure of a model (internal components and external interconnections) is described through the OMNeT++'s topology description language, NED. Then, the behavior of the model is programmed in C++. The UI allows users to interact with the system through a graphical interface (Tkenv) or a command-line interface (Cmdenv).

We have implemented a new Omnet++ module in the MCL, called *graph*, which will be described in detail in section 5.1. It is able to interact with the igraph C package to provide a representation of the network in a graph form, where each element of the network corresponds to a node and each communication link corresponds to an edge. The Data model module in igraph handles directed and undirected graphs. It describes each graphs through a table of metadata, to specify the properties of the graph (whether the graph is directed or undirected, the number of vertices,...) and a multiset of ordered (if directed) or unordered (if undirected) labeled pairs. igraph API includes all the functions for creating and manipulating the graphs. Unfortunately, igraph is not able to analyzing performance of communication networks, since it has been designed to analyze graphs without any knowledge of the physical system modeled through the graph. To perform measurements and draw statistics from the graph meaningful for a communication network, we have implemented an additional library of igraph, called *statistics*, which will be presented in detail in section 5.2. It implements all the specific functionalities meaningful for graphs modeling communication networks, such as functionalities for analyzing clusters and evaluating the average shortest path between two specific nodes and the average degree of nodes.

5.1 The graph component

Omnet++ manages network topologies (both in wired and in wireless scenarios) through objects of the class *cTopology*. A *cTopology* object stores an abstract representation of the network in graph form, where each *cTopology* element corresponds to a node, and each *cTopology* edge corresponds to a connecting link. In the resulting graph, all the nodes are at the same level and graph edges are directed. The *graph* module maps a *cTopology* object according to the igraph environment.

Following the logical organization of Omnet++, the *graph* module is organized in a .ned file, to describe components and connections, and the c++ code with its header file, to specifies its functionalities. The ned file of the *graph* module is shown in Figure 3. The *nedName* parameter gives an identification to a *graph* instance for the experiment; the *statistics* parameter is a string that specifies the types of statistics that have to be performed in the experiment. Coding of available statistics is listed in Table 1. The last three parameters specify the output files. In fact, the *graph* module provides outputs for graphical interaction by producing graphml (*fileOut* parameter) and graphviz



```
package statistics;

simple graph {
    parameter s :
        string nedName;
        string statistics;
        string fileOut;
        string Gviz;
        string hist;
}
```

Figure 3: *graph* NED file

(*Gviz* parameter) files, which are well-known formats for graph visualization. The *hist* parameter specifies the file where data for histograms on measurements are formatted. Statistics in text format on the overall behavior of a simulation are included in the standard scalar output of Omnet++.

PARAMETER	DESCRIPTION
hconn	number of components strongly connected
sconn	number of components weakly connected
path	mean minimum path
connodes	mean connectivity degree of nodes
conedges	mean connectivity degree of edges
inf	number of nodes and edges
gclust	global clustering coefficient
lclust	local clustering coefficient
ist	histogram on minimum paths

Table 1: Code for statistics in graph.ned

The C++ code implements all the functionalities necessary to call the functions in the *statistics* library.

To perform studies on WMNs, we have used the INET Framework developed for Omnet++, which implements models for wireless communications, nodes mobility, wireless multi-hop routing protocols. In particular, in the INET Framework, each mobile wireless network has an instance of the *ChannelControl* module (see Figure 4). It stores information on the location and movement of nodes, and determines which nodes are within the communication or interference range of other nodes. These information are then used by the radio interfaces of nodes at transmissions. In wireless scenarios, two nodes are connected, if they are in the communication range of each other, they interfere if they are out of their communication range and within the interference range, and they are disconnected if they are out of their interference range. To support mobility in wireless scenarios, the *graph* module dynamically updates edges in the graph, according to information coming from the *ChannelControl* module. In particular, we have included additional capabilities to the *ChannelControl* module, as shown in Figure 4.

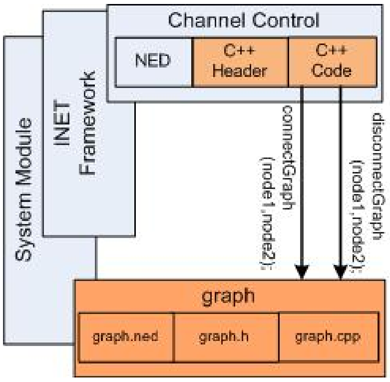


Figure 4: Inyraction between ChannelControl and graph modules

Every time it detects a change in nodes connections, it alerts the *graph* module sending a *connectGraph* message, if a new connection has been established between *node*1 and *node*2, or a *disconnectGraph* message, if the connection between *node*1 and *node*2 has been broken. Then, the *graph* module updates the information on the current graph and applies again the functions of the *statistics* library on the new topology. This approach allows to perform a real-time analysis of the graph following the dynamic evolution of the network.

5.2 The statistics library

The *statistics* library extends the igraph package to offer new functionalities useful for analyzing networking topologies. igraph stores graphs (both directed and undirected) in the internal data structure *igraph_t*. The *igraph_vector_t* data type is a simple and efficient interface to arrays containing numbers.

Currently, the *statistics* library implements all the functions in Table 2. The string *mode* in the *clusters* function can assume the following values: *IGRAPH_STRONG*, if the parameter of interest is the strong connectivity, and *IGRAPH_WEAK*, if the parameter of interest is the weak connectivity.

In the next Section we show evaluations on SW configurations in WMNs performed through our new simulation tool. In particular, we evaluate the real benefits of SW configurations in WMN, analyzing the effects at the physical layer, network layer and application layer.

6 Evaluation Results

We have analyzed the impact of SW configurations in a WMN by using our new investigation tool based on Omnet++ and igraph.

FUNCTION	RETURN VALUE
int clusters(igraph_t g,char mode[])	number of components connected in the graph
int mean_path_length(igraph_t g)	mean minimum path
long int nodes_connect(igraph_t g)	mean connectivity degree of nodes
long int edges_connect(igraph_t g)	mean connectivity degree of edges
igraph_vector_t histo(igraph_t g)	histogram on minimum paths

Table 2: Functions in Statistics library

6.1 Simulation Settings

We built a scenario with 900 nodes over a squared grid. Each of them is equipped with a 802.11 wireless interface and transmits with a transmitting power of 1 mW. Then we have elected H nodes as Leaders and set their transmitting power to 1 W. At the network layer, we have used AODV as routing protocol, the most used routing protocol for WMNs. However, it works just with bidirectional links, since packets have to move in both directions along a routing path. To support unidirectional links at the routing layer in our experiments, we have used a modified version of AODV as routing protocol, as described in section 6.2.

6.2 AODV Implementation

The AODV protocol implemented in the INET framework manages unidirectional links by including the nodes that do not collaborate in the route discovery in a blacklist. However, this approach allows to detect unidirectional links very slowly, waiting for timeout expirations and error handling. For our purposes, the management of unidirectional links is essential, since leader short-cuts cover wide networking areas, establishing many unidirectional links with nodes. Nodes periodically exchanges HELLO packets to have knowledge of the neighborhood. Thus, we have modified the structure of the HELLO packet, in order to include also information on the neighbor table of each node. For example, assume node A sends an HELLO packet in broadcast. It includes its neighbor table in the packet, which identifies all the nodes one-hop far. When a node B receives an Hello packet from A, it means there is a link from A to B. Then B checks if in the neighbor table of A there is an entry for B. If it is, it means the there is also a link from B to A and, therefore, the link is bidirectional. Otherwise, the link is unidirectional and B insert A in its blacklist, ignoring from that moment all its signaling packets (e.g RREQUEST, RREPLY, ...). B will again verify the status of the $A-B$ link whenever it will receive a new HELLO packet from A.

6.3 Experimental results

The first step of our study has been to verify if the reference scenario experiences properties of a SW system. In order to analyze the properties of the graph of the system, through igraph we analyzed the clustering coefficient C and the path length L, to verify if the reference scenario experiences properties of a SW system. In our evaluations, short-cuts between Leaders drastically reduce L, whereas C does not change (it is about $0,45$). So, according to equation 4, in presence of at least 25 Leaders, the network is a SW system, as shown in Figure 5 (green line). Under this condition, we expect an high improvement of network performance, thanks to the drastic reduction of L. The red line in Figure 5 draws the mean routing path experienced by AODV, in order to perform a comparison between the graph and the routing path properties. We notice that trends of path length and route length are slightly different. AODV benefits from the SW configuration since the mean routing path length decreases by increasing H. However, such a reduction is almost linear, while the topological path length reduces exponentially. When $H = 25$, despite of a reduction of L of about 58%, we have a reduction of the routing path length of just 35%. It implies a slow adaptation of the routing protocol to changes in the system connectivity, due to the effects of shortcuts at lower layers.

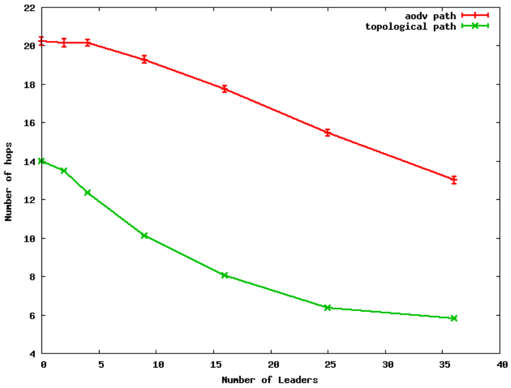


Figure 5: Path lenghts

In fact, advantages at the routing layer occur at the cost of an increased number of collisions at the MAC layer and of an higher interference degree at the physical layer. This is confirmed by the results shown in Figures 6 and 7, where respectively the number of collisions and the SNR are drawn with the number of

Leaders in the network. In the range [2;9] of the x asses, increasing the power transmission of very few Leaders does not significantly reduce the size of the communication systems in terms of path length, but reduces the communication capacity of the system in the areas around the Leaders themselves, as proved by the high increase in the number of collisions. Thus, the overall performance of the system are poor. By increasing to 16 and more the number of Leaders, the degradation of the channel capacity is balanced by the reduction of the number of retransmissions necessary to deliver a frame thanks to the reduction of the route length. So, the performance of the system improve.

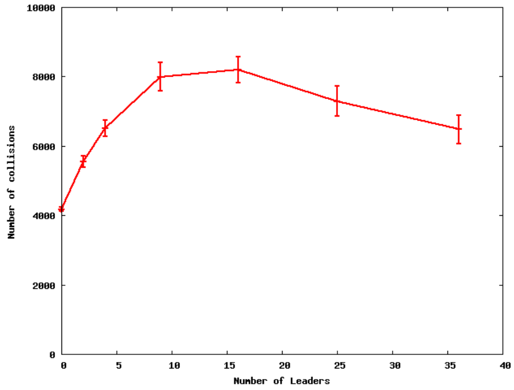


Figure 6: Number of collisions over wireless channels

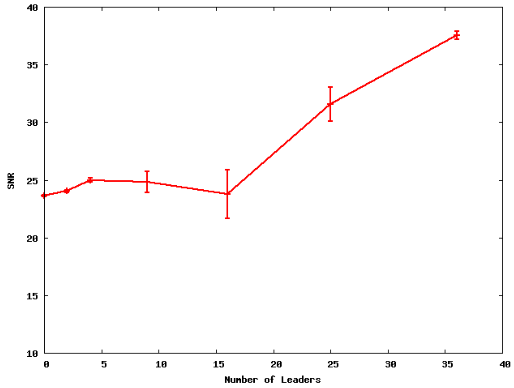


Figure 7: Signal to Noise Ratio

In order to understand how the effects due to the SW configuration of the system combine together, we moved our attention towards the application layer. We have measured the goodput in data delivery, that is is the application level throughput, i.e., the number of useful bits per unit of time forwarded by the network from the source to the destination, excluding protocol overhead and retransmitted data packets. Results on goodput are shown in Figure 8. According to the above considerations on system performance, by increasing the number of Leaders the goodput decreases because of the degradation of transmission at the low layers. When the number of Leaders is higher than 9, performance in terms of goodput increase thanks to benefits at the network layer. We have the maximum goodput when the network hosts 25 Leaders, that is when the system behaves as a SW. However, despite the strong reduction in the path length, the improvement of the goodput in the SW configuration is only of 14%. These results show that advantages of SW configurations in wirelss multi hop networks are not so amazing as we expected. The physical implementation of shortcuts is a very important issue that can drastically affect the performance of the whole system. For this reason, we claim that SW configuration can be useful in WMNs, but specific design strategies of the communication environment are necessary.

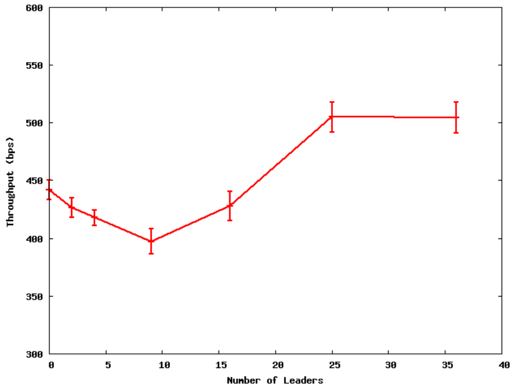


Figure 8: Goodput

7 Conclusions and Future Works

In this paper we have presented a new approach to perform a complete analysis of WMNs based on both simulation tools and the graph theory. In particular we have integrated the igraph library with a well-know simulator for wireless networks, that is Omnet++. Then, we have evaluated the impact of a SW configuration in a real WMN, considering the performance of the system at the physical, mac, network and application layer. We have discussed very interesting results, which show the importance to use specific tools for both graph theory analysis and networking protocols evaluation. We intend to further extend our study to different WMNs scenarios, in order to understand under which conditions we can have higher benefits from the SW configuration. This work will help us to outline the most strategic research activities in this research area.

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