1 Introduction and background

The Internet architecture is today part of everybody's life, thanks to the great progress done in the technologies that allow the use of networks through different type of devices. Despite their different nature, technologies are born with the purpose of ensuring connectivity every-where and every-time: to send information, for example, we can use electromagnetic radiations in infrared frequency band, electric transmission lines or wireless devices, which take advantage of the ether. Since the ether is present everywhere in the world, it is reasonable to exploit the potentiality of this medium in order to use it as a mean of communication, on which information can travel.

This is a very good choice, although there are some limitations, due to its intrinsic nature and physical barriers to be overcame. It is a still open challenge for modern engineering: the limited coverage radius that the current IEEE's standards fail to ensure and the supply management of these devices give the majority of limitations. Other important issues are strictly related to higher-level management, such as data link and network operations (Fazio, 2012), that inherently are subject to interference and physical undesired phenomena. Reasonably, Wireless Sensor Networks (WSNs) (De Rango, 2013) are the subject to some kind of recent studies, given that they are applied for many kinds of applications in real life (Fazio, 2013).

Many recent research efforts have confirmed that, given the natural evolution of telecommunication systems, they can be approached by a new modeling technique, not based yet on traditional approach of graphs theory. The branch of complex networking (Yan, 2010), although young, is able to introduce a new and strong way of networks modeling, nevertheless they are social, telecommunication or friendship networks. Each network present in nature, whether artificial (as the national water supply network) or based on telecommunications, natural (such as brain synapses network) or relative to molecular interactions can be seen as a Complex Network (CN), if appropriately modeled. CNs represent a new paradigm to which the world (seen in its various disciplines of humanities, physical and scientific studies) is shifting.

It is necessary to find a modeling technique which allows us to model a real network as a Small World Network (SWN, a particular branch of CNs) (Guidoni, 2008;Huang, 2012; Xiaojuan&Huiqun, 2010), while maintaining a low network diameter and a high *CC*. Such networks are highly connected, because of their largest connected sub-graph contains a huge proportion of the vertices. For example, the Internet represents a SWN: we know that IP-packets cannot use more than a precise amount of physical links (equal to the value of their Time-To-Live field), thus the structure of the Internet has evolved in a graph with relatively small distances, even though it is rather large.

In this chapter, we propose a new approach, based on CN modeling, able to alleviate the limitations of wireless communications. In fact, many recent studies have demonstrated that telecommunication networks can be well modeled as complex ones, instead of using the classic approach based on graph theory. The study of CNs is a young and active area of scientific research, inspired largely by the empirical study of real-world networks such as computers and social networks. Our proposed modeling technique is applied to Wireless Sensor Networks (WSNs). The proposal has the main purpose of ensuring an improvement of the distributed communication, quantifying it in terms of clustering coefficient and average diameter of the entire network. The main idea consists in the introduction of Hybrid Data Mules (HDMs), able to enhance the whole connectivity of the entire network. As known from literature (Jiang, 2008), a Data MULE (DM) is a node (generally a vehicle with a storage-equipped computer) dedicated to the creation of a link among couple of remote nodes. The term MULE has initially born from the acronym Mobile Ubiquitous LAN Extension. In fact, the main DMs application consists in offering network connectivity to last-mile villages (Pentland, 2004). Our idea starts from this approach: computers with storage and Wi-Fi link (DMs) are attached to public vehicles (generally buses on bus routes) and, when the DM stops to pick-up or leave passengers, the data is exchanged from the on-board router to the infrastructure router, via Wi-Fi connection (let us think to e-mail downloading and uploading). This approach is typical of Delay Tolerant Networks (DTNs) (De Rango, 2014; De Rango, 2008). In this way, DMs can be thought as cost-effective mechanisms for rural connectivity, because they use inexpensive hardware, which can be quickly installed and piggybacked on existing transportation infrastructure. The use of DMs is extensively employed also in environmental monitoring, which represents a class of applications that can benefit from sensor networks (Mainwaring, 2002). In these scenarios, there is no need to have a dense sensor network, so a sparse network would be enough (with related low costs, due to the lower number of needed devices). On the other side, the distance among neighbor sensors may become too high and the communication may require a lot of energy to be done. DMs can help data collection, carrying data from sensors to the main infrastructure router. DMs can move randomly in time or following deterministic (predictable) routes. They are assumed power renewable, while static sensors are typically energy-constrained. Referring to a telecommunication network with dynamic topology, DMs are usually used to create shortcuts the position where data gets on the mule is the beginning of the shortcut, while the position where data gets off the mule is the end of the shortcut. The concept of DM shortcut is different from the traditional (wired) one: DMs carry data on-demand, that is to say when data needs to be forwarded; traditional shortcuts have fixed length and position, while DMs are moving nodes. As explained later, we consider hybrid nodes for obtaining a SWN, since we suppose that they are equipped by two radio interfaces.

The Milgram's approach, introduced in the sixties and largely proved in many experiments, gave a big contribution to the spread of CN theory. There are different modeling methods and we have chosen and tested the one proposed by D. Watts and S. Strogatz in the nineties (Erdős, 1960; Watts, 1998) and then spread by A.L. Barabasi in the first years of the new century (Albert, 2002), that allows to transform a WSN into a CN, by the re-wiring technique. This method provides the random deletion of some links of the network, between couple of adjacent nodes and, then, the connections are created again by randomly linking not adjacent and far nodes. So, the average communication distance between two nodes decreases, linking directly a smaller group of nodes. In our simulations, in order to reconsider really these links, we have equipped the public urban transporting vehicle (a bus) with a modem/router in 3G (or LTE) technology, creating long-range links between transportation vehicles, which represent shortcuts for far nodes. So, the proposed scheme is based on the utilization of public transport means (such as buses, trams and subways), used as DMs in our approach, in order to carry data within the network, interconnecting various network clusters, relatively far one from each other. The considered HDMs are equipped by "special" wireless devices, using two different transmission standards, guaranteeing a "double" action range, which permit to expand the scope of the entire SWN. The introduction of special nodes within the network, contributes to the improvement of network scalability, allowing the addition of new sensors nodes, without substantial changes to the structure of the network. The distribution degree of individual nodes in the network will follow a logarithmic trend, meaning that the most of the nodes are not necessarily adjacent but, for each pair of them, there exists a relatively short connecting path. The effectiveness of the proposed idea has been validated thorough a deep campaign of simulations, proving also the power of complex and small-world networks.

This chapter is structured as follows: in paragraph 2 the main contributions and related works on CNs, SWNs and HDMs are introduced, then in paragraph 3 the proposed idea is illustrated in all the main aspects. Paragraph 4 shows the simulation environment and the performance evaluation, while paragraph 5 summarizes the main conclusions and future trends.

2 State of the art and contribution

The concepts related to CNs have been deeply studied in the modern literature, in fact there are many works focusing their attention on some theories and applications of CNs. Many models have been proposed, as the one introduced by Albert and Barabasi in (Albert, 2002), in which an analogy with the structures of biological and social systems has been made. The authors studied the associations between ideas and concepts and with some artificial networks, including Internet and air routes; the model is famous for its ability to explain the evolution of these systems in terms of adding, removing and editing nodes (Boyd, 2007; Petrou, 2009).

The SWN concept has been investigated in (Verma, 2011), in which the authors deals also with the addition of a few Long-ranged Links (LLs), to significantly bring down the Average Path Length (APL) of the network. The authors introduced a more realistic small-world model, considering the real constraints of wireless networks such as the limited transmission range of LLs, and the limited available bandwidth for wireless links. At the end, they propose the Constrained Small-World Architecture for Wireless Network, evaluating the performance when adding LLs for reducing average APL. They shown that in moderately large WMNs, a 43% reduction in APL can be achieved.

Erdös-Rényi and Watts-Strogatz (Erdős, 1960; Watts, 1998) treated the problem of SW modeling: authors found that many already studied networks and systems (such as biological oscillators, excitable media, neural networks, spatial games, genetic control networks and many other self-organizing systems) can be highly clustered, like regular lattices, with a small characteristic path length, as for random graphs. These kind of networks are called SWNs (by analogy with the small-world phenomenon, popularly known as *six degrees of separation*).By the empirical experiments on CNs of the pioneers Euler and Milgram (Milgram, 1967), it has been shown that, in a network of any kind and form, the communication between two random nodes occurs (with information forwarding) through an average of six nodes before reaching its destination (small-world phenomenon). This is a useful concept, which allows us to analyze and evaluate the performance of a telecommunication network, in terms of efficiency and speed of data exchange. In (Guidoni, 2008), authors demonstrated how a WSN can be well approached by a SWN with two different approaches; as known, in a WSN there is a special node, called sink node, that is either the origin or the destination of a message, while the other types of data communications (relay activities for example) happen between arbitrary communicating entities. Authors found that sink node exhibits the most interesting tradeoff between energy and latency, allowing the design of strict applications that demand a small latency and energy consumption.

The Communications Letters (Guidoni, 2012) proposes to design heterogeneous sensor network topologies with Kleinberg's Small World (SW) model. The authors consider a model to create network shortcuts toward the sink node in order to optimize the communication flow between sink and sensor nodes. The considered end-points, in this model, are equipped with more powerful hardware, forming a heterogeneous sensor network. Many simulation campaigns are led-out in order to show that, the shortcuts toward the sink node, the network presents better small world features and a reduced latency in the data communication compared with the original Kleinberg model.

In (Androutsos, 2006), authors applied the concept of SW Indexing Method (SWIM) for image retrievals in a SW distributed media index. In their studies, they considered that each media object is only responsible for a small portion of the overall index, so the loss of portions of the overall network of data objects accounts for a small degradation in the retrieval procedure. They also introduced SW user agents on a large variety of MPEG-7 images. In (Jiang, 2008) authors investigated the effects of DM insertion in MANETs, instead of wire-lines, that are expensive and cannot be determined a-priori when dealing with mobile nodes. Authors have shown the main advantages reachable with the creation of shortcuts by DMs introduction. In this work, a novel approach for modeling WSNs as SWNs is introduced. It is based on the concept of DMs (called also ferries), that act as special nodes for the enhancement of the SW properties of the considered network. In particular, the authors made a simulation of the relationship between path-length and the numbers of added DMs.

In (Banerjee, 2012) the authors propose a self-organization framework for wireless ad hoc networks. The use of directional beam-forming for creating long-range short-cuts between nodes are investigated. Throughout simulation campaigns for randomized beam-forming the authors have individuated crucial design issues for algorithm design. They have proven that their proposal allows important path length reduction even if the problem of asymmetric paths between nodes is still present. In order to face with this issue they propose a distributed algorithm for small-world creation that achieves path length reduction while maintaining connectivity. These results are proven by a detailed simulation campaigns.

In (Chakraborty, 2014) the authors based their study on the Barabasi observation that states "*the scale-free network is formed by preferential attachment of new nodes in the existing network*". Therefore, a new node is more likely to make a connection with a node having higher neighbor degree in the network. They find that "greedy decision-making" is one of the key characteristics for the transformation of a regular network to a scale-free network. Moreover, they show that pure random addition of new links in a regular network does not result in a scale-free network.

The DM concept has been also used for addressing the problem of energy-efficient data collection in sparse WSNs. In fact, in (Jain, 2006), the authors investigate the impact on the data success rate, latency, and energy cost of a large set of operating parameters (such as data generation rate, sensor buffer size, etc.). In certain application scenarios, different DMs may be required to meet performance requirements. In (Jea, 2005), the authors research about the benefits of using load balancing techniques to assign sensors to DMs when different DMs are used, founding out that the used communication protocol plays an important role in energy management. In (Chakrabarti, 2003)a new protocol is proposed, relying on the assumption of circular transmission range, negligible message loss rate within the transmission range, and predictable DM arrival times.

Another key issue in CNs is related to scalability: different studies in literature investigate the dependence of this characteristic on network topology or, if we consider telecommunication systems, on adopted protocols or architecture. In particular in (Zhou, 2006; De Rango, 2006) the authors investigate about the scalability of wireless ad-hoc networks in terms of protocols. The same analysis is made in (De Rango 2009), with particular emphasis to vehicular networking, while in (Molinaro, 2005) an architectural analysis is carried on. Nowadays, the fundamental issue of network scalability is investigated in terms of dynamics and topology. It has been discovered that scalability depends on dynamical properties and network size. Scale-free networks are scalable for certain types of node dynamics.

As said before, starting from the empirical experiments on CNs by the Euler and Milgram, it can be concluded that *"in a network of any kind and form, the communication between two random nodes occurs with information forwarding through an average of 6 nodes before reaching its destination"*. This is a useful concept, which allows us to analyze and evaluate the performance of a telecommunications networks, in terms of efficiency and speed of data exchange.

With the research activity introduced in this chapter, a new idea applied to a urban WSN is evaluated, increasing the range of action and the communication efficiency. In particular, the chapter contains the following contributions:

- Analysis of the main advantages arising from the introduction of DMs for a WSN;
- Proposal of a hybrid approach, focusing the attention on a double coverage (long and short) for the DM nodes; the traditional shortcut method of DM insertion is extended by the definition of double coverage devices, as illustrated in the next section;
- Implementation of real mobility patterns, instead of synthetic ones (random walk, random way-point, etc.) which may lead to unrealistic results;
- Performance analysis on a real scenario and analysis of the trend of the main parameters related to a SWN.

3 Scenario and Hybrid Model (HM) Proposal

This paragraph is completely dedicated to the proposal of our HM. The idea is illustrated, after a brief set of definitions and a description of the main issues and parameters that have to be taken into account for the argumentation. In order to understand the advantages that can be gained by using HDM nodes, it is necessary to study different parameters and learn about the distribution degree of nodes within the network, with a complete understanding of the functionality of a generic network. As stated before, our main idea consists in the introduction of special nodes (instead of traditional ones), equipped with a long-range and short-range coverage devices. As known from literature, the parameters that have to be taken into account for CNs are three:

a) Average Network DIameter (ANDI): following the classical treatment about networks modeling, a network $G = (V, E)$ can be seen as a graph G, that consists of a set of n nodes $V = \{v_1, . . . , v_n\}$, $||V||=n$ and a set of m edges E, $||E||=m$. Since the network might not be connected, following the definitions of (Chung, 2002; Chung, 2002.2), the average distance in the network can be considered as the average across pairs of path-connected nodes. If $n_l(i,j)$ is the number of links in the shortest path connecting nodes v_i and v_j (its value is infinity if no path exists between v_i and v_j). At this point, the AVerage DIstance (AVDI) of the network is defined as:

$$AVDI(E) = \frac{\sum_{\{v_i v_j\}/n_l(i,j)\neq\infty} n_l(i,j)}{\left\|\{v_i,v_j\}/n_l(i,j)\neq\infty\right\|} \quad (1)$$

while the ANDI is:

$$ANDI(E) = max_{\{i,j\}|n_l(i,j)\neq\infty}\, n_l(i,j) \quad (2)$$

b) Clustering Coefficient (*CC*, conceptually it is the probability of a node *A* to be connected to the node *B*, having as common neighbor a node *C*): by definition, it measures the tendency of two nodes adjacent to a common node to be connected each other, and it represents another important parameter when observing network properties. In practice, it indicates (locally) the connection ability of network nodes and it increases significantly the ANDI. The *CC* of the *i-th* node (indicated with cc_i) is:

$$c_i = \frac{e_i}{k_i(k_i-1)/2} \tag{3}$$

where e_i is the number of edges which interconnect *i's* neighbors and k_i is the number of *i's* neighbors. So, the *CC* of the entire network is defined as the average of all cc_i:

$$CC = \frac{1}{N}\sum_i cc_i \tag{4}$$

c) Degree Distribution (*DD*): in the study of networks and their related graphs, the degree of a node v_i, indicated with $\delta(v_i)$, is the number of connections, or edges, it has to other nodes. It can be indicated as:

$$\delta(v_i) = \sum_{v_j \in V} e_{v_i v_j}, with\, e_{v_i,v_j} = \begin{cases} 1\; if \{v_i, v_j\} \in E \\ 0\; else \end{cases} \tag{5}$$

and *DD* is the probability distribution of these degrees over the whole network. The *DD(k)* of a network, generally indicated also with *P(k)*, is then defined to be the fraction of nodes in the network with degree *k*. Thus if $||V||=n$ and $n_k$nodes have degree *k*, then $DD(k) = n_k/n$. Generally *DD(k)* can be represented by a probability distribution or a pdf. The term $\delta(v_i)$provides an estimation of the importance of node *v* (it is called also degree centrality), related to the analyzed system domain and based on the number of nodes directly related with it. This concept is strictly related to *DD*. Generally, distributions like the Normal one are used but, from many studies, it has been shown that many real networks cannot follow this trend.

Figure1: An intuitive representation of Random and Scale-free SWNs.

A SWN can contain billions of nodes, as an Internet connection: in order to move from one node to another, few intermediate nodes should be crossed. SWNs are called Random SWNs (*R-SWNs*) when the pdf of *DD(k)* is approximately Poissonian. So, it can be modeled by an exponential function ($pdf_{DD(k)} \sim exp(k)$). SWNs are also called Scale-Free (*SF*), if the pdf can be modeled by a power function ($pdf_{DD(k)} \sim k^c$), where *c* is a constant value. Fig. 1 conceptually shows the difference between random and scale-free SWNs: humans often form scale-free networks where some people are very connected and then others are not. The more connected nodes in a SWN are called hubs or authorities.

Figure 2: Different trends of *DD* pdf for Random (a) and Scale-Free (b) for different parameter values.

In (Albert, 2002) it is shown that a network can be classified as CN, more precisely SWN, if it has a high *CC* (necessary condition) and a small ANDI, with a consequent average path length equal, approximately, to six (quantified in hops number). Fig. 2a shows the trend of the Poisson pdf for Random Networks, while fig. 2b shows the trend of the Power law, with c=2.6.

Regarding the Euler and Milgram's rule about the six degrees of separation, many discussions about the intrinsic meaning of that rule have been made, as in (Backstrom, 2012), showing that in some particular cases, four degrees are enough to describes the particular relationship existing among two nodes. In fact, in (Backstrom, 2012) it is stated that we have to think of the two points as being not five persons apart, but 'five circles of acquaintances' apart—five 'structures' apart." In this sense, people are in fact only four world apart, and not six: on the average, when considering another person in the world, a friend of your friend knows a friend of their friend.

To the aim of our proposal, since $0 \leq CC \leq 1$, a value near to 1 indicates a high connection between neighboring nodes (obviously in a fully connected network this value is exactly equal to 1). Therefore, the first step is to develop a mathematical model with some statistical properties "similar" to the ones of SWN; in this way, it is possible to obtain a platform on which it is possible to perform some mathematical analysis. For the proposed HM, we start from a real regular network (already existing) and, then, we model it in order to consider the obtained topology as a CN (SWN in particular). It will have an average path length L near to six (we based our idea on the classical Milgram's theory) and an average clustering coefficient near to one (as desired). As stated before, natural systems (regular or random) presents complex properties related to internal connections of nodes: traditional network models are not able to express the "complexity" of their connections, so CNs are chosen to do that, by modifying the layout of the starting network. The modeling technique suggested in this chapter has the purpose of shaping a real WSN in a CN with the SW property, with all the benefits that this kind of modeling can carry to the network, in terms of safety, speed and connection stability.

In this chapter, we describe a HM. It is based on DMs insertion (Jiang, 2008) and it considers two types of nodes. One node composed by traditional DMs (urban buses, metropolitan vehicles for example) and the second one composed by nodes with double coverage range (for example, based on two interfaces with different power or two different technologies); we demonstrate that, in this way, it is possible to increase *CC*, with a consequent decrease in the average path length. Depending on the considered mobility model, there are two ways to realize the DM insertion.

If we are considering "deterministic" networks in which, for example, urban buses and sensors follow standard roads, we can decide what route these nodes should follow in order to obtain a complex structure (without deleting routes casually). In this way, DM routes are known and deterministic.

If we are considering a "non-deterministic" network in which, for example, accidents or fires happen in random points or in which sensors are deployed casually, we should investigate on the number (and/or the position) of mules to insert, for reducing battery consumptions (De Rango, 2012; De Rango, 2013) and coverage radius. In this last case, a markovian process (Fazio & Tropea, 2012; Fazio, 2013 November) can describe DMs movements, for example. In particular, Discrete Markov Chain Models (DMCMs) can be considered for this purpose. First of all the geographical area is subdivided in a discrete number of regions, then a state of the chain is associated to each region. That is, given a geographical area A, it can be described as $A=\{a_1, a_2, ..., a_Z\}$, where a_i, $i=1,..,z$, are the considered adjacent zones, as illustrated in fig. 3.

Figure 3: Geographical map subdivision and the associated Markov states.

Associating a state $s_i \in S$, where $S=\{s_1,...,s_z\}$ is the set of the considered Markov chain states, to a zone $a_i \in A$, then it is possible to define the DM transition probability p_{ij}, from state s_i to state s_j (the probability of movement of DM from a_i to a_j):

$$p_{ij} = \begin{cases} \frac{1}{q_i}, & if\, s_i\, and\, s_j\, are\, adjacent \\ 0, & Otherwise \end{cases} \quad (6)$$

where q_i is the number of adjacent areas of a_i and each state $s_i \in S$ represents the condition related to the presence of a DM in a specific area.

By the application of Watts-Strogatz's algorithm, it is possible to reduce the average path-length from $L=n$ to $L'=log(n)$, where n is the number of nodes. So, considering a sensor network composed by n nodes, with an average *DD* equals to k, with $n>>k>>ln(n)>>1$, the related graph $G=<V,E>$with nk/2 edges ($||E||=nk/2$) can be obtained by following the Watts-Strogatz's algorithm. Each node is connected until a regular ring network is obtained, where the n nodes are linked to k neighbors, so $k/2$ for each side. Remembering that $V=\{v_1,\dots,v_n\}$, with $||V||=n$, then the edge $e_i=(v_i,v_j)$ will exist if and only if:

$$0 < |i-j| \, mod\left(n-\frac{k}{2}\right) \leq \frac{k}{2} \quad (7)$$

At this point, for each node v_i, the edge $e_i=(v_i,v_j)$ with $i<j$ is removed and rewired with a certain probability β, where $0< \beta<1$. If the rewiring is made, the old link e_i is replaced by link $e_t=(v_i,v_t)$, where t is chosen uniformly, in order to avoid loops and link duplications.

During the analysis of real cases, it is possible to achieve the goal of path-length reduction by exploiting the urban buses and the mobile routers (as HDMs), equipped with a double radio coverage system. As shown later, it is possible to reach high values of *CC* and lower values of *L*. Intuitively, the number of mobile nodes to insert within the network has an upper bound, which varies according to the physical size of the entire network.

So, HDMs are means that allow to rewire links, adding new shortcuts, without removing any existing node. The main objective of the HM proposal is to model any existing network as a SWN, with CC $\rightarrow$ 1 and route's average length $L \approx 6$, as learned from Milgram's experiences (Milgram, 1967). HDMs, in fact, are not only mobile nodes, but are transmission devices with an increased range: this additional condition makes possible to create some long-range links between different DMs added in the network, drastically reducing the average path length *L*, bringing it at the right condition (near to 6). The special nodes can be implemented by Wi-Fi router with MIMO standard, which use different IEEE standard transmissions as IEEE 802.11n for short-range links (coverage radius r) and UMTS for long-range links (coverage radius r_u).

4 Performance Analysis and Simulation Results

Different simulation campaigns have been carried on in order assess the effectiveness of the proposed idea. First of all a Java simulator has been implemented, able to describe the behavior of a network and to verify the described proposal. It consists of a multi-thread system, based on real maps, extracted from OpenStreetMap (Open Street Map, 2015) and SUMO (SUMO, 2015). In this way, node movements are forced to follow real roads, giving the possibility to obtain more realistic results. We considered two different maps regarding Cosenza (south Italy) and Paris (France), with the same maximum size of 630x1150 m^2. Fig. 4 shows the couple of considered maps. Given the maps below, we considered "deterministic" networks.

Figure4: Geographical map subdivision and the associated Markov states.

In our Java tool, the Graph class has been created, recording every movement of each node and saving the information in a matrix adjacency structure. The pattern is based on one or more objects, called observers (or listeners) that are registered to handle an event that could be generated by the "observed" object. The simulation results are shown before and after the DMs insertion. Simulations have been performed for: a) density calculation, b) calculation of the average path length with only sensor nodes, c) calculation of the average path length by varying the number of special nodes, d) evaluation of the trend of the clustering coefficient. A short coverage range of [70, 100] meters has been considered (we do not specify a particular technology):we assume that fixed sensor nodes can extend their coverage within those values, also on the basis of the path-loss and fading phenomena. As DMs we assumed that public transportation vehicles (such as buses) can be equipped with a standard interface (the same of the sensor nodes) and an extended one (such as 3G or 4G connection). In this way, as shown in the curves, isolated islands of sensors can be connected with a lower number of hops, obtaining a gain in terms of energy consumption. A preliminary campaign has been carried out in order to evaluate the density of the graph for different map dimensions, avoiding considering scattered networks in the whole campaign. In particular, we considered four different areas of simulation: Area 1 of 400x400 m^2 (minimum extension), Area 2 of 550x550 m^2, Area 3 of 550x900 m^2 and Area 4 of 630x1150 m^2 (maximum extension). For the preliminary campaign, the coverage range has been set to 90m.

Figure5: Average shortest path length in the network without special hubs.

From Fig. 5, it is possible to see, only as example, the typical values of the average shortest path length *L* for different area extensions, without the corrections introduced by DMs. When special nodes are inserted into the system, we can observe that we get the expected gains since we have a substantial decrease in the average length of the shortest path. In fact, from Fig. 6, it can be seen how there is huge decrease in the *L* value. In addition, we can notice how there exists an upper bound of the number of DMs to be included within the considered network. It has no sense adding a number of special nodes higher than 9 or 10. It is clear, furthermore, that the variation of *L*, is very similar in the different scenarios.

Figure6: Average shortest path length in the network with special hubs, Cosenza and Paris cases.

Let now see what happens to the system in terms of *CC* (Fig. 7). It represents another key feature in CNs, indicating the ability of a network to create a certain number of SWs. Special HM, once applied, tends to slightly increase this value compared to the one of the original network.

The maximum gain is about two percentage points. As stated before, a value of *CC* near to 1 indicates a high connection between neighboring nodes (obviously, in a fully connected network, such value is equal to 1).

Figure 7: The trend of the average *CC* with and without HDMs, for Cosenza (CS) and Paris (PA).

Figure 8 shows a comparison among the traditional DM insertion method and the proposal of HDMs. In particular, we fixed the map (Paris), the number of added DMs to 10, as suggested by Fig. 6, the short coverage range (R_1) to 100meters (the same range for all fixed sensors). We analyzed what happens to the system in terms of *L* and *CC* when the long coverage range (R_2) is varied into the set [100, 400] meters.

Figure 8:The trend of the average of *L* and *CC* in function of R_2.

It is clear that, in respect of the traditional ferries insertion, there is no dependence on R_2. In fact, for both *L* and *CC* there is a constant trend: the average value are 16.1 (hops number) and 0.512 respectively. For the HDM case, the trend of the curves is heavily affected by R_2: for higher values of R_2, each added HDM is able to cover a bigger area, containing a higher number of sensor nodes. In this way, there is a heavy reduction of the number of hops involved in a generic path. Maintaining the same map size and increasing more the value of R_2 (over the value of 400 meters) the system will reach a value of *L* equal to 2, because each HDM will be able to connect directly source and destination nodes. The decreasing trend will also reflect on the energetic point of view: all the nodes can decrease the transmission power, because the HDM nodes will be able to connect directly more couple of nodes. Referring to *CC*, it is observable that it will reach higher values for bigger covered areas. In this way, all the nodes will have a direct connection with a higher number of neighbors.

5 Conclusions and future trend

This chapter proposed a new approach suitable for complex networks for obtaining the small world character, starting from an original wireless network (WSN in particular). We proposed a hybrid model, able to sensibly reduce the average path length, and increasing (even if only slightly) the average clustering coefficient, thus obtaining those characteristics that mark the complex networks as small-world. The core idea consists of the introduction of hybrid nodes, that is to say data mules equipped with a dual coverage interface. Gaining the small world property may be advantageous, especially for the reduction of the shortest path length. Data mules are also able to perform load balancing along the various paths of the network, avoiding overloads and preventing any performance degradation. The reduction of the average length of the shortest path and the increase of the clustering coefficient contribute to the enhancement of network performance, also in terms of fault tolerance. We also shown how the hybrid behavior of data mules outperforms the traditional approach of single coverage mobile ferries, not able to introduce an additional enhancement in terms of clustering coefficient and path length. We did not consider the energetic point of view, but future research may be based on investigating and evaluating the energetic behavior of sensor nodes, after the introduction of the hybrid data mules. We expect that batteries will have longer durations, since the sensor nodes may reduce the transmission range when under coverage of data mules. In addition, considering the current future trends, we can say that there are many works in literature tending to study analytical models, in order to take into account latency issues, due to the upload and download of data to/from mules. Of course, this is very suitable in DTNs, where nodes are able to spend time to receive the needed information. Other current studies regards the possibility of implementing peer-2-peer communication protocols, able to give the possibility to mobile data mules to exchange some signaling messages, aimed at the optimization of upload/download operations. Additional works regards the possibility to increase the sensor sleep time, without the needing of staying continuously in listening mode to find-out if a mule is under coverage.

References

Albert R.; Barabási A.-L. (2002). Statistical mechanics of complex networks. Reviews of Modern Physics. 74: pp.47–97.

Androutsos, P., Androutsos, D., & Venetsanopoulos, A. N. (2006). A distributed fault-tolerant MPEG-7 retrieval scheme based on small world theory.Multimedia, IEEE Transactions on,8(2), 278-288.

Backstrom, L., Boldi, P., Rosa, M., Ugander, J., & Vigna, S. (2012, June). Four degrees of separation. InProceedings of the 4th Annual ACM Web Science Conference(pp. 33-42). ACM.

Banerjee, A., Agarwal, R., Gauthier, V., Yeo, C. K., Afifi, H., & Lee, F. B. (2012). A self-organization framework for wireless ad hoc networks as small worlds.Vehicular Technology, IEEE Transactions on,61(6), 2659-2673.

Boyd, D., Ellison, N. (2007). Social Network Sites: Definition, History, and Scholarship. Journ. of Computer-Mediated Comm., 13, article 11.

Chakrabarti, Sabharwal A., Aazhang A. (2003). Using PredictableObserver Mobility for Power Efficient Design of Sensor Networks. Proc. IPSN 200, Palo Alto, USA.

Chakraborty, A., Manoj, B.S. (2014). The Reason Behind the Scale-Free World. Sensors Journal, IEEE, 14(11), pp. 4014-4015.

Chung, F., & Lu, L. (2002). The average distances in random graphs with given expected degrees.Proceedings of the National Academy of Sciences,99(25), 15879-15882.

Chung, F., & Lu, L. (2002). Connected components in random graphs with given expected degree sequences.Annals of combinatorics,6(2), 125-145..

De Rango F., Gerla M., Marano S. (2006). A scalable routing scheme with group motion support in large and dense wireless ad hoc networks. Computers & Electrical Engineering 32 (1), 224-240.

De Rango, F., Tropea, M., Laratta, G.B., Marano, S. (2008). Hop-by-Hop Local Flow Control over InterPlaNetary Networks Based on DTN Architecture. In Communications, IEEE International Conference on, pp.1920-1924, 19-23 May.

De Rango F., F. Veltri, P. Fazio, S. Marano (2009). Two-level trajectory-based routing protocol for vehicular ad hoc networks in freeway and Manhattan environments. Journal of Networks 4 (9), 866-880.

De Rango, F., Guerriero, F., & Fazio, P. (2012). Link-stability and energy aware routing protocol in distributed wireless networks.Parallel and Distributed Systems, IEEE Transactions on,23(4), 713-726.

De Rango F., Amelio S., Fazio P. (2013). Enhancements of epidemic routing in delay tolerant networks from an energy perspective. 9th International Wireless Communications and Mobile Computing Conference, IWCMC 2013 pp. 731 – 735.

De Rango F., Amelio S., Fazio P. (2014). Epidemic Strategies in Delay Tolerant Networks from an Energetic Point of View: Main Issues and Performance Evaluation. In Journal of Networks 10 (01), 4-14.

Erdős, Paul, A. Rényi (1960). On the evolution of random graphs. Pub. of the Mathematical Institute of the Hungarian Academy of Sciences, pp. 17–61.

Fazio P., De Rango F., Sottile C. (2012). An on demand interference aware routing protocol for VANETS. Journal of Networks 7 (11) pp. 1728 – 1738.

Fazio, P., & Tropea, M. (2012). A new markovian prediction scheme for resource reservations in wireless networks with mobile hosts.Advances in Electrical and Electronic Engineering,10(4), 204-210.

Fazio, P., De Rango, F., Sottile, C., Santamaria, A.F. (2013). Routing optimization in vehicular networks: A new approach based on multiobjective metrics and minimum spanning tree. International Journal of Distributed Sensor Networks.

Fazio, P., Tropea, M., Marano, S., & Sottile, C. (2013, November). Pattern prediction in infrastructured wireless networks: Directional vs temporal statistical approach. InWireless Days (WD), 2013 IFIP(pp. 1-5). IEEE.

Guidoni, D.L., Mini, R.A.F., Loureiro, A.A.F. (2008). Creating small-world models in wireless sensor networks. Personal, Indoor and Mobile Radio Communications, PIMRC, IEEE 19th International Symposium on.

Guidoni, D. L., Mini, R. A., & Loureiro, A. A. (2012). Applying the small world concepts in the design of heterogeneous wireless sensor networks.Communications Letters, IEEE, 16(7), 953-955..

Huang, Jie, Xie, Qihui, Huang, Bei (2012). Creating Small-World Model for Homogeneous Wireless Sensor Networks. Wireless Communications, Networking and Mobile Computing (WiCOM), 8th International Conference on , Page(s): 1 - 4.

Jain S., Shah R., Brunette W., Borriello G., Roy S. (2006). ExploitingMobility for Energy Efficient Data Collection in Wireless Sensor Networks. ACM/Springer Mobile Networks and Applications, Vol.11, pp. 327-339.

Jea D., Somasundra A., Srivastava M. (2005). Multiple ControlledMobile Elements (Data Mules) for Data Collection in SensorNetworks. Proc. IEEE DCOSS 2005, Marina del Rey, USA, 2005.

Jiang, C. J., Chen, C., Chang, J. W., Jan, R. H., & Chiang, T. C. (2008, June). Construct small worlds in wireless networks using data mules. InSensor Networks, Ubiquitous and Trustworthy Computing, 2008. SUTC'08. IEEE International Conference on(pp. 28-35). IEEE.

Mainwaring A., Polastre J., Szewczyk R., Culler D., Anderson J. (2002). Wireless Sensor Networks for Habitat Monitoring. Proc. ACM WSNA, pp. 88-97 Atlanta, USA.

Milgram, S. (1967). The small world problem.Psychology today, 2(1), 60-67.

Molinaro A., De Rango F., Marano S., Tropea M. (2005). A scalable framework for in IP-oriented terrestrial-GEO satellite networks. Communications Magazine, IEEE 43 (4), 130-137, 2005.

Open Street Map (2015), https://www.openstreetmap.org/

Pentland S. A., Fletcher R., Hasson A. (2004). DakNet: Rethinking Connectivity in Developing Nations. IEEE Computer, vol. 37, no. 1, pp. 78-83.

Petrou, M., Tabacchi, M.E. (2009). Networks of concepts and ideas. Computer Journal.

SUMO Mobility manager (2015), http://sourceforge.net/projects/sumo/

Verma, C. K., Tamma, B. R., Manoj, B. S., & Rao, R. (2011). A realistic small-world model for wireless mesh networks.Communications Letters, IEEE,15(4), 455-457.

Watts, Duncan J.;Strogatz, Steven H. (1998). Collective dynamics of 'small-world' networks. Nature 393(6684), pp.440–442.

Xiaojuan Luo, Huiqun Yu (2010). Constructing wireless sensor network model based on small world concept. Advanced Computer Theory and Engineering (ICACTE), 3rd International Conference on, Vol.5, pp. 501-505.

Yan C., Qiao Ji-Hong (2010). Application analysis of complex adaptive systems for WSN. Computer Application and System Modeling (ICCASM), International Conference on (Volume:7).

Zhou B., Lee Y.Z., Gerla M., De Rango F. (2006). Geo-LANMAR: a scalable routing protocol for ad hoc networks with group motion. Wireless Communications and Mobile Computing 6 (7), 989-1002.