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Sensor networks powered by solar energy using multiple radio channels

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PREPARAÇÃO DA DISSERTAÇÃO

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February 18, 2015

Resumo

Future Cities é um projecto implementado na cidade do Porto que pretende transformar a cidade num laboratório vivo à escala urbana, onde novas tecnologias, serviços e produtos, podem ser desenvolvidos, testados e avaliados. Um dos desafios por endereçar é a criação de um sistema de video-vigilâcia de baixo custo, alimentado a energia solar e baseado em Wi-Fi, capaz de cobrir grandes zonas não ligadas à rede, como praias e parques. Os nós deste sistema possuirão poucos recursos em termos energéticos, de processamento e de memória. Devido a isto, e também devido à finalidade do sistema, verifica-se que este se enquadra na definição de rede de sensores multimédia sem fios. As principais limitações deste sistema serão a sua capacidade e o seu tempo de vida.

Neste relatório apresentam-se as soluções, que são consideradas estado da arte, para ultrapassar as limitações relacionadas com a capacidade e o tempo de vida do sistema. São também apresentadas um conjunto de simulações computorizadas que permitem analisar mais pormenorizadamente o seu funcionamento. Por fim é apresentada a solução proposta para superar as limitações impostas pelo sistema a ser implementado. Esta solução englobará a utilização de múltiplos canais rádios para aumentar simultaneamente a capacidade da rede e o seu tempo de vida.

Abstract

Future Cities is a project implemented in the city of Porto which aims to transform this city in an urban-scale living lab, where new technologies, services and products, can be developed, tested and evaluated. One of the challenges still unsolved is the creation of a low-cost solar powered video-surveillance systems based in Wi-Fi, to cover large unconnected areas such as parks or beaches. The nodes of this system will possess low resources in terms of energy, processing, and memory. Due to this, and also due to the overall goal, this system can be classified as a Wireless Multimedia Sensor Network. The main limitations of this system will be its capacity and its lifetime.

In this report are presented the solutions that are considered state of the art, to surpass the limitations regarding the capacity and lifetime of this system. There are also exposed a set of computer simulations that allow to analyse in detail its operation. At last is presented the proposed solution to overcome the limitations imposed by the system to be implemented. This solution will use multiple radio channels to simultaneously increase the network capacity and its lifetime.

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Abbreviations

WMSN	Wireless Multimedia Sensor Network
WMSNs	Wireless Multimedia Sensor Networks
WSN	Wireless Sensor Network
WSNs	Wireless Sensor Networks
WMN	Wireless Mesh Network
WMNs	Wireless Mesh Networks
EMRP	Energy-Aware Mesh Routing Protocol
HWMP	Hybrid Wireless Mesh Protocol
ETE	Expected Transmission Energy
IEEE	Institute of Electrical and Electronics Engineers
MIMO	Multiple Input Multiple Output
SSCH	Slotted Seeded Channel Hopping
LB-MCP	Load Balancing Multi Channel Protocol
CSMA/CA	Carrier Sense Multiple Access Collision Avoidance
TDMA	Time Division Multiple Access
TH-UWB	Time-Hopping Ultra-Wide Band
QoS	Quality of Service
ETE	Expected Transmission Energy
NS-3	Network Simulator 3
kbps	Kilobits per Second
Mbps	Megabits per Second

Chapter 1

Introduction

1.1 Context

Future Cities is a project that is currently being implemented in the city of Porto, in Portugal. The main idea of this project is to transform the city of Porto in an urban-scale living lab, where new technologies, services and products, can be developed, tested and evaluated. These technologies, services and products can explore several subjects like sustainable mobility, urban-scale sensing or even the quality of life of the citizens.

One of the challenges still unsolved is the creation of low-cost solar powered video-surveillance systems based in Wi-Fi, to cover large unconnected areas such as parks or beaches. These systems fit in the definition of Wireless Multimedia Sensor Network (WMSN). WMSNs are networks of interconnected wireless devices, that allow retrieving multimedia content, like video streams, audio streams or static images. WMSNs are a recent technology that emerged from Wireless Sensor Networks (WSN), which in its turn emerged from Wireless Mesh Networks (WMN). As stated in [1] these networks can be useful in numerous applications such as person locator systems, traffic avoidance systems, control systems, environmental monitoring systems and multimedia surveillance systems.

1.2 Problem Characterization

This thesis, focuses on the design of a networking solution to improve the performance of a Carrier Sense Multiple Access (CDMA) based WMSN, regarding two major factors: the network capacity and the network lifetime. The network capacity is a major limitation because the WMSN has to be capable of transmitting large amounts of data, extracted from the video-surveillance system, to the appropriate destination, within a minimum pre-defined delay time. Capacity can clearly limit the network performance, if not taken into account. The network lifetime is also a major limitation, since it is expected to deploy a WMSN powered by solar energy, and due to this fact the network lifetime may be greatly reduced, restraining the network operation.

It is essential to come up with solutions to overcome these limitations, in order to deploy a functional, reliable and effective WMSN. This is really important since this emerging type of network can bring great advantages as stated in [1]. This work focuses on trying to design a single solution that, at the same time, increases the network capacity and extends the network lifetime. By doing this, it is possible to improve the performance of WMSNs, allowing them to transmit a higher amount of multimedia data, within a minimum pre-defined delay time, and increasing the period in which they can collect information. This allows the deployment of WMSNs with better characteristics in terms of performance and reliability.

There are several strategies to increase the capacity of the network and to extend its lifetime. This thesis will adopt a multi-channel approach. With this approach it will be possible to increase the network capacity and, with a proper dynamic channel assignment procedure, it will also be possible to extend the network lifetime. Thus this thesis attempts to specify an energy-aware channel assignment algorithm which takes into account the battery level of the WMSNs nodes, and the solar energy availability. The idea is to develop a centralized channel assignment algorithm capable of adapting to changes in the energy parameters of the network. The reason behind the centralized approach has to do with the low processing and memory resources, owned by the WMSN nodes.

The energy-aware channel assignment algorithm that it is expected to be developed is an improvement of the channel assignment algorithm named TILIA described in [2]. The idea is to add an energy factor to this channel assignment algorithm, in order to adapt TILIA to situations where the energy availability is a strong limitation.

1.3 Contributions

The main expected contribution of this thesis will be a centralized energy-aware channel assignment algorithm for WMSNs capable of extend the lifetime of the network. This algorithm will take as input the network graph, with all the gateways and all the connections between the network nodes, and will output the channel assigned to each node.

The second expected contribution of this thesis will be the identification of the topology metrics that affect the most the WMSNs lifetime.

1.4 Structure

This document is organized in four more chapter. In chapter 2 are presented the state-of-the-art solutions to increase the network capacity and to achieve energy efficiency in wireless multi-hop networks. In chapter 3 are presented some computer simulations which analyse the capacity and the delay characteristics of wireless multi-hop networks with regular topologies. In chapter 4 is revealed the proposed solution, the methodology to be adopted, the tools to be used and the planning of the future work. In chapter 5 is presented the final conclusion of this report.

Chapter 2

State-of-the-Art

The first section of this chapter, presents a set of procedures that can be used to increase the capacity of wireless multi-hop networks based in Wi-Fi. The second section of this chapter exposes a set of approaches, proposed to save the energy resources of wireless multi-hop networks. This chapter concludes with an analysis relating the solutions capable of increasing the network capacity with the energy saving solutions. This analysis will then be useful for the development of the solution for the problem proposed in this thesis.

2.1 Capacity of Wireless Multi-Hop Networks

The collection of multimedia data normally generates large volumes of data which requires a high capacity network, capable of transmitting all the information to its destination, within a certain time interval. The network capacity depends on many factors like the network architecture, network topology, traffic patterns, network node density, number of communication channels used for each node, transmission power level and node mobility, as stated in [3]. Since there are many factors that influence the network capacity there are also several approaches designed to increase it. This section presents the relevant approaches and solutions that combine them. Special attention is given to a channel assignment proposal due to its importance for this thesis.

2.1.1 Capacity Improvement Approaches

There are numerous ways to improve the capacity of wireless multi-hop networks, being the following the most adopted approaches:

Reduce Interference: In order to increase the network capacity it is possible to design solutions to reduce, or to completely avoid, the interference between simultaneous communications. By doing this, the number of possible simultaneous communications increases, allowing to achieve a higher network capacity. For instance, in [4] is proposed a routing metric, designated iAWARE, which aims to reduce the interference in the network, increasing its throughput. In [5] the authors propose a solution that, based on a channel assignment procedure, modifies the network topology to minimize the interference, increasing the throughput and the QoS of the network.

Design Routing Protocols/Metrics: It is possible to take advantage from routing protocols and metrics to achieve a higher network capacity. In [6] is studied the performance gain, in terms of throughput, obtained by making routing decisions with the awareness of network coding. In [7] is proposed a set of metrics to enable the routing protocol to find paths with low levels of interference, reliability in terms of packet success rate, and high available transmission rate.

Using Multiple Communication Channels: One of the most common approaches to increase the network capacity is to use multiple communication channels in the same wireless multi-hop network. This approach enables to have a higher amount of simultaneous communications which substantially increases the overall throughput of the multi-hop network. This type of approach is referred in [8] and in [9].

Using Multiple Network Interfaces: Using multiple networks interfaces can also be used to increase the capacity of a wireless multi-hop network. By combining this approach with the multiple channel approach it is possible to achieve a much more better performance in terms of capacity. In [10] is specified a channel assignment algorithm to be used in multi-radio WMNs that avoids interference by trying to assign non-overlapping channels to nodes which are near from each other. In [11] is proposed a network model for analysing the capacity of multi-radio multi-channel WMNs.

2.1.2 Capacity Improvement Solutions

Combining the approaches above described several researchers come up with concrete solutions to enhance the capacity of wireless multi-hop networks. In [12] is proposed a link-layer protocol, named SSCH, that uses frequency diversity, with orthogonal channels, to increase the network capacity of the IEEE 802.11 standard. The idea of the protocol is to switch the channels of the nodes that want to establish communication, in order to overlap them. At the same time, the protocol avoids to interfere with the nodes that are not interested in that particular communication, by assign them non-overlapping channels. To allow the communication between all the neighbour, each node has a frequency hoping pattern which is regularly broadcasted. SSCH can be applied in both single-hop and multi-hop wireless networks, and requires only a single radio interface per node.

In [13] it is theoretically demonstrated that it is feasible to increase substantially the capacity of interference-limited wireless networks, by using antenna spatial diversity (multiple antennas) together with optimum combining. By making use of multiple antennas in the same communication, it is possible to improve the reliability of a wireless link, because, even if one the antennas receive a weak signal, it is likely that one of the other antennas receives the signal in good conditions. With optimum combining it is possible to join all the different received signals and obtain a reliable representation of the original signal.

In [14] the authors exposed a solution to increase the throughput of wireless networks, based on a radio technology designated Pulsed Time-Hopping Ultra-Wide Band. With this technology it is possible to strictly limit the radiated power, without sacrificing the acceptable data rate required. Instead of using protocols like CDMA/CA or TDMA to manage interference and multiple-access, this solution adopts a rate control strategy. By taking advantage of the pulse nature of TH-UWB it is possible to reduce the impact caused by the interferences, increasing significantly the network throughput.

In [15] it is demonstrated that by introducing one dimensional mobility in the nodes of some ad-hoc networks, it is feasible to significantly improve the network capacity. The idea that the mobility of the nodes can enhance the capacity of the network is also present in [16].

In [17] is disclosed a routing protocol, designated LB-MCP, to be used in wireless multi-hop networks, which aim to extend infrastructure networks that own several access points. The wireless multi-hop network must have a multi-channel architecture, and each node of the network must have only one network interface. This routing protocol tries to balance the traffic load in each one of the network channels, enhancing their utilization and hence increasing the capacity of the network. Each node discover several routes to the access points, and choose the one that originates a more balanced traffic load, maintaining all the other routes for backup purposes.

In [18] it is stated the fact that the use of multiple channels in a wireless network improves the network capacity, and it is presented a routing protocol specified to multi-hop networks, with multiple channels and multiple interfaces in each node, and an algorithm to assign the channels to the nodes interfaces. The use of multiple channels in order to increase the capacity is also present in the standard 802.11a which offer 12 non-overlapping channels as is described in [19]. In [20] is proposed a multi-channel WMN architecture, designated Hyacinth, that equips each one of the WMN nodes with multiple 802.11 network interface cards. Together with the architecture of the network, the authors presents also a distributed channel assignment and routing algorithm, which uses only the local traffic load information to dynamically assign channels and route packets. In [21] is exposed a link layer protocol and a routing protocol for increasing the capacity in multi-channel networks. The link layer protocol was designed to be implemented over 802.11 hardware, and the routing protocol was designed to be used in multi-channel and multi-interface wireless networks. In [22] it is stated that if the number of network interfaces on the nodes is smaller than the number of available channels, there will be a degradation in the network capacity in many scenarios.

2.1.3 TILIA Algorithm

This sub-section focuses on the TILIA algorithm, described in [2], since this thesis is based on this algorithm. TILIA is a centralized channel assignment algorithm for single radio WMNs. This algorithm tries to improve the performance of multi-channel single radio WMNs by assigning the best channel to each node, using solely the network topology information. It adopts a centralized approach because WMNs are normally formed by low cost nodes, with small memory and reduced processing capability. So the main goal of TILIA is to centrally assign the channels in which WMN's nodes will operate, optimizing the network performance and avoiding to disconnect it. To do this, TILIA uses a breadth-first tree growing technique, but instead of growing a single tree, it grows a forest, which is composed by several trees rooted at each gateway. Each tree operates in a different radio channel, avoiding interference between them. The growth of the trees is simultaneous and their union spans the network. In Table 2.1 is presented the meaning of some terms used to describe TILIA algorithm.

Term	**Meaning**
Gateway	Special node of the network which is the destination of most of the traffic generated by the other nodes. It is usually connected to an infra-structured network
Tree	Set of nodes that communicate with the same gateway
Forest	Set of trees that span the WMN
Parent	When a node, that isn't in the neighbourhood of a gateway, wants to send information, it forwards the data to his parent
Tree Load	Assuming that the total traffic of each node is constant (λ), the tree load is given by $\sum_{v \in V_{gi}} \lambda d(v, gi)$, where v represents a node, *Vgi* represent the set of nodes that are attached to the tree i and *d(v,gi)* is the hop count between the node v and its gateway gi. Since the total traffic of each node is assumed to be constant, it's possible to remove this parameter from the tree load expression: $\sum_{v \in V_{gi}} \lambda d(v, gi)$
1st Ring	Nodes which are only one hop count away from the gateway

Table 2.1: TILIA terms

TILIA requires, as input, the network graph, with all the nodes and links between them, and the location of the existent gateways. Given the required input, it starts by initialize a tree in each one of the existent gateways and analyses the network nodes, one by one, attaching them to the best tree. Every time a node is attached to a certain tree, TILIA carefully selects the next node to be analysed. First the algorithm chooses the nodes which are neighbours from a previously attached node, and selects the ones with the lower hop count to the closest gateway. From these nodes it picks the nodes which have the smallest number of nearby channels and then it picks the nodes which have the smallest number of nearby parents. Then it selects the nodes with the lower number of hidden links and randomly chooses one of these nodes. For the selected node TILIA determines the most appropriate channels. In order to do this it finds the channels which were previously assigned to the neighbours of the selected node, and selects the ones that belong to the trees with the lower traffic load. After that, based on the set of channels selected, TILIA determines the best parent candidates, for the selected node. To do this it starts by selecting the neighbours operating in one of the channels of the set. Then it chooses the ones with the lower hop count to their respective gateway, and, from this set, picks the ones which are attached to the trees with the smallest traffic load. Finally, from the set of candidate parents obtained, are picked up the ones that present less problems due to hidden nodes. If after this selection only remains one candidate parent, the node is attached to the tree of this candidate and selects him as his parent. If the set of candidate parents is greater than one but there is only one parent in the first ring, the node selects him as his parent. If the set of candidate parents is greater than one, and there isn't any candidate in the first ring, the node randomly selects one of the candidates to be his parent. If the set of candidate parents in the first ring is greater than one, the TILIA algorithm employ a recursive procedure to explore all the possible alternative forests. By using recursion, the TILIA algorithm allows to create alternative forests, and then select the forest that present the best characteristics, according to a certain metric. This is done because after several computer simulations it was discovered that the network topology near the gateways, had great impact in the overall performance of the network. This procedure is repeated for every node in the network until all the nodes have been assigned with a channel, and belong to a certain tree. In the end of the algorithm is used a metric, denominated *tmet*, to determine the forest that leads to the better network performance. This metric is exposed in Equation 2.1.

$$tmet: \quad \theta = k_l\theta_l + k_lb\theta_lb + k_r1\theta_r1 + k_r1b\theta_r1b + k_m\theta_m \tag{2.1}$$

The *tmet* metric is composed by five components that enable to measure the performance of the forest. These five components are:

Total Load (θ_l): This component represents the ratio between the minimum load of the network and the sum of all the loads of the trees that constitute the forest. In the best case $\theta_l = 1$ and this occurs when the load on the forest equals the minimum load of the network.

Total Load Balancing (θ_lb): This component represents the fairness of the load distribution among all the trees that constitute the forest. In the best case $\theta_lb = 1$ and this occurs when all the trees have exactly the same load.

Total Number of 1st Ring Nodes (θ_r1): This component represents the ratio between the sum of the connectivity degree of the trees and the size of the set that contain the gateways neighbours of the original network. In the best case $\theta_r1 = 1$ and this occurs when all the nodes in the neighbourhood of gateways of the original network are assigned to one of their closest gateways.

1st Ring Balancing (θ_r1b): This component represents the fairness of the distribution of 1st ring nodes among the gateways. In the best case $\theta_r1b = 1$ and this occurs when the sizes of the 1st ring of each tree are equal.

1st Ring Miss Ratio (θ_m): This component measures the hidden node problem on the gateways neighbourhood. In the best case $\theta_rm = 1$ and this occurs when there are no hidden nodes in the gateways neighbourhood.

To each of these component is attached a weight which represents the importance of that particular component to the network performance. The higher this weight the more important is the component associated. So, given all the possible forests, TILIA algorithm selects the one with the higher *tmet* metric, since that forest is probably the one that achieves greater performance. In Figure 2.1 is presented a possible forest, with the respective trees, for a WMN with three gateways and nine nodes. In Figure 2.2 is presented an alternative forest, that result from the TILIA recursive procedure, for the same WMN.

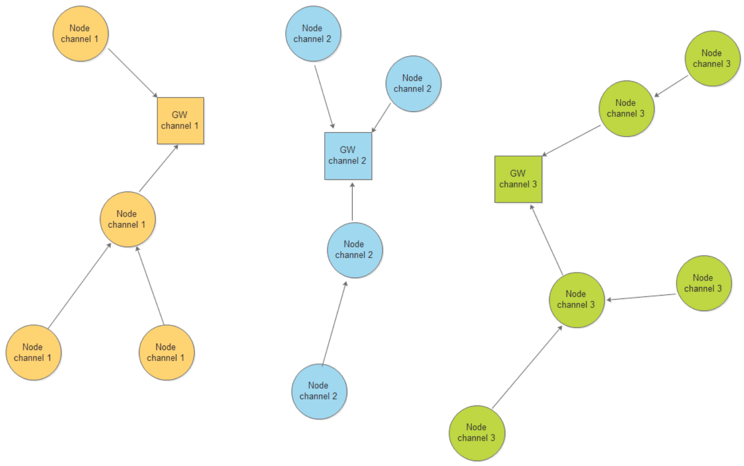


Figure 2.1: TILIA forest example

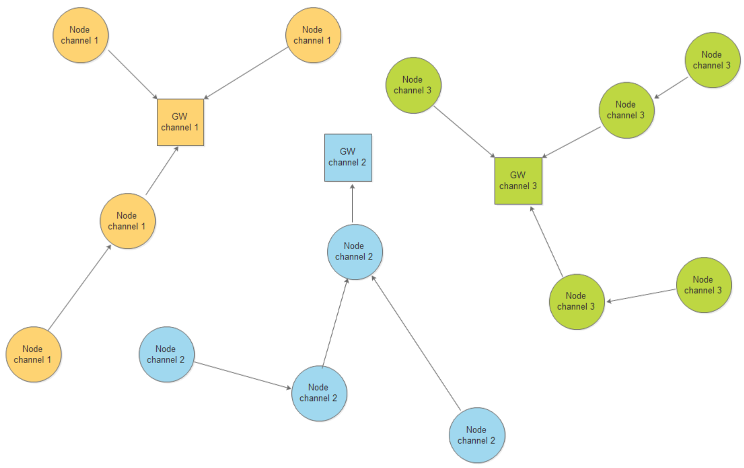


Figure 2.2: TILIA alternative forest example

2.2 Lifetime of Wireless Multi-Hop Networks

In order to deploy wireless multi-hop networks it is necessary to have an energy source to power the nodes, since the capacity of the existing batteries has strong limitations. If the network is deployed in an outdoor environment, the best option to obtain the necessary power for the network operation is to take advantage from solar energy. However, the uncertainty related to the solar energy availability can be a major problem, and so it is necessary to assure that the network does not breakdown during scenarios of low availability of solar energy. In this section are presented some of the existent solutions to extend the lifetime of wireless multi-hop networks.

2.2.1 Lifetime Extension Approaches

To decrease the energy consumption of wireless multi-hop networks is possible to modify several aspects of their functioning. As stated in [23] the main energy-efficient mechanisms are:

Radio Optimisation: The radio is the component which mostly affects the battery depletion of the nodes in wireless multi-hop networks. So by optimising the radio parameters, a great improvement can be obtained, in terms of energy efficiency. It is feasible to do this by optimising the radio modulation, transmission power, the type of antennas or by adopting an cooperative communication scheme. In [24] is showed that is possible to minimize the energy consumption, satisfying some given throughput and delay requirements, by optimizing the transmission time. In [25] is presented a study about the energy efficiency of three distinct modulations schemes. In [26] is described an algorithm for transmission power control, which improves the energy efficiency. In [27] is presented a study about the use of directional antennas for energy efficiency. In [28] is stated that is possible to achieve better energy performance, in sensor networks, by using cooperative MIMO techniques.

Data Reduction: Energy-efficiency can be achieved by reducing the amount of traffic that is transferred on the network. In order to do this, it is conceivable to use information aggregation techniques such as adaptive sampling, network coding algorithms or compression methods. A survey about data aggregation techniques is available in [29]. In [30] is presented a study that adjusts the sampling frequency, in a human activity recognition application, according to the level of movement. In [31] is described a network coding algorithm that improves the energy efficiency of the network, and a survey about data compression techniques can be consulted in [32].

Sleep/Wakeup Schemes: To minimize the amount of energy wasted by the nodes, it is viable to use schemes that temporarily put the nodes in sleep mode, when they aren't in an active mode. A device that is capable of implementing a passive wake-up radio sensor network, is presented in [33]. In [34] is presented a solution capable of minimizing the energy consumption of a WSN by activating only a subset of the existent nodes.

Energy-Efficient Routing: The energy drained from the nodes can increase significantly, if they are systematically chosen to forward packets that are destined to other nodes. Thus the routing algorithm could really affect the network lifetime, if not done carefully. In [35] are described two energy aware cost based routing algorithms, and in [36] is presented a multipath routing protocol.

Battery Repletion: The use of rechargeable batteries in the network nodes can really improve the network energy efficiency. By using solar energy, wind energy or even wireless charging to recharge these batteries, it is possible to increase the network lifetime. A survey about various aspects of energy harvesting sensor systems is available in [37]. In [38] is presented a study about wireless charging in WSNs.

2.2.2 Lifetime Extension Solutions

Based on the mechanisms above referred, several researchers come up with energy-efficient solutions that can be applied in wireless multi-hop networks, in order to increase their lifetime. In [39] the authors present a study about the behaviour of batteries, which declares that the discharged power of the batteries is higher than the power actually needed. The study also states that this over-discharged power can be recovered, if the battery has a sufficiently long recovery time. Based on this battery behaviour, the authors developed two algorithms to extend wired network infrastructures: the coverage algorithm and the back-haul routing algorithm. The main idea of the coverage algorithm, is to adjust the transceivers radius of the network nodes, in a collaboratively way, allowing them to recover the over-discharged power, while providing the necessary network coverage for the network clients. As for the back-haul routing algorithm, the objective is to forward the packets of the network nodes, to their neighbours with the lower over-discharged power. With these two algorithms it is viable to improve the energy efficiency of the network, by providing the necessary recovering time to the nodes with higher over-discharged power.

In [40] was created an algorithm which aim to turn off the largest possible number of radio interfaces, while maintaining a certain level of performance. So when the network load decreases the algorithm turn off some radio interfaces, and when the network load increases the algorithm turn on more radio interfaces. When a radio interface is turned on, its channel is carefully selected to better use the network resources. By doing this the algorithm can save power since the unnecessary radio interfaces are turned off. This algorithm assumes that the channel assignment and routing decisions were already made, and only tries to optimize the energy efficiency of the network.

In [41] was created a new routing metric for WSNs which takes in account the energy factor. To do this the authors take the HWMP airtime metric, defined in IEEE 802.11 standard, which reflects the amount of channel resources consumed by transmitting the frame over a certain wireless link, and add an energy factor to this metric. The authors assume that every node is considered equally important in the WMN and the objective is to ensure that each one of them consumes a similar quantity of energy. Thus they come up with a metric, named ETE, that takes into account the remaining energy (after transmission) and the initial energy of the nodes along the route.

In [42] is defined a new routing algorithm destined to WMNs which use solar energy and wind energy as a power supply. In order to save the power of the nodes, this routing algorithm specifies a new routing metric based on the traditional minimum hop metric. The idea is to add a hop penalty factor to the minimum hop metric, based on the remaining energy of the nodes. For every possible route between two nodes, a routing cost value is calculated. Each node in the route adds a penalty, based on its remaining energy, and the route with the lowest routing cost value is selected as the best route.

In [43] is proposed a new routing algorithm, for WSN's, named EMRP. This algorithm divides the network in several clusters and in each cluster, a cluster head is selected. This cluster head is responsible for aggregate the information of every other element of the cluster, and send it to a base station. The base station is the destination node of the information of all the nodes in the network. The EMRP is an event-driven cluster based algorithm, which means that clustering and data transmission to the base station, only happens when a certain event occurs. To save the power of the network the cluster head is chosen based on the energy available in the nodes. Thus the nodes with higher energy are the ones which are selected. That way the algorithm avoids using the nodes with low energy level to forward information, of other nodes, to the base station. In what concerns the routing problem there are two different situations: when the cluster head is in the transmission range of the base station and when the cluster head is out of the transmission range of the base station. In the first case the cluster head aggregates the information of the cluster nodes, and sends it directly to the base station. In the second case the cluster head tries to discover two relay nodes to the base station: a relay node and a backup relay node. This relay node discovering is repeated by the nodes elected by the cluster head, until a relay node in the transmission range of the base station is found. Then, by monitoring the energy of each of the relay nodes, this algorithm can switch between the two paths in order to achieve energetic efficiency. By adopting this switching strategy this algorithm provides reliability of routing paths, even load balance and energy efficiency.

2.2.3 Network Failure Point

To analyse the proposed solutions is necessary to precisely define the circumstances in which is considered that the network failed. This is equivalent to define the meaning the term network lifetime. This definition is crucial in order to compare two distinct algorithms, since the comparison is only valid if both algorithms are evaluated by the same criteria. In [39] the lifetime of the network is defined as the duration between the network set up and the moment when the routers can no longer cover the entire area. In [41] the network is considered active while there is, at least, one active node. However the author keeps track of the moment when each node becomes inactive, which allows to have a detailed record of the network behaviour regarding its lifetime. In [43] the simulation is executed until all the nodes which have the base station in their transmission range, become inactive. In [35] the lifetime of network is considered to be the amount of time between the network set up and the moment when the first node depletes its energy. There are also approaches that define the lifetime as the period between the network set up and the moment when a percentage of the network nodes depletes its energy, as is referred in [44].

From the examples above referred it is noticeable that the definition of lifetime is not universal, and is very dependent of the type of application of the network. Due to this is necessary to precisely define the meaning of the term lifetime before evaluate a certain energy efficient solution. In this thesis will be adopted the definition proposed by [43]. We will consider that the network is active until all the nodes which have the gateway in their transmission range, became inactive. This approach makes sense in the context of this thesis, because when all the nodes that can reach the gateways, become inactive, the video-surveillance system will fail since not even a single node will be capable of transmitting the video information to the appropriate destination.

2.3 Conclusion

The first section of this chapter described a set of approaches to improve the capacity of wireless multi-hop networks, such as reduce the interference, designing new routing protocols and metrics, using multiple communications channels and using multiple network interfaces. Given these approaches, it were exposed several solutions, proposed by different authors, to surpass this problem. In the second section of this chapter it were presented the most important parameters that affect the lifetime of wireless multi-hop networks. Given these parameters, it were exposed some solutions capable of reducing the energy waste in these networks.

By analysing all the possible approaches and solutions capable of increasing the capacity of wireless multi-hop networks we have conclude that the best option is to use multiple communication channels. Using multiple communication channels allows us to have several simultaneous communications without having interference between them, and the complexity associated to this type of approach is reasonably acceptable. This type of approach is very dynamic since it is possible to add a new communication channel, if there is an increment in the number of nodes of the network, or to remove some of the existing communication channels, if there is a decrement in the number of nodes of the network. In what concerns energy efficiency, we can use a channel assignment algorithm, capable of modifying the network topology according to the energy of the nodes, to extend the lifetime of the network. If this channel assignment procedure is done regularly it is possible to adapt to changes in the energy levels of the network, avoiding, for example, to forward traffic through nodes with low remaining energy.

To conclude we can point out that the research regarding the state of the art, in what concerns capacity and energy efficiency of wireless multi-hop networks, allowed us to determine the best approach to solve the proposed problem.

Chapter 3

Wireless Multimedia Sensor Network Simulation

In order to better understand the behaviour of WMSNs a set of simulations were carried out. By modifying the number of nodes in the network, the number of gateways/channels and the traffic rate of each node, it was possible to gain insight about the response of the network. This chapter presents the methodology and the results obtained in these simulations, focusing specially on the network capacity and network delay.

3.1 Methodology

To analyse the behaviour of WMSNs three main parameters were taken into account: the number of nodes in the network, the number of gateways/communication channels and the traffic rate of each node. The simulations were performed in a 3x3, 4x4 and 5x5 grid topology, and each topology was tested with 1, 2, 3 and 4 gateways/communication channels. Each one of these configurations was simulated with a traffic rate of 500kbps and 1Mbps. When multiple communications channels were used, it was necessary to run TILIA algorithm to assign a channel to each node. In Appendix A is exposed the graphical representation of all the topologies simulated, before and after the TILIA channel assignment procedure. In the images on the left, the red circles represent the gateways and the black squares represent the ordinary nodes. The numbers identify the node, and the lines between the nodes represent link layer connectivity. Both vertical and horizontal links measure 100 meters. In the images on the right, the nodes with the same colour have the same communication channel, and the lines with an arrow allow to visualize the trees constructed by TILIA algorithm. The nodes with the same colour connected by a line without an arrow can also establish communication.

The simulation tool NS-3, available in [45], was used. To simulate the desired network it was used the wireless mesh network model provided by NS-3 and referred in [46]. Within this model it was adopted the standard 802.11s for mesh networks which is explained in [47]. The layer 2 routing protocol used in the simulations was the Hybrid Wireless Mesh Protocol (HWMP), specified

Parameter	**Value**
Wifi Physical Standard	802.11a
RTS/CTS Mechanism	Yes
Minimum Packet Size to Require RTS/CTS	1000 bytes
Node Distance	100 m
Packet Size	1024 bytes
Flow Source Type	Constant bit rate (500kbps/1Mbps)
Routing Protocol	HWMP
Time before deleting proactive HWMP route	3600 seconds
Time before deleting proactive HWMP route	3600 seconds
Maximum number of packets retained while waiting for ARP reply	1000 packets
Maximum number of packets retained in wifi output queue	10000 packets

Table 3.1: Simulation parameters

in [48]. To improve the access to the wireless medium it was also used the RTS/CTS mechanism. Each node generated a UDP traffic flow, with a constant bit rate, destined to the appropriate gateway. The UDP protocol was chosen because it doesn't have the slow start mechanism and the retransmissions associated to the TCP protocol, allowing this way a better analysis of the results. The constant bit rate is used because video surveillance systems normally generate constant rate traffic. In Table 3.1 are presented some of the parameters used on the simulations. The parameters that are not referred in Table 3.1 were configured with the default value assigned by NS-3. Each simulation ran during 125 seconds and the simulation time was divided in three phase:

0 seconds - 5 seconds: During the first 5 seconds there are no traffic flows. This period enables the initialization of the HWMP protocol, allowing each node to create its routing table. The expiration time of the routes set up in this period is set up to be larger than the simulation time, to avoid the exchanging of routing traffic during the simulation of the main flows.

5 seconds - 105 seconds: During the next 100 seconds each node sends a UDP traffic flow, with a constant bit rate, to the respective gateway. This may imply the generation of approximately 6102 packets with 500kbps applications, or 12204 packets with 1Mbps applications.

105 seconds - 130 seconds: The last 25 seconds enable the packets to be dequeued.

Each topology was simulated two times. To guarantee that the results obtained from each simulation are independent we used the sub-stream capability provided by NS-3, instead of using a different seed for each simulation. We used this strategy because by using a different seed for each simulation it is not possible to guarantee that the streams produced by each seed will not overlap. By using the sub-stream capability, the seed is the same for each simulation, but the sub-stream of the random number generator is distinct, guaranteeing statistically independent simulations. This strategy allows for a maximum of $2.3x10^5$ independent replications, which is more than enough to the simulations that were carried out.

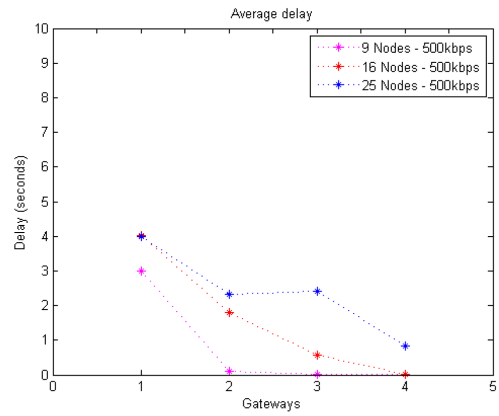
3.2 Results

To retrieve the results from the simulation we used the flow monitor tool provided by NS-3, and described in [49]. With this mechanism a flow is characterized by its source/destination address, source/destination port and protocol, and each flow is independently monitored. Using this tool it is possible to determine the time of the first and last transmitted or received packet, the delay sum of all received packets or even the amount of transmitted, received, lost or dropped packets for a certain flow. In these simulations we focused on analyse the number of transmitted/lost packets and also the delay characteristics of each topology. This enabled us to better understand the behaviour and limitations of WMSNs.

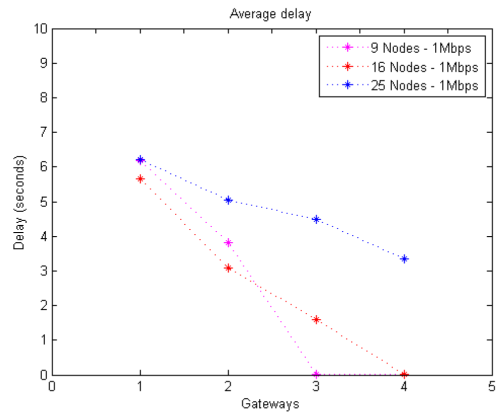
Number of Nodes	**Number of Gateways**	**Traffic Rate**	**Delay (seconds)**	**Lost Packets (%)**
9	1	500kbps	2.9967	61.77
9	2	500kbps	0.0948	13.85
9	3	500kbps	0.0036	0.00
9	4	500kbps	0.0021	0.00
9	1	1Mbps	6.1870	78.76
9	2	1Mbps	3.8026	25.27
9	3	1Mbps	0.0052	0.00
9	4	1Mbps	0.0052	0.00
16	1	500kbps	4.0348	81.47
16	2	500kbps	1.7837	53.56
16	3	500kbps	0.5652	18.49
16	4	500kbps	0.0086	0.00
16	1	1Mbps	5.6526	86.90
16	2	1Mbps	3.0953	73.51
16	3	1Mbps	1.5803	41.41
16	4	1Mbps	0.0150	0.03
25	1	500kbps	4.0055	85.97
25	2	500kbps	2.3240	71.75
25	3	500kbps	2.3998	59.84
25	4	500kbps	0.8431	26.00
25	1	1Mbps	6.2149	92.06
25	2	1Mbps	5.0521	85.10
25	3	1Mbps	4.5002	76.08
25	4	1Mbps	3.3449	55.17

Table 3.2: Simulation results

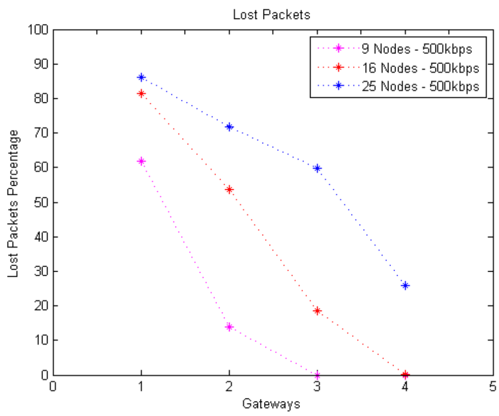
In Table 3.2 is exposed the percentage of lost packets and the average packet delay for each topology simulated. In Figure 3.1 and in Figure 3.2 this information is graphically represented. As was expected, when the number of nodes increases, the percentage of lost packets also increases, due to the saturation of the wireless medium. As can be seen in the results obtained, the insertion of a higher number of gateways in the network allow to minimize this problem as was stated in section 2.1.1. This allows us to confirm that the use of multiple communication channels, in a wireless multi-hop network, can in fact increase the capacity of the network.



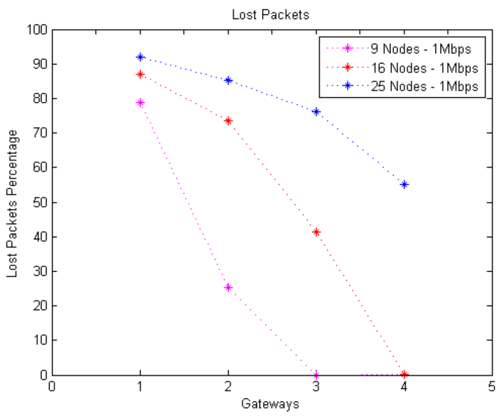
(a) Average Delay: 500kbps



(b) Average Delay: 1Mbps

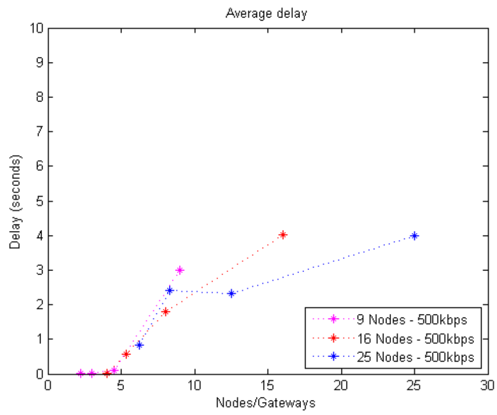


(c) Lost packet percentage: 500kbps

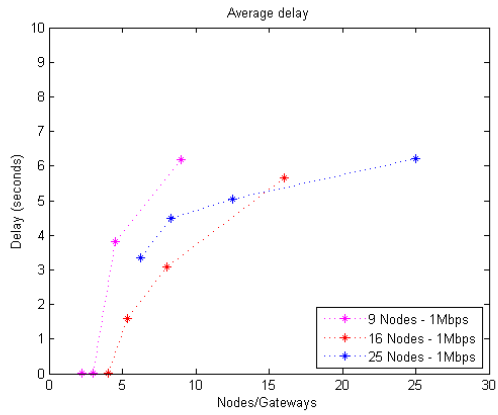


(d) Lost packet percentage: 1Mbps

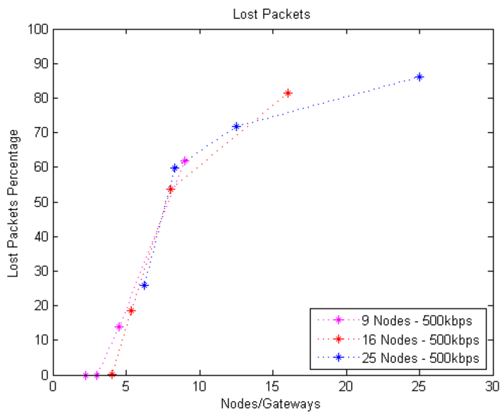
Figure 3.1: Simulation graphs (vs number of gateways)



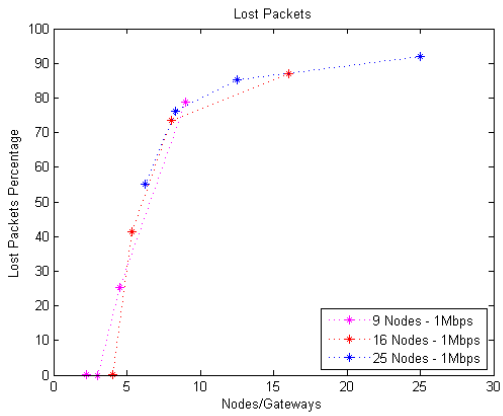
(a) Average Delay: 500kbps



(b) Average Delay: 1Mbps



(c) Lost packet percentage: 500kbps



(d) Lost packet percentage: 1Mbps

Figure 3.2: Simulation graphs (vs number of nodes/number of gateways)

3.3 Conclusion

In this chapter were exposed a set of simulations that were carried out to better understand the behaviour of WMSNs regarding their capacity. In the first section it was described the methodology followed in the simulations, including the configuration of the network topology, the simulation parameters used and the tools and models utilized to obtain the necessary simulation results. In the second section were described the results of the simulations regarding the packet loss and the average packet delay. With these results it was possible to verify the capacity improvement that result from using multiple communication channels in wireless multi-hop network.

Chapter 4

Proposed Solution

This chapter presents the proposed solution and describes the methodology that will be followed to design, implement and test this solution. This chapter also contains a detailed work plan for the future.

4.1 Constraints

WMSNs are responsible for retrieving multimedia information, and normally this generates large data traffic volumes. This is specially true in a WMSN designed to retrieve multimedia information from a video-surveillance system. To be able to transfer all the collected information to its destination, within a minimum pre-defined time delay, it is necessary to have a network with an appropriate capacity. If this requirement is not fulfilled, the network capacity will greatly constrain the system. The proposed solution has to be capable of surpass this constraint in order to allow the deployment of a fully functional and effective WMSN.

A WMSN powered by solar energy is also constrained by its lifetime, due to the instability of that power source. Using solar panels to provide energy to the WMSN nodes is a good option when an electrical infrastructure is not available, or is too costly, but it can also constrain the network if the energy availability is not sufficient for the nodes operation. The proposed solution has to be capable of managing efficiently the energy resources of the network in order to prolong its lifetime.

The low processing and memory capabilities of the nodes and the fact that each one of the nodes can only have one network interface may represent an extra constraint on the system. Thus the proposed solution must also take this into account.

4.2 Description

The proposed solution tries to surpass the two main constraints, related with the network capacity and the network lifetime, with a single solution. The approach adopted by the proposed solution is to make use of multiple communication channels. By adopting a multi-channel approach, the proposed solution will allow more simultaneous communications between the nodes of the network, thereby increasing the capacity. Using non-overlapping channels will help to reduce the interference of simultaneous communications, which will translate in a better utilization of the WMSN resources. The number of communications channels necessary will depend on the data rate required by the video-surveillance system, and on the number of network nodes.

To extend the network lifetime the proposed solution will modify the network topology, using a channel assignment procedure, to avoid forwarding traffic through nodes with low level of energy. This way these nodes will only transmit their own information, and their energy will not be wasted by forwarding information from other nodes. To do this the proposed solution will take the TILIA algorithm referred in section 2.1.3 and will add to it an energy parameter. The idea is to modify TILIA in order to achieve energy efficiency, leading to a new channel assignment algorithm named E-TILIA.

With this proposed solution it is expected to increase the capacity of the network, even with only one network interface per node, and to extend the network lifetime. It is to important to point out that E-TILIA, like TILIA, is a centralized algorithm. That means that all the computation is made in an outside station, which have all the computational power and energy availability required to execute the algorithm. This way the computational power and the energy of the nodes of the WMSN are not consumed, thereby saving their low resources. It is also relevant to notice that E-TILIA is an algorithm that must be executed regularly in order to adapt to changes in the energy of the nodes of the WMSN.

This algorithm will be implemented in the scripting language Python and it will be tested using the Network Simulator 3 (NS-3) available in [45]. To test E-TILIA there will be created multiple topologies, both regular and random, with a variable number of nodes and will be used a energy consumption model. This model will have to take into account the solar energy received by the nodes. Through the computation of multiple simulations it will be possible to evaluate the performance of this algorithm, both in terms of network capacity and network lifetime. This way it will be possible to compare E-TILIA with other existent solutions.

4.3 Tools

One of the most important tools to be used on this thesis is NS-3. NS-3 is an open source discrete event network simulator, written in C++, which is capable of simulating practically any kind of network. This simulation tool provides, through its source code, several models that allow the simulation of a vast set of networks. To make use of NS-3 we only have to set-up the network, defining its topology, its elements, and the models to be used, and this tool simulates the behaviour of designed network. To set-up the WMSNs desired we will recur to the mesh networking model provided by NS-3 and described in [46]. To simulate the energetic behaviour of the network we will use the energy framework specified in [50]. To extract all the necessary data from the simulations we will use a tracing tool provided by NS-3 named Flow Monitor and referred in [49]. To create the NS-3 simulations we will use the C++ coding language, and to create the energy aware channel assignment algorithm we will use the Python scripting language. To test the algorithm in real conditions, instead of using computer simulation, we will make use of several Raspberry Pi computers to establish a WMSN. Using Raspberry Pi enable us to set up a low cost fully functional mesh network, to test and evaluate our channel assignment algorithm.

4.4 Work Plan

To achieve the proposed goals a detailed work plan was carefully elaborated. This work plan is composed by several tasks, and each one of these tasks is fundamental to the success of this thesis. In Figure 4.1 is exposed the Gantt diagram related to this work, followed by a detailed description of each one of the tasks.

Figure 4.1: Gantt diagram of the work plan

Thesis Writing: The thesis writing will be done throughout the semester, occurring in parallel with all the other tasks. During the development of the thesis a special attention will be given to the writing of the final document, in order to properly report the work done and all the results obtained.

Implementation in NS-3 of the test scenario of multi-hop networks with variable available energy: In this period it is intended to implement and test several WMSNs in which the energy level of the nodes does not remain constant, making use of the NS-3 tool. To do this we will use a mesh networking model, based on the standard IEEE 802.11s, along with an energy framework capable of modelling the energy source and the energy consumption of the network nodes. All these models are already provided by NS-3. In these simulations we will generate several topologies, both regular and random, and we will constantly monitor the energy levels of the nodes. The simulations will be performed multiple times for each topology to ensure that the results obtained are reliable. The integration of this energy model with the simulations of WMSNs already performed and exposed in chapter 3 of this report, will be very important, since it will allows us to simulate and evaluate the energy-aware channel assignment algorithm proposed on this thesis.

Specification of the algorithm for radio channel assignment based on the available energy, in Wireless Multi-Hop Networks: In this period we will specify the mode of the operation of the channel assignment algorithm. The main goal is to develop a solution to assign the communication channels to the nodes, capable of improving the energy efficiency of the network. Taking into account the state of the art solutions exposed in chapter 2 of this report, we will try to design a solution which, based solely on the network topology and on the energy level of the nodes, will be able to improve significantly the lifetime of WMSNs. The specification of this algorithm will probably result in a modification of the TILIA algorithm, giving rise to a new algorithm named E-TILIA.

Algorithm implementation: After the designing of the algorithm we will implement E-TILIA in a Python script. The idea is to modify the existent TILIA Python script, adapting it to the new algorithm.

Algorithm testing, in NS-3, with regular topologies: In this period we will extensively test the algorithm developed, using the Python script implemented. To do this we will generate several regular topologies, each one having a different number of nodes, and we will run the E-TILIA regularly to evaluate if the algorithm is capable of improving the energy efficiency of the network.

Algorithm testing, in NS-3, with random topologies: After the extensive testing with regular topologies we will then test our algorithm with random topologies, following the same procedure.

Test-bed preparation, based in Raspberry Pi, for supporting the algorithm: After the algorithm has been tested extensively with the simulation tool, we will then prepare a test-bed, using Raspberry Pi computers, to test the algorithm in real conditions. The idea is to create a WMSN using several Raspberry Pi computers. In this preparation a special attention has to be given to the routing protocol to be used, and to the procedure that is going to be responsible for gathering all the necessary input data for E-TILIA.

Algorithm adaptation for the test-bed based in Raspberry Pi: In this period the algorithm will be adapted to be used in the Raspberry Pi test-bed.

Test-bed testing: In this period, after the preparation of the test-bed, the algorithm will be extensively tested in real conditions. This will be extremely important because it will allow us to understand if the simulated results are in agreement with the results obtained in real conditions. This will ultimately enable us to assess the algorithm quality.

Statistical analysis of the data (in collaboration with Imperial College of London): In this period we will analyse the information gathered through the computer simulations and through the Raspberry Pi test-bed, in collaboration with the Imperial College of London. This task will allows to understand the mathematical fundamentals of our algorithm.

Article writing for international conference (in collaboration with Imperial College of London): Based on the results obtained from the extensive computer simulation and from the Raspberry Pi test-bed, and supported by the statistical analysis of the data from these experiments, we will write an article with the goal of present it on an international conference.

Thesis Review: In this period it is expected to review the thesis report and improve it for the final evaluation.

Chapter 5

Conclusion

The present report described the main problems associated with a video-surveillance system intended to be implemented by Future Cities project, in the city of Porto. The overall goal of the system, associated with the characteristics of the nodes in terms of energy, processing and memory, leads to its classification as a WMSN. The main limitations of this WMSN are the network capacity and the network lifetime.

In this report were studied the state of the art solutions to improve the capacity of this system, and the state of the art solutions to increase its lifetime. To increase the capacity the most relevant mechanism are to reduce interference, design new routing protocols/metrics, use multiple communication channels and use multiple network interfaces. To increase the lifetime the most relevant mechanism are radio optimisation, data reduction, sleep/wakeup schemes, energy-efficient routing and battery repletion. By analysing the state of the art solutions, regarding the capacity and lifetime of wireless multi-hop networks, it was possible to select a single approach to simultaneously increase the capacity and the lifetime of the network. The approach is to use multiple communication channels. Using multiple communication channels allows us to have several simultaneous communications without having interference between them, increasing the capacity of the network. This approach also allows to increase the network lifetime by designing a channel assignment procedure capable of adapt to changes in the energy levels of the network, avoiding, for example, to forward traffic through nodes with low remaining energy.

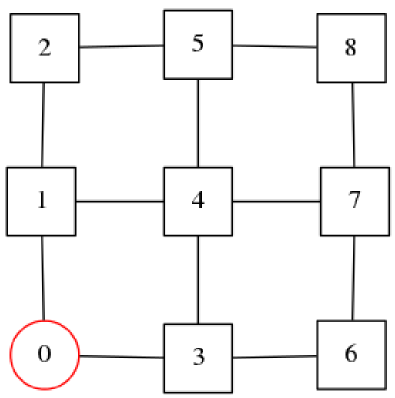
To better understand the implications of the use of multiple channels in a wireless multi-hop network a set of simulations were carried out. These simulations, which are described in this report, allowed us to analyse the influence of multiple channels in the network throughput and delay.

Finally a description of the solution to overcome the problems above referred is also exposed in this report. Together with this description is exposed the work plan to implement it and the tools which are going to be used.

Thus this report constitutes a preparation for the future work, where is intended to design, implement and evaluate a channel assignment algorithm to surpass the referred problems.

Appendix A

Topologies Simulated



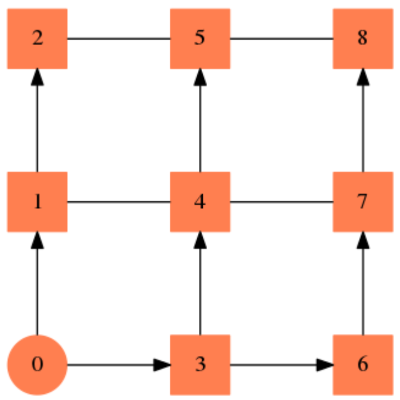
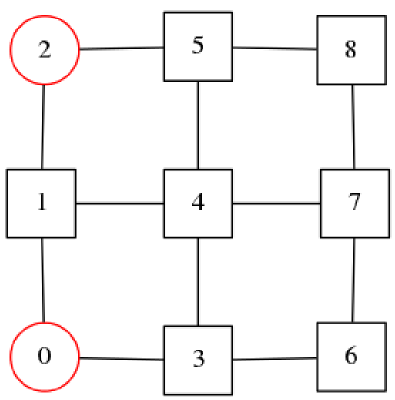


Figure A.1: 9 Nodes, 1 Gateway: Original Topology vs Tilia Topology



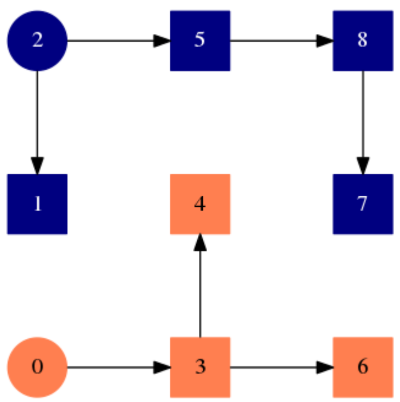


Figure A.2: 9 Nodes, 2 Gateways: Original Topology vs Tilia Topology

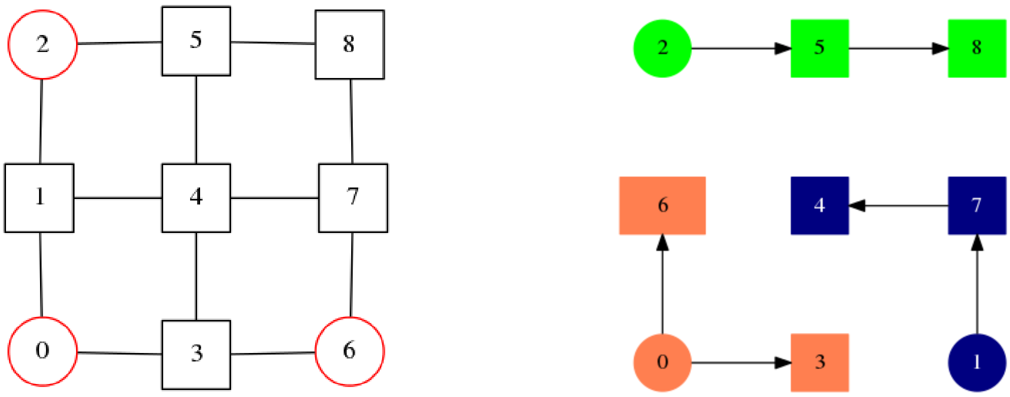


Figure A.3: 9 Nodes, 3 Gateways: Original Topology vs Tilia Topology

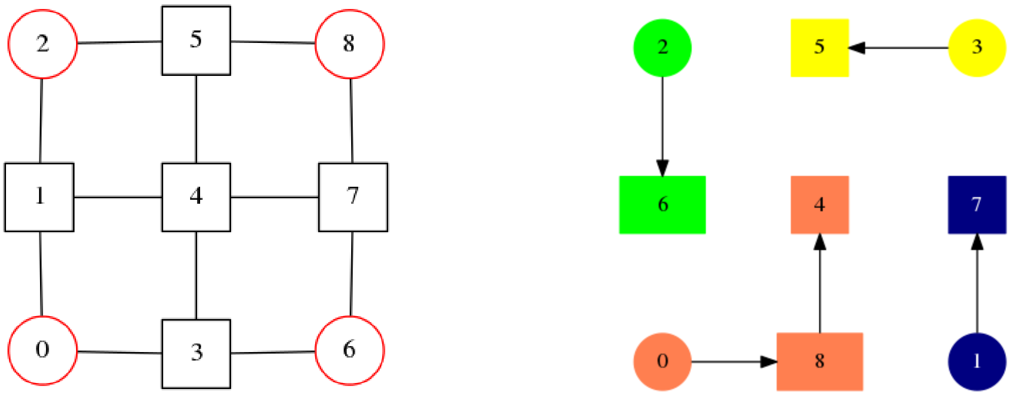


Figure A.4: 9 Nodes, 4 Gateways: Original Topology vs Tilia Topology

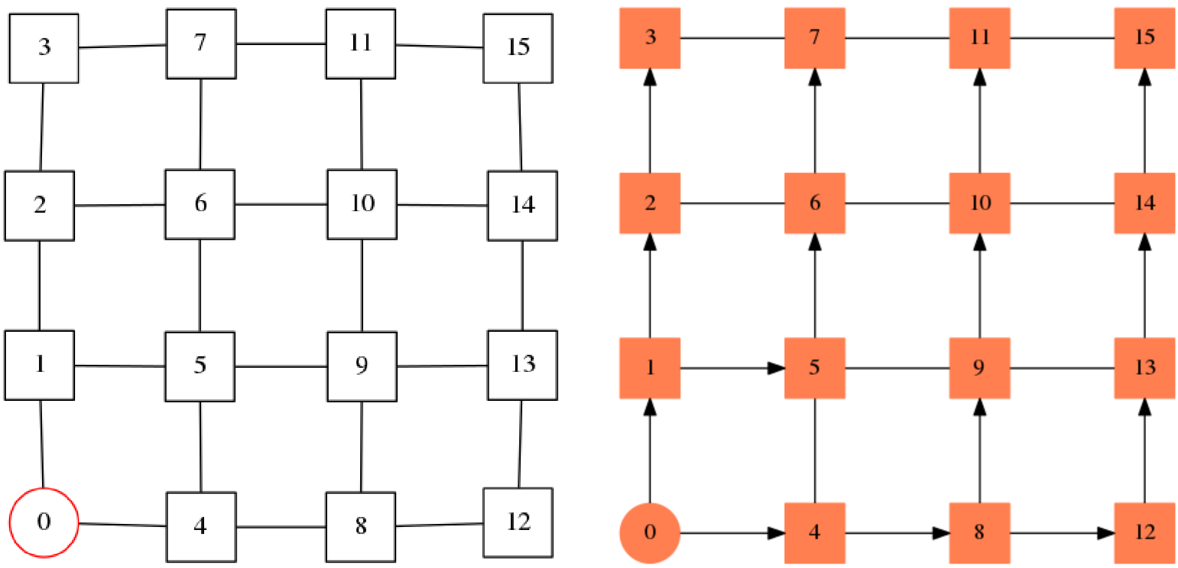


Figure A.5: 16 Nodes, 1 Gateway: Original Topology vs Tilia Topology

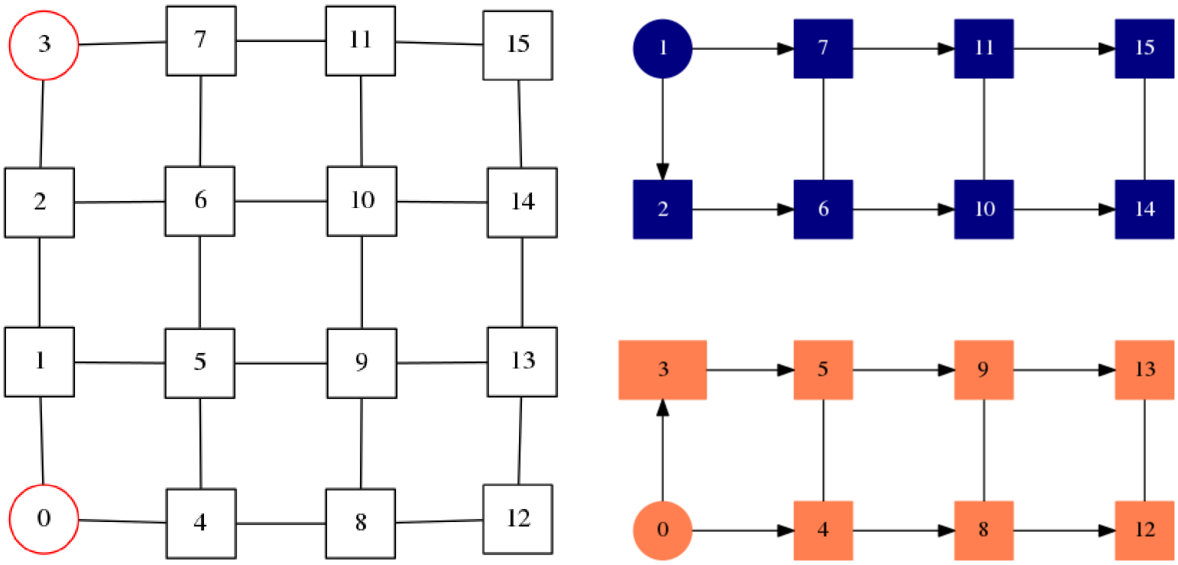


Figure A.6: 16 Nodes, 2 Gateways: Original Topology vs Tilia Topology

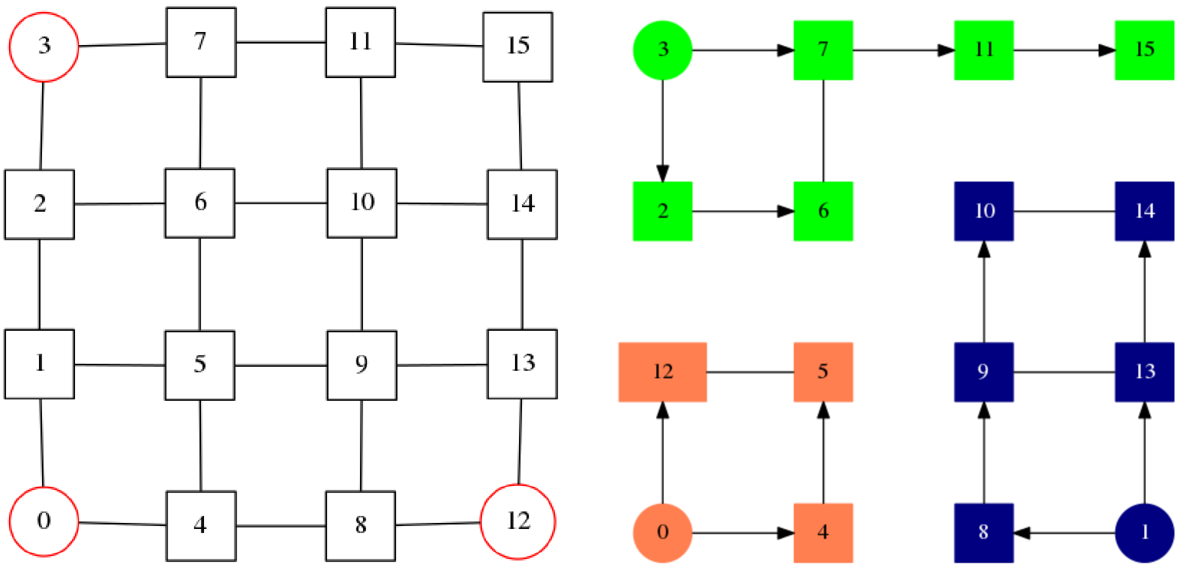


Figure A.7: 16 Nodes, 3 Gateways: Original Topology vs Tilia Topology

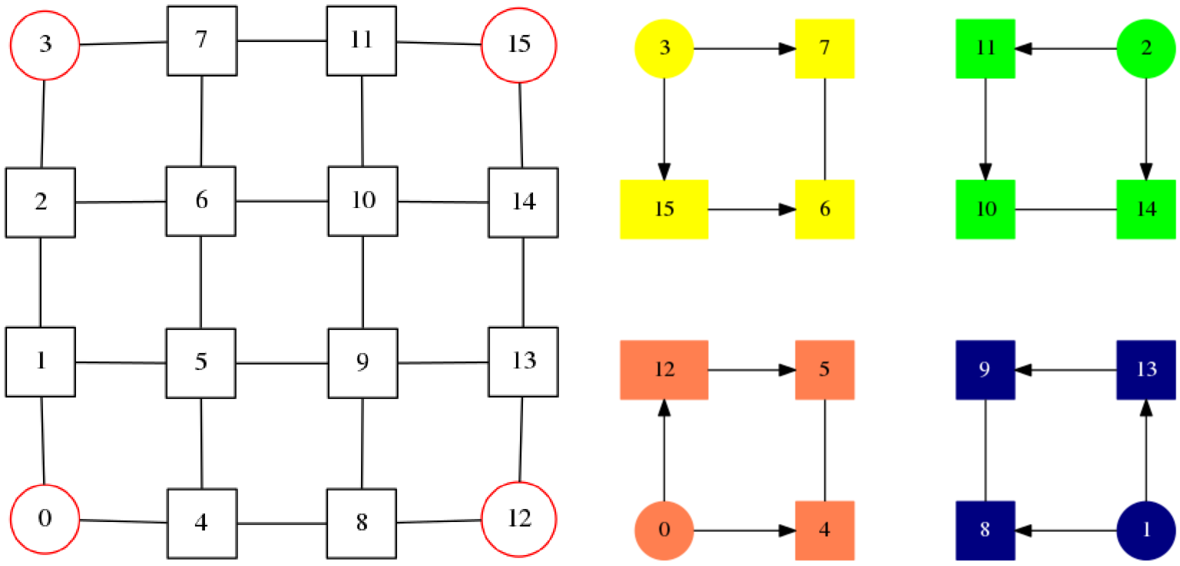


Figure A.8: 16 Nodes, 4 Gateways: Original Topology vs Tilia Topology

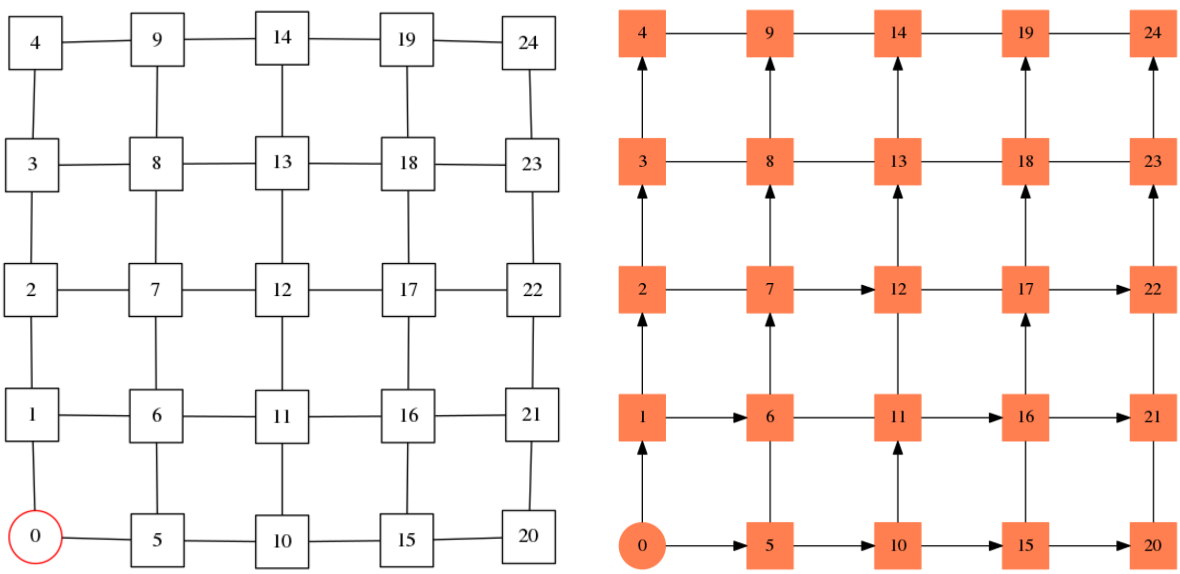


Figure A.9: 25 Nodes, 1 Gateway: Original Topology vs Tilia Topology

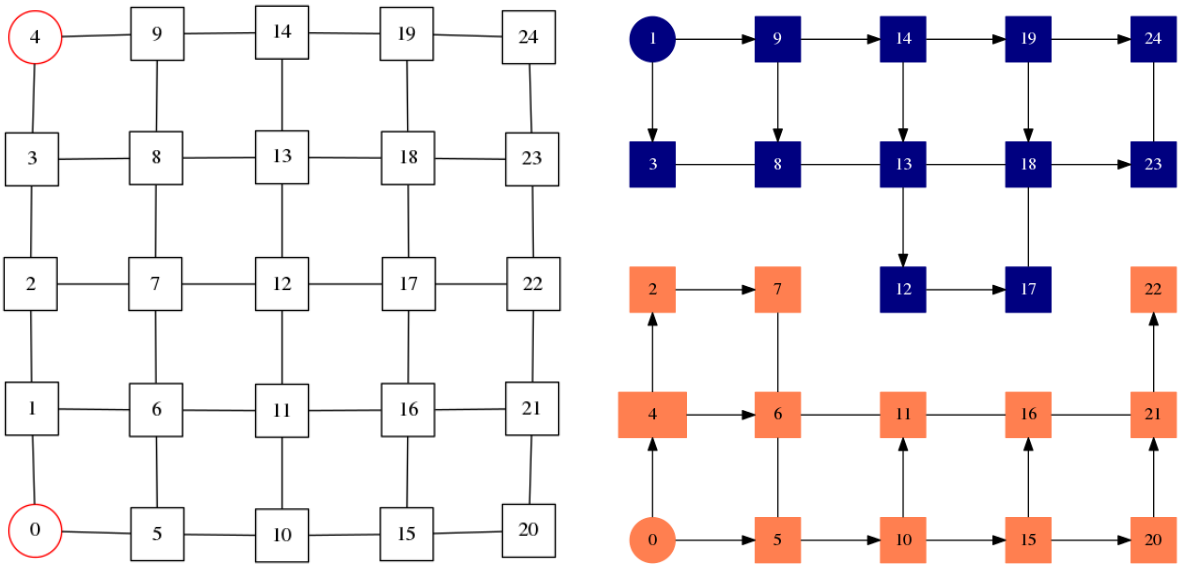


Figure A.10: 25 Nodes, 2 Gateways: Original Topology vs Tilia Topology

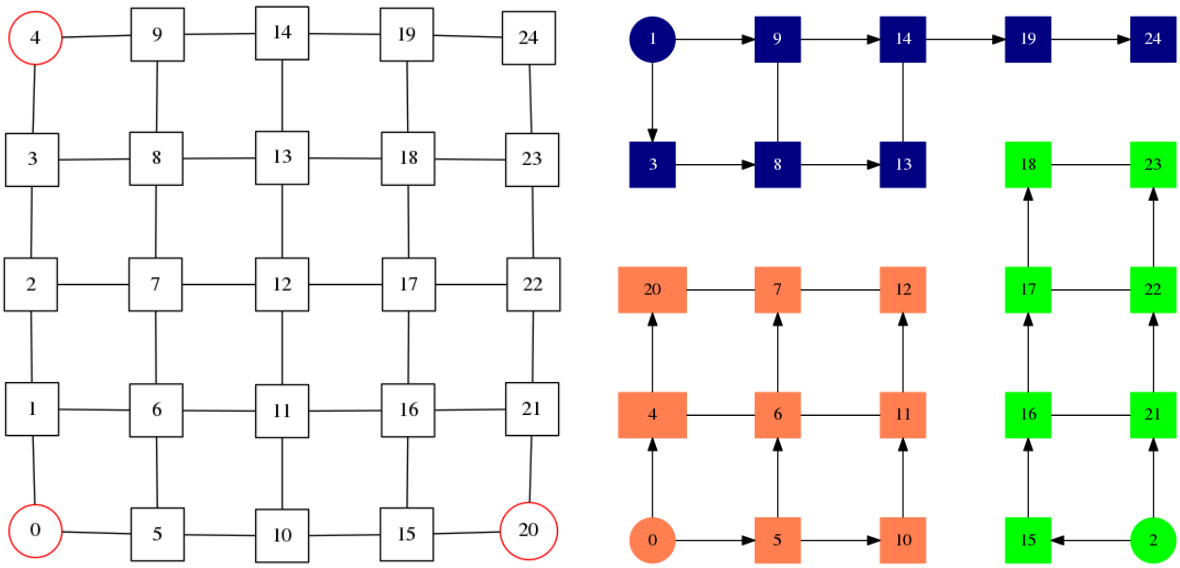


Figure A.11: 25 Nodes, 3 Gateways: Original Topology vs Tilia Topology

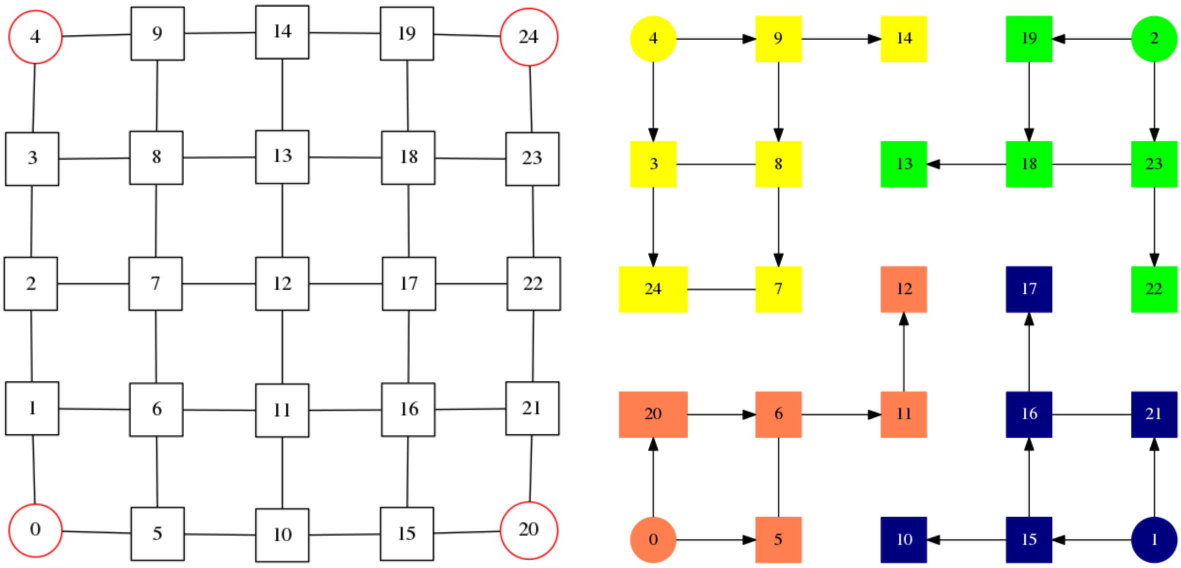


Figure A.12: 25 Nodes, 4 Gateways: Original Topology vs Tilia Topology

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