A DISTRIBUTED TOPOLOGY CONTROL TECHNIQUE FOR LOW INTERFERENCE AND ENERGY EFFICIENCY IN WIRELESS SENSOR NETWORKS

by

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SUMMARY

A DISTRIBUTED TOPOLOGY CONTROL TECHNIQUE FOR LOW INTERFERENCE AND ENERGY EFFICIENCY IN WIRELESS SENSOR NETWORKS

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Wireless sensor networks are used in several multi-disciplinary areas covering a wide variety of applications. They provide distributed computing, sensing and communication in a powerful integration of capabilities. They have great long-term economic potential and have the ability to transform our lives. At the same time however, they pose several challenges – mostly as a result of their random deployment and non-renewable energy sources.

Among the most important issues in wireless sensor networks are energy efficiency and radio interference. Topology control plays an important role in the design of wireless ad hoc and sensor networks; it is capable of constructing networks that have desirable characteristics such as sparser connectivity, lower transmission power and a smaller node degree.

In this research a distributed topology control technique is presented that enhances energy efficiency and reduces radio interference in wireless sensor networks. Each node in the network makes local decisions about its transmission power and the culmination of these local decisions produces a network topology that preserves global connectivity.

The topology that is produced consists of a planar graph that is a power spanner, it has lower node degrees and can be constructed using local information. The network lifetime is increased by reducing transmission power and the use of low node degrees reduces traffic interference.

The approach to topology control that is presented in this document has an advantage over previously developed approaches in that it focuses not only on reducing either energy consumption or radio interference, but on reducing both of these obstacles. Results are presented of simulations that demonstrate improvements in performance.

OPSOMMING

’n VERSPREIDE TOPOLOGIE BEHEERTEGNIEK VIR LAE STEURING EN DOELTREFFENDE ENERGIE IN DRAADLOSE SENSOR NETWERKE

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Draadlose sensor netwerke word gebruik in verskeie multi-dissiplinêre areas wat ’n wye verskeidenheid toepassings dek. Hulle voorsien verspreide berekening, bespeuring en kommunikasie in ’n kragtige integrasie van vermoëns. Hulle het goeie langtermyn ekonomiese potentiaal en die vermoë om ons lewens te herskep. Terselfdertyd lewer dit egter verskeie uitdagings op as gevolg van hul lukrake ontplooiing en nie-hernubare energie bronne.

Van die belangrikste kwessies in draadlose sensor netwerke is energie-doeltreffendheid en radiosteuring. Topologie-beheer speel ’n belangrike rol in die ontwerp van draadlose informele netwerke en sensor netwerke en dit is geskik om netwerke aan te bring wat gewenste eienskappe het soos verspreide koppeling, laer transmissiekrag en kleiner nodus graad.

In hierdie ondersoek word ’n verspreide topologie beheertegniek voorgelê wat energie-doeltreffendheid verhoog en radiosteuring verminder in draadlose sensor netwerke. Elke nodus in die netwerk maak lokale besluite oor sy transmissiekrag en die hoogtepunt van hierdie lokale besluite lewer ’n netwerk-topologie op wat globale verbintenis behou.

Die topologie wat gelewer word is ’n tweedimensionele grafiek en ’n kragsleutel; dit het laer nodus grade en kan gebou word met lokale inligting. Die netwerk-leeftyd word vermeerder deur transmissiekrag te verminder en verkeer-steuring word verminder deur lae nodus grade.

Die benadering tot topologie-beheer wat voorgelê word in hierdie skrif het ’n voordeel oor benaderings wat vroeër ontwikkel is omdat dit nie net op die vermindering van net energie verbruik of net radiosteuring fokus nie, maar op albei. Resultate van simulasies word voorgelê wat die verbetering in werkverrigting demonstreer.

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CONTENTS

LIST OF ABBREVIATIONS

AFR	Adaptive Face Routing
ALERT	Automated Local Evaluation in Real Time
ANDA	Ad hoc Network Design Algorithm
AODV	Ad Hoc On Demand Vector
AP	Access Point
APO	Application Object
ASCENT	Adaptive Self-Configuring sEnsor Networks
BSS	Basic Service Set
CMOS	Complementary Metal–Oxide–Semiconductor
DARPA	Defense Advanced Research Projects Agency
DG	Delaunay Graph
DSN	Distributed Sensor Networks
DSSS	Direct Sequence Spread Spectrum
EOFS	Environment Observation and Forecasting System
ESS	Extended Service Set
FFD	Full Function Devices
GAF	Geographic Adaptive Fidelity
GFR	Greedy Face Routing
GG	Gabriel Graph
GOAFR	Greedy Other Adaptive Face Routing
GPSR	Greedy Perimeter Stateless Routing
GRG	Geometric Random Graphs
HEED	Hybrid Energy-Efficient Distributed Clustering
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronic Engineers
LEACH	Low Energy Adaptive Clustering Hierarchy
LINT	Local Information No Topology
LLC	Link Layer Control
LMST	Local Minimum Spanning Tree
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
MDS	Minimum Dominating Set

MEMS	Micro-Electro-Mechanical Systems
MST	Minimum Spanning Tree
OSI	Open Systems Interconnection
PDA	Personal Digital Assistant
QoS	Quality of Service
RA	Range Assignment
RF	Radio Frequency
RFD	Reduced Function Devices
RN	Random Network
RNG	Relative Neighbourhood Graph
SBYaoGG	Smart Boundary Yao Gabriel Graph
SensIT	Sensor Information Technology
SIG	Special Interest Group
SSIM	Smart Sensors and Integrated Microsystems
TASS	Tactical Automated Security System
TC	Topology Control
UCB	University of California, Berkeley
UDG	Uniform Disk Graph
UWB	Ultra Wideband
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WMSN	Wireless Multimedia Sensor Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
YG	Yao Graph
ZDO	ZigBee Device Object

CHAPTER 1

RESEARCH OVERVIEW

1.1 INTRODUCTION

Multifunctional wireless sensor nodes are a development brought about by recent advancements in wireless communications and electronics [1]. These sensor nodes are small in size and communicate unrestrictedly over short distances. They have sensing, data processing and communication capabilities and their features have enabled, as well as provided, impetus to the idea of Wireless Sensor Networks (WSNs). WSNs are part of a new class of networks that have appeared over the last few years. These networks are powerful in that they are amenable to support a lot of real world applications that vary considerably in terms of their requirements and characteristics. This flexibility however makes them a challenging research and engineering problem [2].

There is no single set of requirements that clearly classifies all WSNs and there is no single technical solution that encompasses the entire design space. Specific existing applications that make use of WSNs occupy different points in the design space. Initial research into WSNs was mainly motivated by military applications with the Defense Advanced Research Projects Agency (DARPA) providing funding for a number of leading research projects such as Smart Dust and NEST. It is commonly regarded as the cradle of sensor network research [3]. These applications led to a de facto definition of a wireless sensor network as a large-scale, wireless, ad hoc, multi-hop network of homogeneous, tiny, mostly immobile sensor nodes that would be randomly deployed in an area of interest.

Of late, other civilian application domains of wireless sensor networks have been considered, such as agriculture, production and delivery, environmental and species monitoring and healthcare. WSN projects targeting these application areas have widened the design space and necessitated the definition of WSNs to be extended to include heterogeneous and mobile sensor nodes. A single hardware platform will most likely not be sufficient to support the wide range of possible applications and the same is true of software. It would be ideal to avoid developing application-specific hardware or software but to rather develop technologies that cover as wide a range of the design space as possible.

Each application that makes use of WSNs will have its own set of characteristic requirements such as the type of service, quality of service, lifetime, scalability and so forth. Innovative mechanisms for a communication network need to be developed in order to meet these requirements. Wireless communication and energy-efficient operation are two key mechanisms that form part of a typical WSN. In a densely deployed wireless network, a single node will have many neighbouring nodes which it can communicate with directly when using sufficiently high transmission power. However, high transmission power requires a lot of energy and using many neighbours is a burden for a medium access control (MAC) protocol. Routing protocols suffer volatility in the network when nodes move around and frequently sever or form many links between one another [2].

In order to meet these challenges, topology control (TC) can be applied. Topology control is one of the most important techniques used in WSNs to reduce energy consumption and radio interference [4]. It lends itself to the mechanisms of multi-hop communication and energy-efficient operation. Topology control aims to control the graph representing communication links between nodes, with the purpose of meeting a global property of the graph – such as connectivity, while reducing energy consumption and radio interference.

Different approaches to topology control can be classified based on various features. One feature is the way in which the network topology is generated; the method for generating the topology can be distributed, local or centralized. Another feature is the structure of the generated network which can be flat, hierarchical or clustered.

Whether or not nodes have the same transmitting power is another distinguishing feature; in homogeneous topology control, nodes are assumed to use the same transmitting power whereas in non-homogenous topology control, nodes are allowed to have different transmitting power. The information that is used to build the network topology can also be used for classification. Choices in this category include node location information, node direction information and node neighbour information.

1.2 CURRENT LITERATURE

In homogeneous topology control, the critical transmitting range is the transmitting range that produces communicating graphs that are connected with high probability. Determining the critical transmission range using homogeneous topology control has been considered analytically as well as practically. For sparse homogeneous networks the critical transmission range has been analysed using occupancy theory and it has been proven [5] that under certain assumptions a formula can be used for range assignment that is connecting with high probability. Similar derivations have been made for dense homogeneous networks using the probabilistic theory of geometric random graphs. The critical transmitting range in homogeneous networks has also been considered practically, resulting in the development of protocols such as COMPOW [5].

To tackle the range assignment problem using non-homogeneous topology control, the body of research on distance spanners in computational geometry can be used. Some geometric graphs that have been used in wireless networks include the Relative Neighbourhood Graph, the Gabriel Graph, the Yao Graph and the Delaunay Graph [6]. Some protocols include the k-Neighbours [7] and the Mobile Grid protocols which are neighbour based, the Cone Based Topology protocol which is direction based, and LMST protocol which is location based. Some topology control protocols reduce the number of node adjacencies using hierarchies such as the HEED protocol [8] while others make use of clustering such as the LEACH protocol [9].

1.3 MOTIVATION

The type of topology control used in a wireless network determines, among other things, the neighbours of each node in the network as well as each node’s transmitting power. The number of neighbours of each node will have a direct impact on the routing protocol in that it determines the amount of redundancy there is in the network, whether or not the network is connected, the size of routing tables and the amount of time it will take the routing protocol to generate routing tables. Therefore it is ideal to have a networking-layer-friendly topology control mechanism that produces a connected network and results in small routing tables.

The choice of transmitting power on the other hand, determines the quality of the signal received at the receiver. It also determines the range of transmission and the magnitude of interference created for other receivers [10]. As a result of this, power control:

- affects the physical layer, since it determines the quality of the received signal;
- affects the network layer and routing, since it affects the transmitting range;
- affects the transport layer, since interference causes congestion;
- affects medium access control, since contention is dependent on transmitting range.

Important network attributes and performance measures affected by topology control include:

- network connectivity,
- network throughput capacity,
- network contention,
- network energy consumption and
- network link symmetry.

It is clear therefore that the choice of power level, determined by the topology control mechanism, has far-reaching effects across different layers of the wireless network's protocol stack. The performance of the whole system is therefore affected by the choice of topology control and a holistic approach to topology control is needed that takes into consideration the various cross-layer concerns.

1.4 OBJECTIVES

The objective of this research is to design a topology control mechanism that will produce a wireless network with the following characteristics:

- Low radio interference.
- High energy efficiency.

The topology control mechanism must have the following features:

- it must be distributed,
- it must use local information,
- it must produce a connected network and

- it must produce a sparse network.

1.5 SCOPE

Topology control can be treated from a theoretical, probabilistic approach using occupancy theory and the theory of geometric random graphs in the case of the homogeneous topology control. This research takes a practical approach as it focuses on heterogeneous topology control. Emphasis is placed on the type of proximity graphs generated by the topology control mechanism as well as on how they are generated. Concepts from graph theory and computational geometry are used and explored to get the desired network topology, which will then be evaluated through simulation.

The research is limited to the algorithms and heuristics that are necessary in order to generate the desired network topology. The focus is on topology control in wireless sensor networks, as it is in these networks that the problems solved by topology control are of greater consequence. Local information is used to generate the desired topology in a distributed way. This approach is well suited to networks where nodes have the same capabilities and are deployed ad hoc. It is envisaged that the topology control technique produced by this research can be used in other types of wireless networks and can form the basis of a topology control protocol.

This research focuses on topology control through the assignment of transmitter power in flat networks. Generating clustered and hierarchical networks through topology control is not explored as an answer to the research question, as this is done more for the purpose of routing and does little to reduce radio interference, which is predominantly a transmitter power issue dependent on node deployment.

1.6 DESIGN

The research question is, "*Is it possible to develop a light-weight, heterogeneous, symmetric topology control technique that can address performance issues in wireless sensor networks in terms of extending network lifetime, reducing radio interference and lowering energy consumption in a distributed fashion?*".

This research study is an empirical one. Primary numeric data is used to evaluate the new technique against secondary data from previous approaches to topology control. The research involves a high degree of control, involving statistical modelling and computer simulation of previous approaches to topology control and the topology control technique envisaged in this research.

The following questions were constructed in order to better understand the research question and achieve the research goals.

1. What are the different approaches to topology control?
2. What is the taxonomy of topology control?
3. What was the objective of past topology control studies?
4. Which methods of topology control are used in WSNs?
5. How do the existing approaches to topology control compare to one another?
6. Does hierarchical or clustered topology control reduce radio interference?
7. What layers of the wireless network stack are affected by topology control?
8. What layer of the wireless network stack is a topology control protocol best suited for?
9. How do location, direction and neighbour based approaches to topology control compare to one another?
10. What method for creating proximity graphs in a wireless network is the least computationally intensive?
11. What is the relationship, if any, between the hop-stretch factor and the energy stretch factor?
12. Which WSN applications are suited for homogeneous topology control and which WSN applications are suited for heterogeneous topology control?

1.7 METHODOLOGY

The research methodology consists of the following.

1. A literature study.
    a. Relevant literature on wireless sensor networks was identified.
    b. Relevant literature on topology control in wireless networks was identified.
    c. The identified literature was studied.

    d. Various approaches to topology control were identified.
    e. The different approaches to topology control were studied.
2. Design of a topology control technique.
    a. This entailed the design of a distributed topology control technique that uses local information and seeks to minimise radio interference and enhance energy efficiency in the network.
3. Implementation
    a. This was the visualisation of the network topology created by the new technique, using a graph visualisation program for different networks.
    b. This was the simulation of WSNs that use the designed topology control technique to evaluate how it fairs in terms of performance.
    c. This was the identification and collection of data that gave statistically significant results that could in turn be evaluated and compared to results from past studies.
4. Assessment
    a. The new topology control technique was compared to other existing approaches to topology control.
    b. The results were analysed and discussed.

1.8 CONTRIBUTION

Previous topology techniques have focused solely on reducing node energy consumption in wireless networks. This research goes further by looking at ways to reduce radio interference using topology control and investigating the possibility that there is some Pareto optimality between these two goals.

CHAPTER 2

WIRELESS SENSOR NETWORKS

2.1 CHARACTERISTICS

Wireless sensor networks (WSNs) are computer networks of spatially connected devices called nodes that are able to interact with their environment by sensing or controlling physical parameters; these nodes have to collaborate to fulfil their tasks, as a single node is usually incapable of doing so; and they use wireless communication to enable this collaboration [2]. Sensor nodes, also known as motes, involve low-costs, low power and are multifunctional; they are small in size and communicate unrestrictedly over short distances. Each sensor node consists of sensing, data processing, storage and communicating parts.

Sensor nodes can be deployed inside or in close proximity to a phenomenon of interest, which may be on the ground, in the air, underwater, underground, on bodies, in vehicles or inside buildings. This deployment may be fixed and planned, or ad hoc [11]. The possibility of random deployment means that the algorithms and protocols employed in sensor networks must be self-configuring. WSNs have a distinguishing feature of cooperative effort; this is evident in various network tasks involving collaborative signal and information processing.

Wireless sensor networks have their roots in defence applications such as battlefield surveillance and enemy tracking. A large part of their evolution is due to programmes of the Defence Advanced Research Projects Agency (DARPA) notably the Distributed Sensor Networks (DSN) and Sensor Information Technology (SensIT) programmes. The features of sensor nodes enable a wide variety of applications that go beyond the military field. Present and potential applications for WSNs include habitat monitoring applications, environment observation and forecasting systems, health applications as well as home and office applications [12]. The attributes of WSNs are summarised in Table 2-1 below.

Table 2-1: Attributes of wireless sensor networks [11]

Sensors	*Size*	Small (e.g. micro-electro-mechanical systems (MEMS))
	Number	Small, Large
	Type	Passive, Active
	Composition	Homogeneous (same types of sensors) Heterogeneous (different types of sensors)
	Spatial coverage	Dense, Sparse
	Deployment	Fixed and planned (e.g. factory networks) Ad hoc (e.g. air dropped)
	Dynamics	Stationary (e.g. seismic sensors) Mobile (e.g. on robot vehicles)
Sensing entities of interest	*Extent*	Distributed (e.g. environment monitoring) Localised (e.g. target tracking)
	Mobility	Static, Dynamic
	Nature	Cooperative (e.g. air traffic control) Non-cooperative (e.g. military targets)
Operating environment	Benign (e.g. factory floor) Adverse (e.g. battle field)	
Communication	Wireless networking Low bandwidth	
Processing architecture	Centralised (all data sent to central site) Distributed (located at sensor or other sites) Hybrid	
Energy availability	Constrained	

Part of the current vision for WSNs is to have sensor nodes that can last forever without external power sources or having to change their batteries. A technique that can be used to achieve this is that of piezoelectric power generation in which a micro-electro-mechanical systems (MEMS) cantilever converts mechanical motions into electrical power. Two mechanisms that have been explored in order to propel the cantilever's movements are the use of a radioactive isotope and the harvesting of vibrations from the environment [13]. An energy harvesting wireless sensor node that shows the state of the art of wireless sensor nodes is shown in Figure 2-1 below.

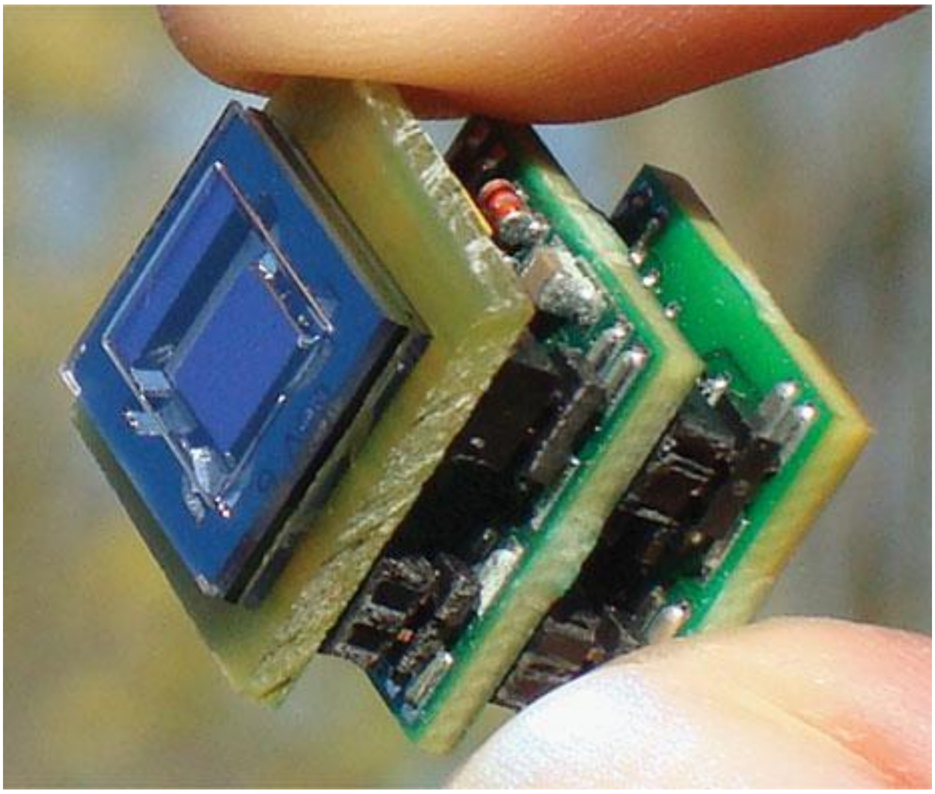


Figure 2-1: An Imec forever node [13].

2.2 APPLICATIONS

There are several concrete applications of WSNs that have advanced beyond a mere vision. Some of these applications are field experiments, others are commercial products and some are research projects. The different applications give an idea of how extensive the WSN design space is and each application can be characterised by its type.

2.2.1 Types

Many WSN applications share some common characteristics that define a certain type of application. In the majority of cases, a clear distinction can be made between source nodes that sense data and sink nodes that receive data. Sinks can either be part of the network or in some cases they are part of systems outside of the network such as gateways to fixed networks or handheld PDA’s communicating with the network. Sources outnumber sinks in many cases and their identity is of secondary concern with the data itself being of greatest importance.

Patterns of interaction between sources and sinks illustrate some typical patterns. Some patterns that are useful in classifying different applications are as follows [2].

Event detection – Sensor nodes report data on a specified event to sinks once it has occurred and is detected.

Periodic measurements – Sensor nodes report data on measured values of the environment to sinks at regular intervals.

Function approximation – Sensor nodes find an approximation to a function representing the distribution of a measured phenomenon with location and report it to sink nodes.

Edge detection – Sensor nodes find isolines that connect points in space that have equal values of the phenomenon being measured and report them to sink nodes.

Tracking – Sensor nodes report updates on the position of a specified event to sink nodes where the source of the event is mobile.

The interaction patterns highlighted above can have temporal and spatial restrictions placed on them, allowing events to be reported over certain time intervals or in certain areas.

Each application includes a certain set of options that need to be considered beforehand. These include *deployment options*, *maintenance options* and *energy supply options*.

Deployment options – These include planned fixed deployment and random deployment. Once deployed the sensors may remain static in the same position or may become mobile, either by their own accord or as a result of being attached to a mobile object.

Maintenance options – These include whether or not it is feasible and practical to perform maintenance on the sensor nodes. These also include whether the sensor nodes should go unattended for extended periods of time and whether maintenance is out of the question due to reasons such as short mission time.

Energy supply options – These include whether or not energy supply should be replenished externally or if sensor nodes should do so themselves through energy harvesting. These also include whether wired power from an external source or self sustained power is to be used. Price, size and capacity must also be considered.

2.2.2 Examples

Military Applications

One of the main uses of WSNs in a military setting is remote sensing. The sensor nodes can be deployed en masse into a hostile environment, where they establish an ad hoc network and perform passive observation of foreign military units [14]. In one project the goal was to detect and accurately pinpoint enemy snipers using acoustic sensors [15]. Systems such as the Tactical Automated Security System (TASS) are used for perimeter security. The U.S. army has a Disposable Sensor Program that aims to deploy 10^4-10^7 disposable sensors with seismic acoustic RF, magnetic, chemical, biological and infrared sensors. Such a dense deployment will help in providing an almost complete picture of any environment.

Habitat Monitoring Applications

Habitat monitoring has been described as a driver application for WSNs. The use of WSNs in habitat monitoring allows data that is unaltered and untainted by human interaction to be gathered. The presence of humans in some environments may cause a disturbance and interfere with the observed data. In one study it was observed that even a negligible human presence in certain seabird colonies could result in an increase in the mortality rate of cormorant colonies over a given breeding year [16]. Some deployed applications include the Great Duck Island (GDI) system in Maine by researchers from University of California, Berkeley (UCB) and the Intel research laboratory to monitor the behaviour of storm petrel [16]. The PODS research project [17] was conducted by the University of Hawaii and in it a WSN was built to investigate why endangered species of plants grown in one area but not in other neighbouring areas.

Environment Observation and Forecasting System (EOFS)

These applications are natural candidates for using WSNs, since the variables to monitor are usually distributed over large areas. An EOFS is a large, distributed system that spans large geographical areas and monitors, models and forecasts physical processes that may include floods, wildfires and environmental pollution. Such a system can be used for disaster relief. A prototype EOFS is the CORIE system for the Columbia River [12].

Automated Local Evaluation in Real Time (ALERT) was developed by the national weather service of the Unites States of America in the 1970s to provide important real time water level and rain fall information to judge the possibility of flooding and WSNs can be used to develop such a system. Researchers at the University of Southampton have places wireless nodes in and around the Briksdalsbreen glacier in Norway with the intention of monitoring the behavior of ice caps and glaciers and determine their effect on global weather trends [18].

Health Applications

The use of WSNs in these applications is potentially controversial and includes telemonitoring of human physiological data, monitoring and tracking of doctors and patients inside a designated health care area, the automatic administration of drugs to patients and others. Mobile telemedicine has the potential to extend healthcare to patients without them having to have extensive stays in hospital or paying several visits to the hospital.

One proposed system uses a multimedia telemedicine application with the integration of 3G-cellular and WSNs [19]. The Smart Sensors and Integrated Microsystems (SSIM) project sought to create an artificial retina. In it a retina prosthesis chip consisting of 100 micro sensors is built and implanted within a human eye [20]. This would then allow patients with limited or no vision to see at an acceptable level.

Multimedia Applications

Wireless multimedia sensor networks (WMSNs) are WSNs that allow the retrieval of video and audio streams, still images and scalar sensor data [21]. They are an extension of traditional WSNs brought about by the availability of low-cost hardware such as CMOS cameras and microphones. They enhance existing WSN applications and enable new applications, such as multimedia surveillance sensor networks, advanced health care delivery, industrial process control, person locator services and others.

Other Applications

Other applications of WSNs include traffic control where wireless sensors are deployed at road intersections to detect and count vehicle traffic and estimate its speed. In smart energy applications, the efficiency of an energy provision chain which consists of the generation, distribution and consumption infrastructure is improved through the use of WSNs. Home and office applications of WSNs include the management and automation of facilities as well as surveillance and other security functions. WSNs can also be used in logistics for tracking of goods and maintenance of inventories. In precision agriculture, precise irrigation and fertilizing is enabled by placing humidity and soil composition sensors into fields.

2.3 ARCHITECTURES

2.3.1 Sensor Node

The hardware components of a sensor node are determined to a large extent by the requirements of the application in which the WSN will be used. Influenced by the needs of the application, the form factor of the sensor nodes may vary from the size of a shoe box (e.g. for a weather station) to a macroscopically small particle (e.g. military surveillance) [3]. Likewise, the cost of individual nodes may vary from a small fraction of a Euro (for large scale networks of simple nodes) to hundreds of Euros (for networks of a few powerful nodes). The size and cost constraints will then limit the available energy as well as the communication, storage and computation resources. There is however a set of common features that different sensor nodes have that form the basic sensor node architecture. The five main components of a sensor node are as follows [2]:

1. **Controller** – This processes all relevant data and is capable of executing arbitrary code.
2. **Memory** – This stores programs and intermediate data; data and programs use different types of memory.

3. **Sensors and Actuators** – These are devices that can observe or control physical parameters of the environment and form the actual interface to the physical world.
4. **Communication device** – This sends and receives information over a wireless channel and turns a collection of nodes into a network.
5. **Power supply** – This is the energy source of the device and mostly comes in the form of batteries as an un-tethered power supply is usually unavailable. A form of recharging or energy scavenging from the environment may be available.

The main hardware components of a sensor node are shown in Figure 2-2 below.

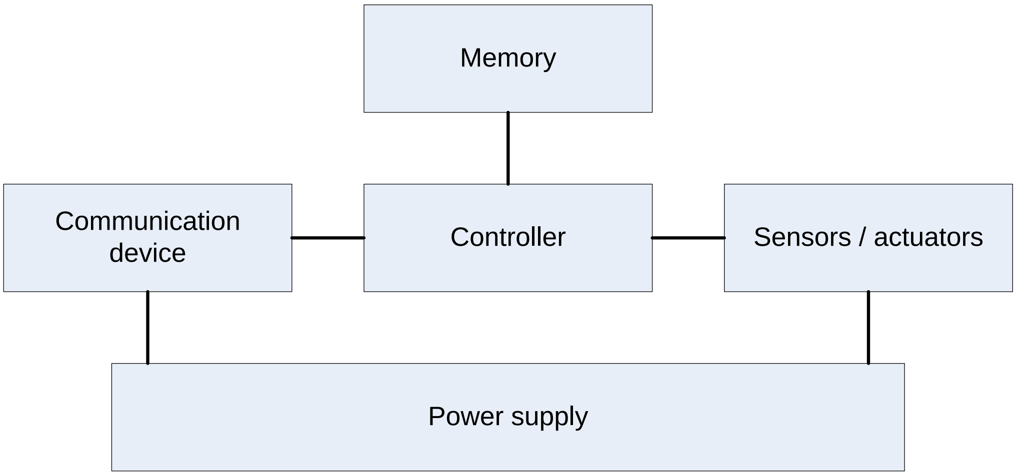


Figure 2-2: Main hardware components of a wireless sensor node [2].

2.3.2 Network

Sensor nodes are usually deployed in a sensor field where they collect data and route it back to a sink. The collection of the sensor nodes and the wireless links created between them forms the wireless network. The sink nodes that receive data may be one of three types; they may be sensor nodes, gateways to a larger network such as the internet, or devices such as PDAs used to interact with the network. Direct communication between source nodes and sink nodes is not always possible in WSNs as they are supposed to operate in difficult radio environments where there is strong attenuation and they are required to cover a lot of ground. As a result simple single-hop sensor network architecture is not always possible; instead, relay stations are used allowing the data to take multiple hops from the source to the sink as shown in Figure 2-3.

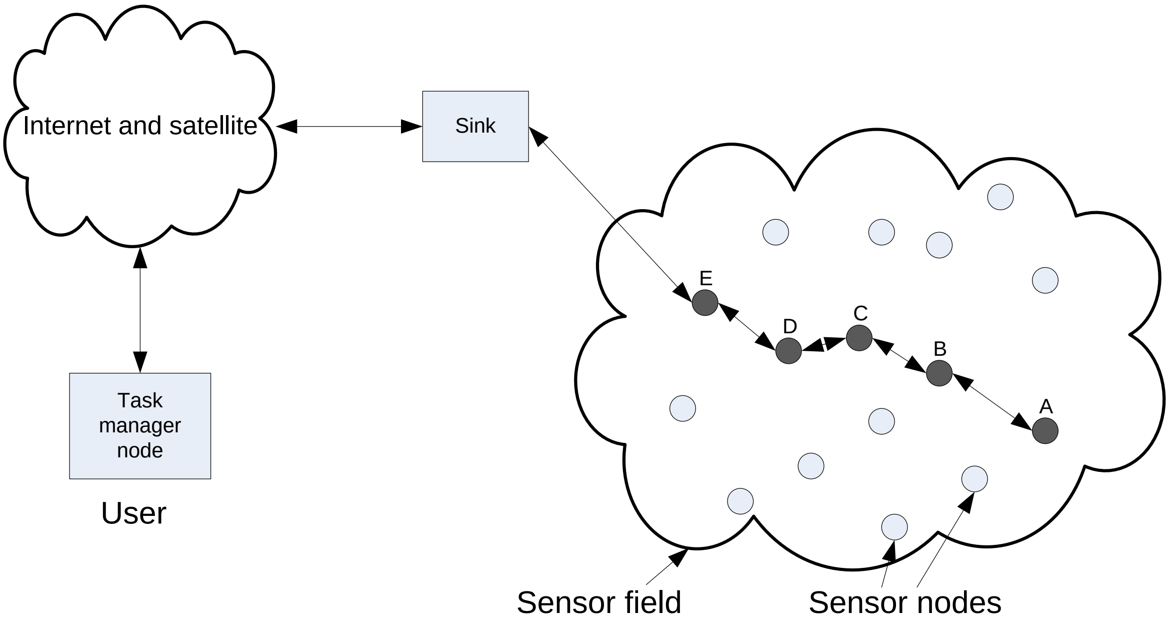


Figure 2-3: Multi-hop network architecture [21].

A multi-hop architecture overcomes the problem of larger distances and obstacles; there are also suggestions that it can improve energy efficiency as less energy is used to relay a message over a short distance than to communicate it directly over a long distance due to the quadratic attenuation of signals in space with distance.

The participants in the WSN may be mobile and this must be catered for by the communication protocols for WSNs. There are three types of mobility that may be present:

1. **Node mobility** – This is where the sensor nodes are mobile.
2. **Sink mobility** – This is where the recipients of data are mobile.
3. **Event mobility** – This is where the events or objects to be tracked are mobile.

The network may be optimised to cater for the different applications and scenarios that may occur. Figures of merit are used to perform this optimisation. Some important figures of merit that are used are:

- Quality of service
- Energy efficiency
- Scalability
- Robustness

2.4 PROTOCOLS AND STANDARDS

2.4.1 Protocol Stack

The protocol stack for WSNs consists of the *physical layer*, *data-link layer*, *network layer, transport layer, and application layer* [1] as show in Figure 2-4 below. The protocol stack is similar to the Open Systems Interconnection (OSI) protocol stack with the exception that there is no session or presentation layer.

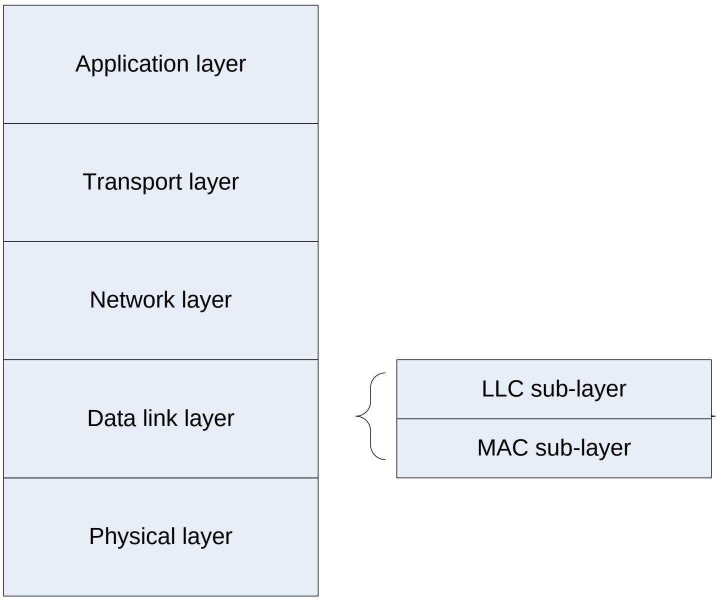


Figure 2-4: The WSN protocol stack [1].

The *physical layer* addresses the needs of simple, low cost and robust modulation, receiving and transmission techniques. It comprises of the functions and components of a sensor node that mediate between the transmission and reception of wireless waveforms and the processing of digital data by the node.

The *data link layer* performs the tasks of Medium Access Control (MAC) and Link Layer Control (LLC). There are several MAC protocols that solve the task of coordinating the times where a number of nodes access a shared communication medium and minimise collisions with neighbour broadcasts. LLC involves of the formation and maintenance of links between neighbouring nodes and reliable and efficient communication using these links. The data-link layer can be split into a lower MAC sub-layer and an upper LLC sub-layer.

The *network layer* is responsible for the routing of data which involves the relaying of packets from source to destination in a multi-hop network where an intermediate node has to decide the appropriate neighbour to forward a packet to. There are several topology control and routing protocols for this purpose.

The *transport layer* assists in maintaining the flow of data according to the requirements of the WSN application. These requirements are usually specified in terms of a desired quality of service (QoS). A key quality of service measure in WSNs is that of reliability. Reliability can be specified in terms of *detection reliability*, *information accuracy* and *reliable data transport*. Another QoS measure is that may be important in some WSN applications is that of timely delivery of data.

The *application layer* provides various services for the development of different types of application software according to the sensing tasks required. These services may include in-network processing such as data aggregation and distributed source coding. Another service that may be provided is security, covering concerns such as confidentiality, data integrity, accountability, availability and access control.

2.4.2 Standards

IEEE 802 is a family of networking standards that cover technology specifications for the physical and data link layers of networks, from Ethernet to wireless. The IEEE 802.11 working group specialises in wireless local area network (WLAN) standards. The IEEE 802.16 working group focuses on standards for fixed wireless metropolitan area networks (WMANs) while standards for mobile WMANs are the focus of the IEEE 802.20 working group.

IEEE 802.15 is the 15th working group of IEEE 802 and focuses on wireless personal area network (WPAN) standards. There are seven task groups within this working group with the most relevant ones for WSNs being task groups 1, 3, and 4. Task group 1 (IEEE 802.15.1) derived a WSN standard based on specifications of Bluetooth v1.1 and later Bluetooth v1.2 for the physical layer and MAC sub layer. Task group 3 (IEEE 802.15.3) focuses on high data rate WPANs whereas task group 4 (IEEE 802.15.4) focuses on low data rate WPANs.

The standards highlighted above only cover the physical and data link layers and as such several technology partners have come together to form alliances that look to address issues regarding the other layers of the protocol stack based on the specifications of a particular 802 standard. These alliances define specifications for the upper layers in the protocol stack and provide certification for interoperable products. Such alliances include the wireless fidelity (Wi-Fi) alliance, the ZigBee alliance, the Bluetooth special interest group (SIG) and the WiMAX forum.

Some specifications that have been developed covering the entire protocol stack for WSNs include Bluetooth, ZigBee, Ultra Wideband (UWB) and Wi-Fi which correspond to the IEEE 802.15.1, 802.15.4, 802.15.3 and 802.11a/b/g standards respectively [22].

Wi-Fi

The Wi-Fi standard includes the IEEE 802.11a/b/g standards for WLANs. Users can connect to a network at broadband speeds in the 2.4, 3.6 and 5 GHz frequency bands through an access point (AP) or without one when in ad hoc mode of operation. The IEEE 802.11 standards support mobility which is transparent to the upper layers. A basic service set (BSS) is the basic cell in the WLAN and is a set of fixed or mobile stations. When a node moves out of its BSS it can no longer communicate directly with it and will require an AP.

When nodes can communicate directly without the need for an AP then the BSS is an independent basic service set (IBSS). For an IBSS configuration the WLAN can be formed without any pre planning and is often referred to as an ad hoc network. When different BSS are connected through access points and a distribution system then an extended service set (ESS) is formed. These different service set scenarios are shown in Figure 2-5.

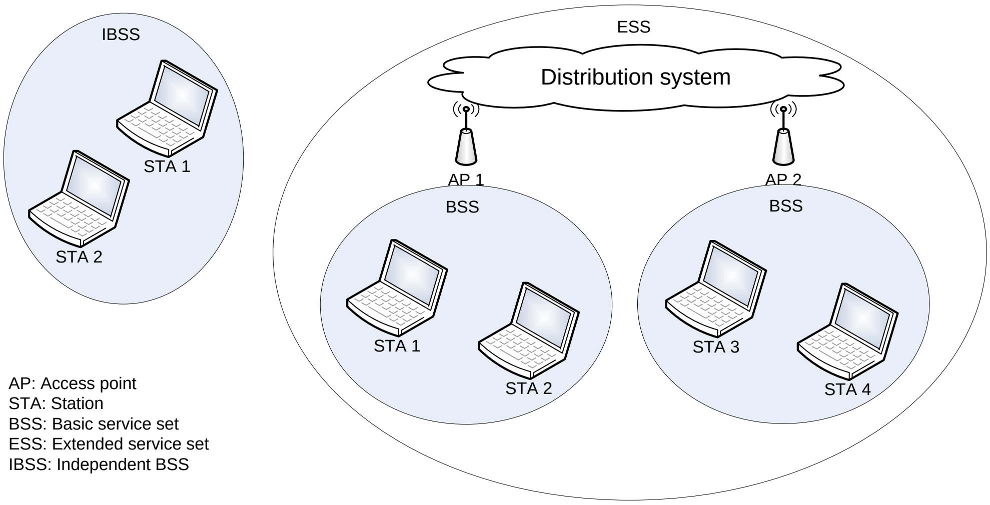


Figure 2-5: BSS, IBSS and ESS configurations in Wi-Fi networks [22].

Bluetooth

Bluetooth is a standard that was originally developed as a data cable replacement technology for computer peripherals such as mice, joysticks, keyboards and printers. It caters for the exchange of data wirelessly over short distances at low power consumption using low cost transceiver chips. There are three classes of Bluetooth with class 1 having a transmission range of 100 metres and a maximum transmitter power of 100 mW; class 2 has a maximum transmitting range of 10 metres and a maximum transmitter power of 2.5 mW; class 3 has a maximum transmission range of 1 meter and a maximum permitted power of 1mW. Bluetooth radio transceivers operate in the 2.4 GHz frequency range.

The IEEE 802.15.1 physical and MAC layers are based on the Bluetooth v1.1 and Bluetooth v1.2 specifications. Two connectivity topologies are defined in Bluetooth, the piconet and the scatternet. A piconet comprises of between 2 and 8 nodes with one of them acting as a master and the rest as slaves connected to the master. A frequency hopping channel based on the device of the master defines each piconet. All communication in the piconet is routed through the master and all devices participating in communications in the piconet are synchronised using the clock of the master. A slave node may be in active mode or in parked or stand by modes to reduce power consumption.

A scatternet is a collection of operational piconets that overlap in time and space. A Bluetooth device may participate in several piconets acting at the same time, such a node is referred to as a gateway. A gateway node uses Time Division Duplex (TDD) so as to only be active in one piconet at a time. A gateway node can be a slave in a several piconets that it is a part of but can only be a master in one piconet. An example of a scatternet is shown in Figure 2-6.

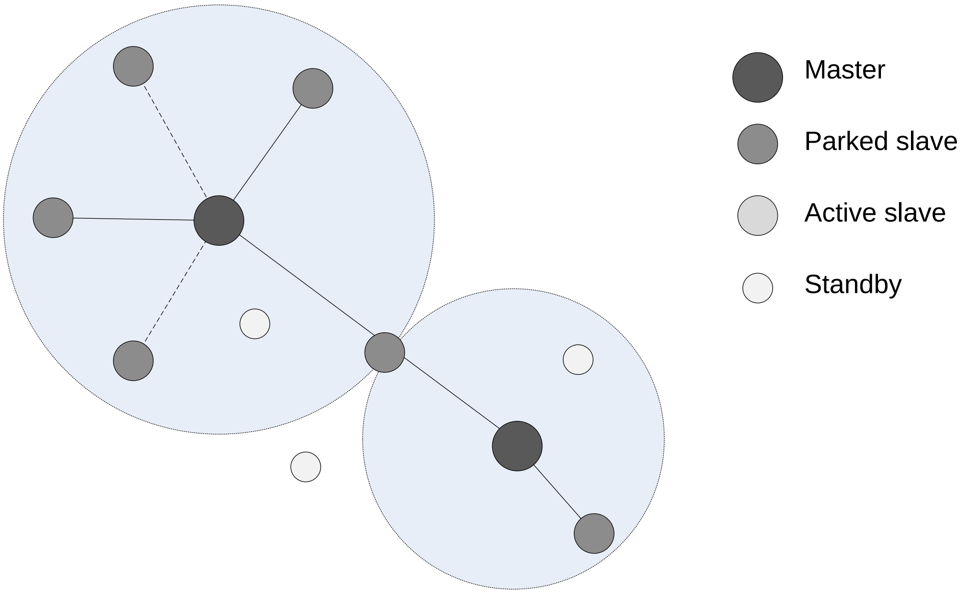


Figure 2-6: A Bluetooth scatternet [23].

Wibree

The Wibree protocol was introduced by Nokia in 2006 as an open industry initiative to extend local connectivity to small devices. The Wibree protocol is similar to Bluetooth in the 0-10 m communication range and 1 Mbps data rate [24]. There are two implementation alternatives to Nokia's Wibree protocol: Stand-Alone Chip and Bluetooth-Wibree Dual-Mode Chip. Applications where only small amounts of data are transferred are the target of the single chip option. The dual mode chip option is meant for use with Bluetooth devices.

Using the Bluetooth-Wibree Dual-Mode chip, Wibree functionality can be integrated with Bluetooth at a small increase in cost through the utilisation of key Bluetooth components and the existing Bluetooth radio frequency. Bluetooth devices will then be able to connect to a new range of tiny battery powered devices. The development of the Wibree protocol is still in progress.

ZigBee

The ZigBee standard defines specifications for low rate WPANs and builds on the IEEE 802.15.4 standard. ZigBee enables self organised, multi-hop, reliable mesh networking with long battery life [22]. ZigBee defines the network layer specifications for different topologies namely the star, tree and peer to peer topologies. ZigBee also provides a framework for application programming in the application layer [25]. ZigBee has the advantages of ease of installation, reliable data transfer, short range of operation, extremely low cost and reasonable battery life while maintaining a simple and effective protocol stack.

The physical layer supports three frequency bands, a 2450 MHz frequency band, a 915 MHz frequency band and an 868 MHz frequency band with all of them using the Direct Sequence Spread Spectrum (DSSS) access mode. The main features of the three bands are shown in Table 2-2 below.

Table 2-2: ZigBee physical layer specification [25]

	2450 MHz	**915 MHz**	**868 MHz**
Gross data rate	250 kbps	40 kbps	20 kbps
No. of channels	16	10	1
Modulation	O-QPSK	BPSK	BPSK
Chip pseudo-noise sequence	32	15	15
Bits per symbol	4	1	1
Symbol period	16 µs	24 µs	29 µs

The IEEE 802.15.4 MAC layer defines two types of nodes, the full function devices (FFDs) and the reduced function devices (RFDs). FFDs are equipped with a full set of MAC layer functions which enable them to act as a network end device or a network coordinator. As network coordinators, FFDs send beacons that provide services for synchronisation, communication and joining the network. RFDs are limited to acting as network end devices only and are equipped with sensors or actuators. RFDs may only communicate with a single FFD.

At the networking layer, ZigBee identifies three types of devices namely a ZigBee end device which may be a MAC layer RFD or FFD acting as a simple device; a ZigBee router which is a FFD with routing capabilities; a ZigBee coordinator (one in the network) which is a FFD managing the whole network. The ZigBee network layer supports the star, tree and mesh network topologies as shown in Figure 2-7.

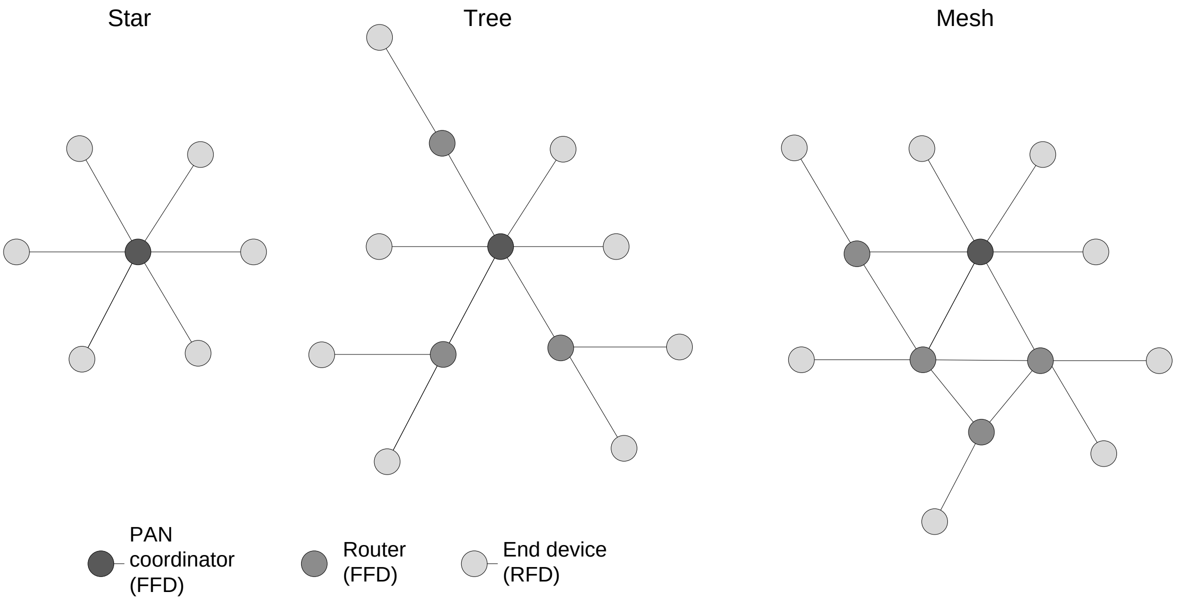


Figure 2-7: ZigBee network topologies [25].

The routing algorithm used depends on the WSN topology that is used. In a tree topology, routing can only take place along the parent-child links that have been established as a result of join operations. Such tree based routing is not the most energy efficient but is very simple and allows routers to operate in a beacon-enabled network.

In mesh topologies routing is more complex to handle and beaconing is not permitted but it is more robust and resilient to faults. Routers maintain a routing table and update it using a route discovery algorithm. Route discovery in ZigBee is based on a well known Ad Hoc On Demand Vector (AODV) routing algorithm.

ZigBee applications must conform to an existing ZigBee application profile that defines message formats and protocols for interactions between application objects (APOs) that together form a distributed application. APOs are pieces of software that control a unit of hardware. ZigBee Device Objects (ZDOs) are special objects that offer services to APOs. One such service is a security service where the ZDO manages the security profiles and the security configuration of a device. Different means to achieve the security requirements of freshness, message integrity, authentication and encryption are provided for by the ZigBee specification.

Ultra Wideband

The ultra wideband standard defines specifications for high rate WPANs and builds on the IEEE 802.15.3 standard. It can be used at very low energy levels for short range high bandwidth communications by using a large portion of the radio spectrum. UWB characterises transmission systems with instantaneous spectral occupancy in excess of 500 MHz or a fractional bandwidth in excess of 20% [26].

One of the desirable features of UWB is that its bandwidth is over 110 Mbps which can satisfy most multimedia applications such as audio and video delivery and it can also act as a wireless data cable replacement for high speed serial bus such as USB 2.0 and fire wire (IEEE 1394).

2.4.3 Comparison

The table below compares the specifications of Bluetooth, UWB, ZigBee and Wi-Fi.

Table 2-3: Comparison of Bluetooth, UWB, ZigBee and Wi-Fi protocols [22]

	Bluetooth	**UWB**	**ZigBee**	**Wi-Fi**
IEEE spec.	IEEE 802.15.1	IEEE 802.15.3b	IEEE 802.15.4	IEEE 802.11a/b/g
Frequency band	2.4 GHz	3.1 – 10.6 GHz	868/915/2400 MHz	2.4, 5 GHz
Max signal rate	1 Mbps	110 Mbps	250 kbps	54 Mbps
Nominal range	10 m	10 m	10 – 100 m	100 m
Nominal TX power	0 – 10 dBm	-41.3 dBm	(-25) – 0 dBm	15 – 20 dBm
Number of RF channels	79	1 – 15	1/10; 16	14
Channel bandwidth	1 MHz	500 MHz – 7.5 MHz	0.3/0.6 MHz; 2 MHz	22 MHz
Modulation type	GFSK	BPSK, QPSK	BPSK	BPSK, QPSK, COFDM, CCK, M-QAM
Spreading	FHSS	DS-UWB, MB-OFDM	DSSS	DSSS, CCK, OFDM
Coexistence mechanism	Adaptive freq. hopping	Adaptive freq. hopping	Dynamic freq. hopping	Dynamic freq. selection, transmit power control
Basic cell	Piconet	Piconet	Star	BSS
Extension of the basic cell	Scatternet	Peer-to-peer	Cluster tree, Mesh	ESS
Max no. of cell nodes	8	8	> 6500	2007
Encryption	E0 stream cipher	AES block cipher	AES block cipher	RC4 stream cipher (WEP), AES block cipher
Data protection	16-bit CRC	32-bit CRC	16-bit CRC	32-bit CRC

2.5 CHALLENGES

2.5.1 Differences to Mobile Ad Hoc Networks

A mobile ad hoc network (MANET) is a self configuring network of mobile devices connected with wireless links set up for a specific purpose to meet a quickly occurring communication requirement. A MANET is sometimes referred to as a mobile mesh network. MANETs are similar to WSN but there are some differences of note [2].

Applications and equipment – The applications and equipment used in MANETs differs to that used in WSNs.

Application specific – A large variety of communicating, sensing and computing technology can be combined in WSNs for a wider variety of application scenarios than in MANETS.

Environment interaction – The data in MANETS is human driven whereas the data in WSNs in usually environment driven and follows a different pattern in terms of data rate and time scale.

Scale – WSNs typically involve a larger number of nodes at a higher density than MANETs.

Energy – WSNs have more stringent requirements for network lifetime and energy efficiency. The recharging and replacing of batteries is less of an option in WSNs and the impact of energy considerations covers the entire system architecture in WSNs.

Self configurations – Both WSNs and MANETS require self configuration but WSNs require new solutions in order to cater for differences in data traffic, energy trade-offs and other WSN specific needs.

Dependability and QoS – Quality of service in WSNs is defined more in terms of the reliability of the data covering measures such as information accuracy and detection reliability as opposed to reliability of individual nodes as in MANETs.

Data centric – Data centric protocols are of importance in WSNs but are largely irrelevant in MANETs.

Simplicity and resource availability – Nodes have limited computational and memory ability in WSNs and energy supply is also scarce and hence scalable, lightweight energy-efficient software solutions are required in WSNs.

Mobility – Mobility is present in both MANETS and WSNs however in WSNs there are additional mobility scenarios other than that of source node mobility which are the mobility of the data of interest and the mobility of sink nodes which must both be catered for.

2.5.2 Design Issues

There are several design factors that must be taken into consideration when developing protocols and algorithms for WSNs. These factors can be used as reference points when comparing different schemes and they represent constraints in WSNs.

Fault Tolerance

Faults may arise in the network due to lack of power, environmental interference or physical damage. The ability to sustain WSN functionality amid these faults is fault tolerance and is represented mathematically as

$$R_k\ (t) = \mathrm{e}^{-\lambda_k t}, \tag{2.1}$$

where λ_k is the failure rate of the node k and t is the time period.

Scalability

The number of nodes in a WSN can vary greatly and may be on the order of hundreds or thousands. The number can grow to be even beyond this depending on the application bearing in mind that some applications exhibit growth. It is therefore necessary to develop schemes that can handle not only the large number of nodes that may be present but can also handle growth of the network. The density of nodes

$$\mu(R) = (N \cdot \pi R^2)/A, \tag{2.2}$$

where R is the radio transmission range and N is the number of nodes in region A.

Hardware Constraints

The four basic components of a sensor node are the *sensing unit, processing unit, receiving unit and power unit.* Additional components are also possible depending on the application such as a *localization unit, mobilize* or *power generator*. The nodes must consume extremely low power, operate in high volumetric density areas, be adaptive to the environment and be autonomous.

Sensor Network Topology

Deploying a high number of nodes densely requires meticulous handling of topology maintenance. There are three phases that are pertinent when considering topology changes and these are as follows.

- *Pre-deployment and deployment phase*: The sensor nodes can either be placed one by one in a sensor field or thrown as a mass. The nodes can be dropped from a plane or deployed in an artillery shell, missile or rocket, or placed one after the other by a human or robot.
- *Post-deployment phase*: After the pre-deployment and deployment phase, topology changes can occur due to changes in the position, reachability or energy of sensor nodes. Topology can also change due to malfunctioning or changes in task.
- *Redeployment of additional nodes phase*: Additional sensor nodes can be deployed to replace faulty or malfunctioning nodes or due to changes in the dynamics of the task at hand.

Power Consumption

The power supply that the sensor nodes can be equipped with is limited. The lifetime of the sensor mode is therefore dependent on battery lifetime and in some applications it is not possible to replace the power source. Power conservation and power management are crucial aspects of WSNs and take on additional importance. It is necessary to develop power aware algorithms and protocols for WSNs. Power consumption can be divided into three main domains namely:

- sensing,
- communication and
- data processing.

Tasks in each of these domains can be optimized for minimal power consumption.

CHAPTER 3

TOPOLOGY CONTROL

3.1 MOTIVATION

Literature poses several solutions to some of the design issues found in WSNs that were highlighted in the previous chapter. These issues include energy-conservation, limited bandwidth, unstructured and varying network topology, low quality communications, operation in hostile environments, data processing and scalability. A considerable amount of effort has been put into finding energy-efficient and mobility-resilient routing, broadcast and multicast protocols [4].

Routing, broadcast and multicast protocols are often focused on energy-efficient communication on a given communication graph that serves as the input to the protocol that generates routing tables. In contrast with wired networks, the topology in wireless networks is not fixed and can be changed by controlling the neighbours of a certain node. If the network topology used to route messages is energy efficient then further energy can be saved in the WSN.

In a densely deployed WSN (Figure 3-1), an individual node has many neighbours with which it can communicate with directly when using a sufficiently high transmission power. This is undesirable because the high transmission power will use a lot of energy particularly in cases when a node communicates directly with a distant node. Many neighbours pose a burden to the MAC protocol due to increased contention and interference and cause routing protocols to suffer volatility due to the need to re-compute routing tables when nodes move even slightly or create and sever links. Topology control can be used to solve these problems and to create an energy efficient network topology.

The idea behind topology control (TC) is to restrict the set of nodes that are considered neighbours of a given node. The goal of topology control is to dynamically change the network topology through either changing the nodes’ transmitter power, introducing hierarchies in the network or by simply turning some nodes off for a certain amount of time [2] in order to maintain some property of the communication graph (e.g. connectivity) while reducing the energy consumed by node transceivers.

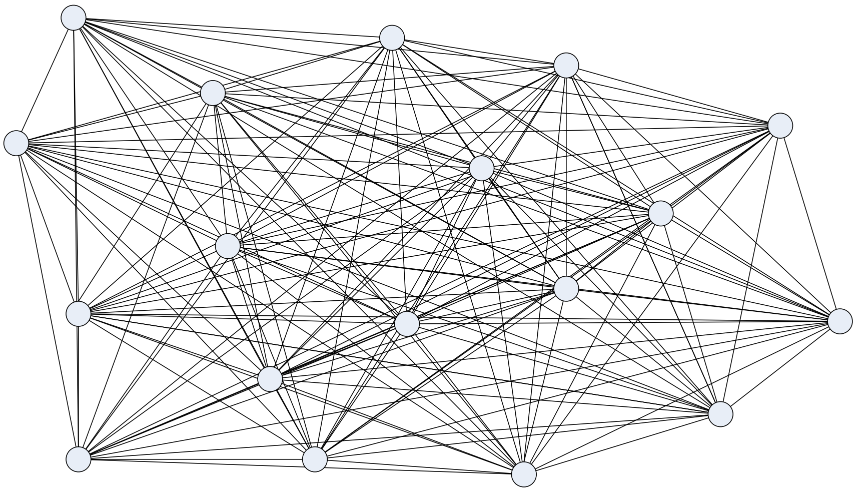


Figure 3-1: Topology in a densely deployed wireless network [2].

3.2 CHARACTERISATION

3.2.1 Taxonomy

There are several different approaches to topology control and it is possible to organise them into a coherent taxonomy. The first distinction is between approaches that control transmitter power and those that impose a hierarchy in the network. Hierarchical approaches change the logical structure of the network in terms of node adjacencies and may be broken down into approaches that use clustering and those that use dominating sets.

The power control approaches act on the transmission power of nodes using several different techniques. The first distinction to make of power control approaches is between homogeneous and non homogeneous approaches. Homogeneous topology control is the easier of the two in which nodes are assumed to use the same transmitting power and the problem of topology control becomes in essence one of finding the value of the transmitter range *r* that satisfies a certain network wide property.

In non homogenous topology control nodes are allowed to select different individual transmitting powers up to a certain maximum that they can support which means that they will have different transmitting ranges. This form of topology control can be split into three different categories according to the type of information that is used to generate the topology. These three categories are location based, direction based and neighbour based.

In location based approaches exact node locations are known and are either used by a centralised authority to calculate a set of transmitting range assignments which optimise a certain measure or are exchanged between nodes to create an approximately optimal topology in a distributed fashion. In direction based approaches nodes are assumed to not know their positions but can estimate the relative direction to each of their neighbours. Lastly in neighbour based approaches the only knowledge nodes have of their neighbours is the neighbour IDs and the IDs are ordered according to some criterion when performing topology control. The taxonomy for topology control is illustrated in Figure 3-2 below.

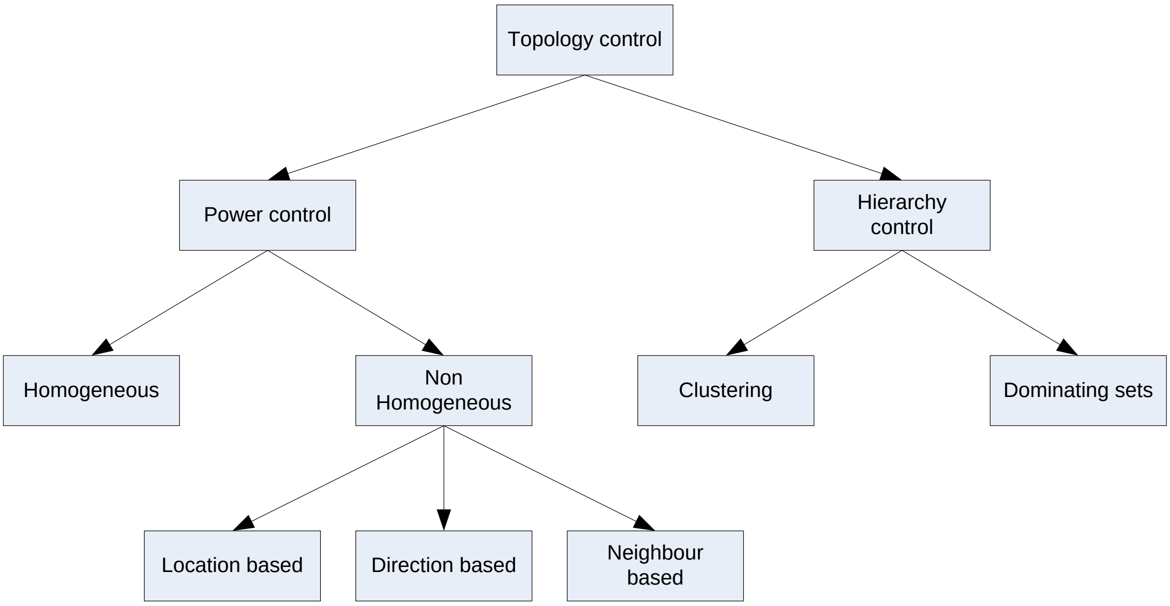


Figure 3-2: Taxonomy of approaches to topology control [4].

3.2.2 Quality Measures

Different approaches to topology control will produce different results. For a collection of nodes V, let G denote the graph on V for which there is an edge from node u to node v only if u can directly reach v. It is desirable to judge the usefulness of a topology T returned by a topology control algorithm and compare it with results from other algorithms. In order to do this, some metrics and measures are required which include connectivity, energy efficiency, throughput and robustness to mobility [27].

Connectivity – If there is a multi-hop path between *u* and *v* in *G* then there should also be a path in *T*. This is a basic requirement for a topology control algorithm, that it should not disconnect a connected graph.

Energy efficiency – The energy consumed for a transmission between *u* and *v* is a polynomial function of the distance between *u* and v. Two common notions of energy efficiency are the *energy stretch factor* and the *hop stretch factor*. The energy stretch factor is the worst increase in energy used to deliver a packet between any pair of nodes *u* and *v* along a minimum energy path between the original graph *G* and the topology controlled graph *T*. The hop stretch is similar except that the focus is on path length as opposed to energy consumption. Formally,

$$\text{energy stretch factor} = \max_{u,v\,\in V} \frac{E_T(u,v)}{E_G(u,v)}, \tag{3.1}$$

where $E_G(u,v)$ is the energy consumed along the most energy-efficient path in graph *G*. Likewise,

$$\text{hop stretch factor} = \max_{u,v\,\in V} \frac{|(u,v)_T|}{|(u,v)_G|}, \tag{3.2}$$

where $(u,v)_G$ is the shortest path in graph *G* and $|(u,v)_G|$ is its length.

Simplicity and maintainability – It is desirable for a topology *T* to be simple and easy to maintain and objective measures that can be used to evaluate these subjective goals are the number of edges in *T* and the maximum node degree (number of neighbours) of any node in *T*. It is desirable also for the algorithm used to have little overhead in terms of computation and communication requirements.

Throughput – It is desirable for the network topology *T* to have a high throughput, where it is possible to sustain a comparable amount of traffic as the original network topology *G*. Several throughput measures can be used [27] one of which is the *bit-meter* which is defined in terms of the bit-distance product. A network transports one bit-meter when it one bit is transported a distance of one meter. The throughput of the network is then the number of bit-meters transported per second.

For *n* identical nodes randomly distributed in a disk of unit area with each node having a fixed transmission range the throughput achievable for each source given a randomly chosen destination measured as a bit distance product is inversely proportional to $\sqrt{n \log n}$. If the source destination pairs are selected optimally then the maximum bit-distance product achievable in the network grows per unit time by $\Theta(\sqrt{n})$; the bit-distance product is therefore inversely proportional to $\sqrt{n}$. Under certain assumptions about traffic patterns and node locations in the network the average throughput per user decreases as the number of users increases.

A different model that captures the throughput capabilities of network in cases other than the best-case and average case (assuming a random traffic pattern) is one for a traffic pattern determined by arbitrary source destination pairs that exchange data at arbitrary rates. In this case the *throughput competitiveness* measure can be used which is the largest $\phi \leq 1$ such that given a set of flows from node s_i to node d_i with rate r_i that are routable in G, the set with rates ϕr_i can be routed in T.

Robustness to mobility – The mobility of nodes causes neighbourhood relationships to change in the original graph G and some other nodes will have to change their topology information. A robust topology should only require a small number of these adaptations and avoid the effects of reorganisation due to local node movement affecting the entire network. A measure of robustness is the *adaptability* [27] which is the maximum number of nodes that need to change their topology information as a result of the movement of a node. Adaptability depends on the size of the transmission neighbourhood of the mobile node u and the relative location of the nodes.

3.2.3 Probabilistic Tools

Some of the solutions to the problem of topology control particularly in approaches that use power control are derived from various probabilistic theories [4]. The primary challenge in the probabilistic analysis of WSNs is that the established theory of random graphs cannot be used. An assumption that is made in this model is that the probabilities of edge occurrence are independent; this however is not the case in wireless ad hoc networks. For three nodes i, j, k such that the distance form i to j (δ_{ij}) is smaller than the distance from i to k (δ_{ik}) then if i has a link to k then it also has a link to j hence the assumption of independence does not hold and the occurrence of edges (i, j) and (i, k) are correlated.

This is the case when using common wireless technologies that use omni-directional antennas and disregarding the effect of channel fading and shadowing.

In order to overcome this problem the *Random Network* (RN) model was introduced as a generalisation of the uniform random graph model in which graphs are selected according to a more general probability distribution. In the RN model graphs are chosen according to an arbitrary non degenerate distribution which is one that does not concentrate on a class of graphs of a relatively small size. A theory that is more recent and still in development is the theory of *Geometric Random Graphs (*GRG*)*. In this theory a set of n points are distributed according to some density in a d-dimensional region R and a property of interest in the node deployment is investigated such as the connectivity.

Two other theories of note that have been used in deriving solutions to topology control are the theory of *continuum percolation* and *occupancy theory*. In the theory of continuum percolation an assumption is made that nodes are distributed with Poisson density λ in $\mathbb{R}^2$ and two nodes are connected to each other if the distance between them is at most r. Occupancy theory assumes that should n balls be thrown independently at random into C cells then the allocation of balls into the cells can be characterised by random variables describing some property of the cells. Occupancy theory aims to determine the probability distribution of these random variables as n and C grows towards infinity. Both the theory of continuum percolation and occupancy theory can be used to analyse connectivity in WSNs.

3.3 POWER CONTROL

3.3.1 Homogeneous

Suppose n nodes are placed in $R = [0, l]^d$ for $d = 1,2,3,$ a question arises as to what are the minimum values of the transmitting range r such that the homogeneous range assignment produces a connected network. This minimum value r is known as the critical transmitting range C_{TR} for connectivity [5]. It is important to study the critical transmitting range as in a number of cases it is not feasible to dynamically change the transmitting range. Some expensive radio transmitters may not allow the transmitting range to be adjusted. In such cases it is reasonable to set the same transmission range for all nodes and the C_{TR} is the only choice to reducing power consumption and increasing network capacity.

Finding the value of C_{TR} depends on the information that is available about node deployment. In cases where the position of nodes is known in advance then C_{TR} is the length of the longest edge of the Euclidean distance Minimum Spanning Tree (MST). Many WSNs however are deployed in an ad hoc manner and node placements are not known in advance. When node placement is not known the minimum value of r that ensures connectivity in all possible cases is $r \approx l\sqrt{d}$ which considers the fact that nodes may be concentrated at opposite ends of the deployment region.

The scenario of nodes been deployed such they are concentrated at opposite ends of the deployment region is unlikely, as a result C_{TR} has been studied with the assumption that nodes are distributed according to some probability distribution in R. The goal in such a case is to characterise the minimum value of r which provides connectivity with a high probability that approaches 1 as the number of nodes increases. A common power throughout the network ensures bi-directionality of links which in turn ensures that the MAC protocol work efficiently. The dense network of Figure 3-1 is shown in Figure 3-3 where power control has been applied to control the network topology.

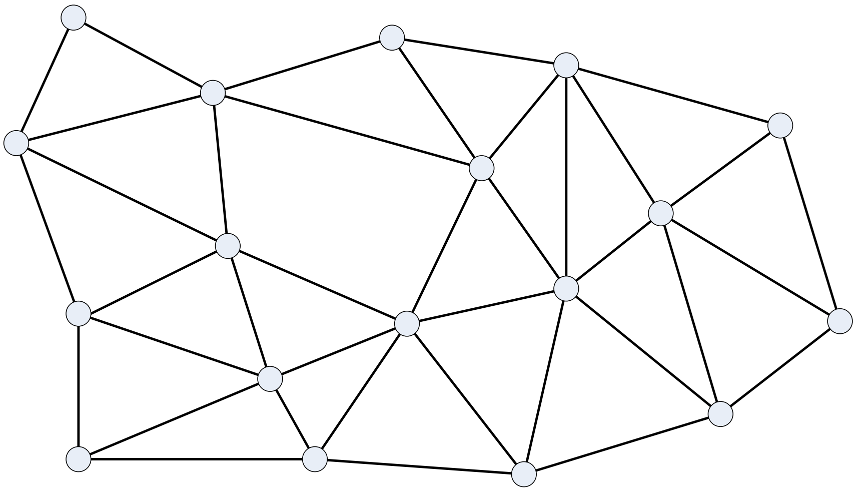


Figure 3-3: Sparser topology after reducing transmission power [2].

Dense networks

The probabilistic theory of geometric random graphs is the theory that is most suitable to analysing C_{TR} in dense networks. Probabilistic solutions for C_{TR} can be derived using results from the asymptotic distribution of the longest MST edge [28]. Under the hypothesis that nodes are uniformly distributed in [0, 1] for one dimensional networks then C_{TR} is

$$r = \frac{\log n}{n}. \tag{3.3}$$

In the case that nodes are uniformly distributed in $[0, 1]^2$ the critical transmitting range for connectivity is

$$r = c\sqrt{\frac{\log n}{n}}, \tag{3.4}$$

for some constant $c > 0$. In three dimensions with nodes distributed at random in $[0, 1]^3$ the critical transmission range for connectivity with high probability is

$$r = \sqrt[3]{\frac{\log n - \log\log n}{n\pi} + \frac{3}{2}\cdot\frac{1.41 + g(n)}{n\pi}}, \tag{3.5}$$

where $g(n)$ is an arbitrary function such that $\lim_{n\to\infty} g(n) = +\infty$ [4].

The theory of GRG has been used to determine C_{TR} for cases when nodes are not uniformly distributed such as the two dimensional normal distribution [4]. GRG theory has also been used to derive an analytical expression to determine the range r that creates for a node density ρ an almost k-connected network with high probability [28]. The probability itself is given by

$$P(G \text{ is } k-\text{connected}) \approx 1 - \sum_{l=0}^{k-1} \frac{(\rho\pi r^2)^l}{l!} e^{-\rho\pi r^2} \text{ [29]}. \tag{3.6}$$

Using the theory of continuum percolation and with R as a disk of unit area is has been shown that C_{TR} is

$$r = \frac{\log n + c(n)}{n\pi}, \tag{3.7}$$

if and only if $c(n) \to \infty$ [5].

Sparse Networks

The theoretical results presented for the case of dense networks have limited applicability in realistic WSN scenarios as real WSNs cannot be too dense as this will limit spatial reuse; when a node is transmitting it will interfere with other nodes within its interference region which is usually larger than its transmitting range. A high node density results in high interference and low network throughput capacity. To overcome this problem C_{TR} has been characterised in a more general model in which the side length l of the deployment region is an additional parameter and n and r may be are arbitrary functions of l [4]. C_{TR} is analysed asymptotically in this case as $l \to \infty$. When using this model, the node density must either converge to 0 or to a constant $c > 0$, or diverge as the size of R approaches infinity. Under the assumption that n nodes are distributed uniformly at random in $R = [0, l]^d$ it has been proven that the r-homogeneous range assignment is connecting with high probability if

$$r = l\sqrt[d]{c\frac{\log l}{n}}, \tag{3.8}$$

for some constant $c > 0$ [5]. If $r \in O\left(l\sqrt[d]{\frac{1}{n}}\right)$ then the r-homogeneous range assignment is not connected with high probability.

Protocols

A popular protocol that has been developed for homogenous topology control is the COMPOW (common power) protocol. COMPOW [30] was motivated by the observation that when assigning transmitter power to all nodes the per-node throughput is only marginally worse than when each node has its own individual power level with the only difference being a factor of $\frac{1}{\sqrt{|V|}}$. Another motivation was that if the transmission power level is kept as low as possible to ensure connectivity then there would be higher spatial reuse. The goal of the optimisation for each node for COMPOW is to choose [10]:

1. a common power level;
2. set this power level to the lowest possible level to keep the network connected; and
3. keep the energy consumption close to a minimum.

The heuristic used by COMPOW is based on the assumption that a finite number of different power levels are available and that a high level of integration between COMPOW and the routing protocol is possible. Each node determines routing tables for each transmission power level and a node will use the smallest transmission power level for which the associated routing table has the same entries as the table for the maximum transmission power. The need to maintain routing tables with entries for all potential neighbours in the network makes the COMPOW protocol unsuitable for WSNs.

3.3.2 Non Homogeneous

Range Assignment

The range assignment problem (R_A) is that of assigning transmitting ranges to individual nodes in the network such that the resulting communication graph T is strongly connected and the energy cost is at a minimum. Let $N = \{u_1, \dots, u_n\}$ be a set of points in region $R = [0, l]^d$ for $d = 1,2,3$, denoting the positions of network nodes. A more formal definition of the range assignment problem is that of finding the connecting range assignment RA such that

$$c(RA) = \sum_{u_i \in N} (RA(u_i))^\alpha, \tag{3.9}$$

is at a minimum. The problem is solvable in polynomial time ($O(n^4)$) in the case of one dimension while it is NP-hard in the cases of 2 and 3 dimensions. Computing the optimal range assignment in dimensions higher than the one dimensional case is therefore virtually impossible. It is possible however to approximate the optimal solution within a factor of 2 if for every node $u_i \in N$, $RA(u_i)$ is defined as the maximum of distances δ_{u_i,u_j} for all nodes u_j that are neighbours of u_i in T.

The communication graph generated by a range assignment is generally not symmetric as it may contain some unidirectional links. MAC protocols are designed to work under the assumption of symmetric links so it is not desirable to implement wireless unidirectional links given the inefficiency and overhead that will be added. Two variants of R_A based on the concept of symmetry are the symmetric range assignment problem (S_{RA}) and the weakly symmetric range assignment problem (W_{SRA}).

For an arbitrary communication graph G, the symmetric sub-graph of G denoted G_S is obtained by deleting all unidirectional links which are edges such that $u, v \in E$ but $v, u \notin E$. W_{SRA} is then solved by determining the range assignment RA such that the symmetric sub-graph G_S is connected and $c(RA)$ is at a minimum. S_{RA} is solved by determining a symmetric range assignment that generates a communication graph that contains only bidirectional links where $RA(u_i) \geq \delta_{u_i,u_j} \Leftrightarrow RA(u_j) \geq \delta_{u_i,u_j}$ such that $c(RA)$ is minimum. S_{RA} is NP-hard in the 2 and 3 dimensional cases and W_{SRA} does not reduce the computational complexity of the problem.

Minimum Energy Unicast

In minimum energy unicast the goal is to compute topologies that have energy-efficient paths between potential source-destination pairs. For a connected communication graph G obtained when all nodes transmit at maximum power, every edge (u_i, u_j) is weighted with the power $\delta^{\alpha}_{u_i,u_j}$ necessary to transmit between u_i and u_j. These edge weights are used to calculate the power stretch factor for a given path $P = u_1, u_2, \dots, u_k$ in G. The goal can then be achieved by identifying a sub-graph T of the maximum power graph G that has a low power stretch factor and is sparser than the original graph. Graph T can then be used to compute routes between nodes and has the advantage that computing routes in T is easier than in G, it involves less message overhead and requires less maintenance in the presence of node mobility.

The routing sub-graph T should ideally have the following features:

a) Constant power stretch factor i.e. T should be a power spanner of G. This ensures that the routes calculated on T are at most a constant factor away from the energy optimal routes.

b) Linear number of edges i.e. T must be sparse. This eases the task of finding routes in T and maintaining the routing graph in the presence of node mobility. It also reduces the routing overhead.

c) Node degree must be bounded. This is because nodes with a high degree have a high likelihood of being bottlenecks in the communication graph.

d) Easy computation in distributed and localised fashion where only information provided by neighbour nodes in G is used. This is essential for fast and effective computation of the routing graph in a real WSN.

There are a number of geometric graphs that satisfy the above requirements and are based on sub-graphs of G. These include the Relative Neighbourhood Graph (RNG), the Gabriel Graph (GG), the Delaunay Graph (DG) and the Yao Graph (YG). These graphs are called *proximity graphs* since the set of neighbours for any node u can be calculated using the position of neighbour nodes in the original graph G. Proximity graphs therefore satisfy property d) above. Different quality measures of these proximity graphs are compared in Table 3-1.

The Relative Neighbourhood Graph of a set of V points in the Euclidean space is the sub-graph $T = (V, E')$ of a graph $G = (V, E)$ where $(u, v) \in E'$ if there is no point $w \in V$ such that $\delta_{u,w} < \delta_{u,v}$ and $\delta_{v,w} < \delta_{u,v}$ [31]. An edge exists between nodes *u* and *v* if and only if there is no other node *w* that is closer to either *u* or *v* than *u* and *v* are apart from each other. An alternative description is that the RNG removes the longest edge from any triangle. The RNG is connected if the original graph *G* is connected and is easy to compute using a local algorithm. Its worst case spanning ratio is $\Omega(|V|)$, it has a polynomial energy stretch factor and has an average node degree of 2.6.

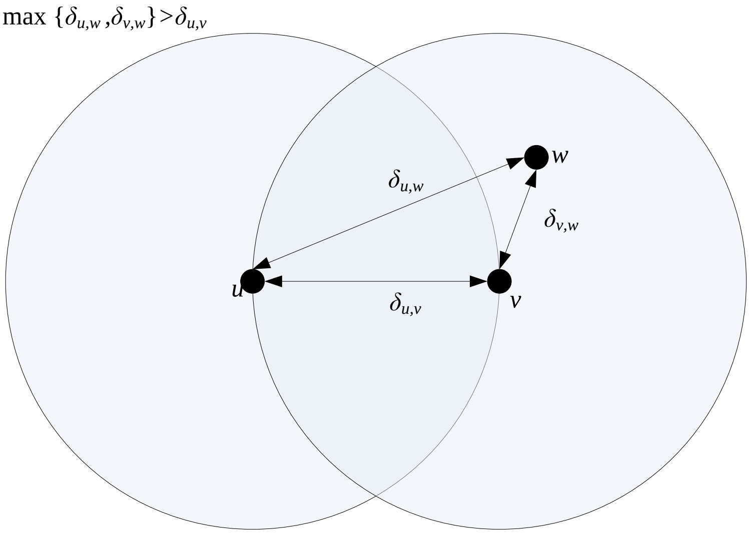


Figure 3-4: Edges in Relative Neighbourhood Graph [4].

The Gabriel Graph of a set of V points in the Euclidean space is the sub-graph $T = (V, E')$ of a graph $G = (V, E)$ where $(u, v) \in E'$ if there is no point $w \in V$ such that $\delta^2{}_{u,w} + \delta^2{}_{v,w} < \delta^2{}_{u,v}$ [2]. An edge is preset between nodes *u* and *v* if and only if the circle with diameter $\delta_{u,v}$ and with nodes *u* and *v* on its circumference contains no other nodes than *u* and *v*. The GG is connected if the original graph G is connected and has a worst case spanning ratio of $\Omega(\sqrt{|V|})$. Its energy stretch factor is $O(1)$ and its worst case node degree is $\Omega(|V|)$. Calculation of the GG is simple if nodes exchange their positions with neighbours.

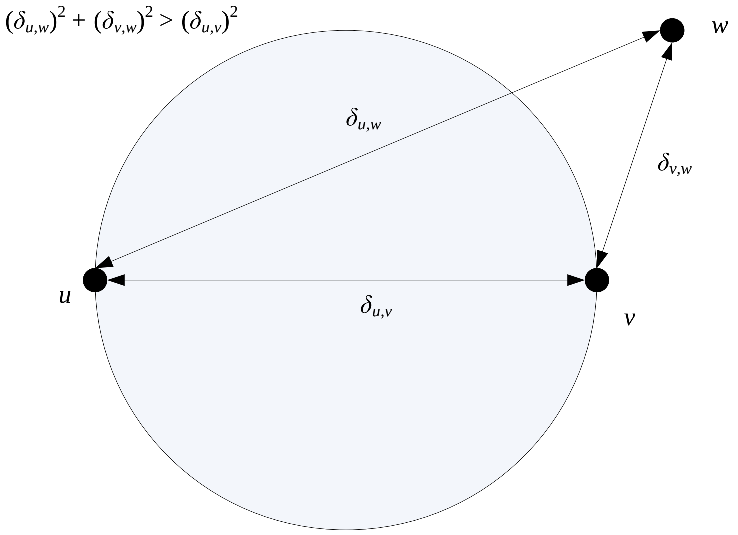


Figure 3-5: Edges in Gabriel Graph [4].

The Delaunay Graph of a set of V points in the Euclidean space is the sub-graph $T = (V, E')$ of a Graph $G = (V, E)$ such that the circumcircle of every triangle contains no points of V in its interior [4]. This is a sparsing construction that leverages a classical structure form computational geometry namely the Delaunay Triangulation. An edge exists between nodes u and v if and only if there is a circle that contains no other node other than u and v; this is the ‘empty circle’ rule. Construction of the DG using the empty circle rule requires global knowledge and the DG may have very long links, longer than the maximum transmission range. In the Restricted Delaunay Graph (RDG) a limit on the maximum edge length is imposed.

The Yao Graph [32] with parameter $c \geq 6$ of a set of V points in the Euclidean space is the sub-graph $T = (V, E')$ of a Graph $G = (V, E)$ where each node $u \in V$ divides the plane into c equally sized cones originating at u denoted by $C_u^1, C_u^2, C_u^3, \dots, C_u^c$ and edge $(u, v) \in E'$ if and only if there exists a cone C_u^i such that v is the closest neighbour of u in C_u^i. The YG uses a region based approach to define connectivity between neighbouring nodes [6]. A node divides surrounding space in such a way that each point can be assigned to a particular region and the node then defines connectivity for each region. If the reverse directed edge from v to u is added then the Reverse Yao Graph is obtained otherwise if edge direction is ignored then the basic Undirected Yao Graph is maintained.

Table 3-1: Quality measures of different proximity graphs [4]

	Distance Stretch Factor	**Power Stretch Factor**	**Node Degree**
RNG	$n-1$	$n-1$	$n-1$
GG	$\sqrt{n-1}$	1	$n-1$
RDG	$\frac{1+\sqrt{5}}{2}\pi$	$\left(\frac{1+\sqrt{5}}{2}\pi\right)^{\alpha}$	$\Theta(n)$
YG	$\frac{1}{1-2\sin\frac{\pi}{e}}$	$\frac{1}{1-\left(2\sin\frac{\pi}{e}\right)^{\alpha}}$	$n-1$

Minimum Energy Broadcast

In minimum energy broadcast the goal is compute broadcast graphs that are energy efficient [4]. The focus is on one to all communication rather than point to point communication. Similar to the energy stretch factor and hop stretch factor used in energy-efficient unicast, the *broadcast stretch factor* can be defined for energy-efficient broadcast. For a connected maximum power graph G, any broadcast generated by node u can be seen as a directed spanning tree T, rooted at u which can be referred to as the *broadcast tree*.

The power factor of the broadcast tree is defined as the total power needed to broadcast a message along T which is given by

$$pc(T) = \sum\nolimits_{v \in V} pc_T(v). \qquad (3.10)$$

Here $pc_T(v)$ is the power consumed by a node v to broadcast the message along T. For a leaf node of T $pc_T(v) = 0$, for any other nodes of T $pc_T(v) = \max_{(v,w)\in T} \delta_{v,w}^{\alpha}$. A tree in G rooted at u and consuming the least amount of power is the *minimum power broadcast tree* of u. For an arbitrary sub-graph G' of G, the broadcast stretch factor of G' relative to G is the worst case increase in the ration between the cost of the minimum power broadcast tree in G' and G. This can be expressed as

$$\beta_{G'} = \max_{u \in V} \frac{pc_{G'}(u)}{pc_G(u)}, \qquad (3.11)$$

where $pc_{G'}$ and pc_G denote the cost of the minimum power broadcast tree of u in G' and G respectively.

The problem of computing a minimum power broadcast tree rooted at node u has been proven to be NP-hard [33] [34] under the assumption that nodes can transmit at different power levels $P = \{p_1, \dots, p_k\}$ where p_i is an arbitrary power level and k is an arbitrary positive constant. The computation is therefore impossible for any realistic scenario. There are heuristics that can be used to simplify the task of finding the minimum power broadcast graph based on the construction of the MST and evaluation through simulation. An approximation algorithm has been proposed that achieves an $O(\log|V|)$ approximation ratio [34].

Protocols

Different solutions to the problem of non homogeneous topology control have been presented covering range assignment and energy-efficient unicast and broadcast. These solutions have sought to optimise a certain network measure with the emphasis being on the quality of the topology produced. A more practical approach to the topology control problem involves designing simple, fully distributed protocols that build and maintain a fairly good topology. These protocols are called *topology control protocols* and may be location based, direction based or neighbour based.

Position Based Protocols

One position based protocol that has been developed makes use of relay regions [35]. Given a node i and another node r, a question can be asked as to which points in the plane i would use r as a relay node in order to reduce total power consumption; the relay region defines these points and may be defined formally as

$$R_{i\rightarrow r} = \{(x,y)|P_{i\rightarrow(x,y)} > (P_{i\rightarrow r} + P_{r\rightarrow(x,y)})\}. \tag{3.12}$$

Figure 3-6 shows the relay region of node i with node r as a possible relay. In this protocol the goal is to minimise the maximum of node transmitting ranges while achieving connectedness. Centralised topology control algorithms are used to achieve this goal. The resulting range assignment is per node minimal and no transmitting range can be reduced further without impairing connectivity.

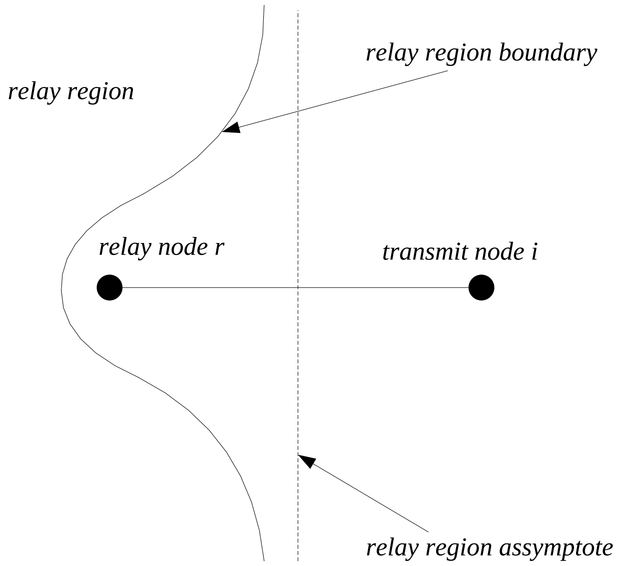


Figure 3-6: Relay region of node i with node r as a possible relay [35].

Another location based protocol is Local Minimum Spanning Tree (LMST) [36] which is a fully distributed and localised protocol aimed at building a MST like topology. In LMST each node builds its LMST independently and only retains on-tree nodes that are one hop away as its neighbours in the final topology. LMST has been proven to have several important properties namely: 1) the derived topology preserves network connectivity; 2) the maximum node degree of any node in the final topology is 6; and 3) the topology can be made symmetric by removing unidirectional links without impairing connectivity of the network. LMST outperforms a direction based protocol CBTC (see following) in terms of average node transmission range and average node degree. LMST however has the disadvantage that the local information it requires can be provided only at considerable hardware and/or message cost.

Direction Based Protocols

A distributed non homogeneous topology control protocol based on direction information is Cone Based Topology Control (CBTC) [37]. The basic idea behind this protocol is similar to the one used in the Yao Graph. A node u transmits at minimum power $p_{u,\alpha}$ that ensures that there is a neighbour that u can reach in every cone of angle α around u. It is shown that taking $\alpha \leq \frac{5\pi}{6}$ is a necessary and sufficient condition to guarantee that the connectivity of the network is maintained. If on the other hand $\alpha > 5\frac{\pi}{6}$ then connectivity of the network in not preserved with high probability. The communication graph produced is made symmetric by adding the reverse edge to every asymmetric link. A set of optimisations are presented that are aimed at pruning energy inefficient edges without compromising connectivity. It is proven that if $\alpha \leq \frac{\pi}{2}$ then every node in the final communication graph has a degree of at most 6.

In another non homogenous topology control protocol that uses direction information the goal is to build a RNG [38]. The choice of a RNG topology was motivated by it providing good graph properties in terms of through, interference, energy efficiency and connectivity. In the protocol, a distributed approach is followed with several optimisation goals such as:

- minimising node degrees,
- minimising the network hop diameter,
- minimising the maximum transmission radius and
- guaranteeing connectivity.

Neighbour Based Protocols

Neighbour based protocols are based on the idea of connecting a node to its k closest neighbours. A popular neighbour based non homogeneous topology control protocol is the *K*-NEIGH protocol [7]. The approach used is based on the principle of limiting the number of physical neighbours of every node equal to or slightly below a specific value *k*. A network topology with bounded interference is generated as a result of having a non-trivially bounded physical node degree. Symmetry is enforced in the graph that is produced and as a result the operation of higher layers is made easier. The value of *k* that guarantees connectivity of the communication graph with high probability is estimated theoretically and through simulation.

K-NEIGH is distributed and localised. It is based on distance estimates between nodes and requires a total of 2|V| message exchanges. In *K*-NEIGH nodes announce their identifiers at high transmission power and collect their observed neighbours; neighbours are sorted by distance and the *k*-nearest neighbours that can mutually reach each other are computed. Each node then uses the minimum transmission power that is sufficient to reach all the neighbours it has computed. Network topologies produced by *K*-NEIGH show good performance in terms of energy consumption and expected interference.

A protocol similar to *K*-NEIGH is the XTC protocol [39]. In XTC the neighbours of a node *u* are ordered according to some metric such as distance or quality and *u* makes a decision as to which nodes to keep in the final topology based on a simple rule. Unlike *K*-NEIGH which produces a connected network with high probability XTC builds a topology that is connected whenever the maximum power communication graph is connected. In order to achieve this, the upper limit on the number of neighbours' *k* is dropped. In XTC a node may have up to *n*-1 neighbours in the final topology.

The MobileGrid [40] and LINT [41] protocols attempt to maintain the number of neighbours of a node within a high and low threshold centred at an optimum value [4]. The transmission range is increased or decreased depending on whether or not the number of neighbours lies within the threshold values. No target for the number of neighbours for a node is given and neighbours are discovered based on overhearing ongoing communications and hence the information obtained on the number of neighbours is not very accurate as for example nodes that are not currently communicating will not be discovered.

Comparison

The various features of the non-homogeneous topology control protocols just presented are shown in Table 3-2 below.

Table 3-2: Main features of different non homogeneous topology control protocols [4]

Protocol	**Approach**	**Connectivity**	**Fault Tolerance**
R&M	Location Based	Yes	No
LMST	Location based	Yes	Yes
CBTC	Direction based	Yes	Yes
RNG	Direction based	Yes	No
LINT	Neighbour based	Unknown	No
MobileGrid	Neighbour based	Unknown	No
K-NEIGH	Neighbour based	Highly probable	No
XTC	Neighbour based	Yes	No

3.4 HIERARCHY CONTROL

The approaches to topology control that vary transmission power control the number of neighbours of a node. Hierarchical topology control approaches select which specific nodes that are in radio range should be neighbours of given nodes. Some neighbours may be nearby whereas others may be far away. The selection of neighbours usually implies some form of hierarchy in the network.

3.4.1 Dominating Sets

In this approach to topology control some nodes are selected to form a virtual backbone known formally as a dominating set. A set of nodes $D \subset V$ where all nodes in V are in D or are one hop neighbours of some node $d \in D(\forall v \in V: v \in V \vee \exists d \in V: (v, d) \in E)$ form a dominating set [2]. Dominating sets simplify routing in a number of ways such as enabling dominated nodes to simply forward non local packets to their neighbouring backbone nodes which will forward the packets towards their correct destination. Smaller the dominating sets are desirable in order to provide some form of advantage over the original set where $V = U$ which can be used as a dominating set to no advantage. The number of nodes in the dominating set can be used as a measure of how small the dominating set is.

The *Minimum Dominating Set* (MDS) problem is one of finding a minimal size dominating set, when a further requirement is for all the nodes of the dominating set to be connected then the problem becomes one of finding the Minimum Connected Dominating Set (MCDS). Individual nodes must have knowledge of whether they are part of the dominating set and if not then which of their neighbours are. The dense network of Figure 3-1 is shown in Figure 3-7 where a dominating set has been used to control the network topology.

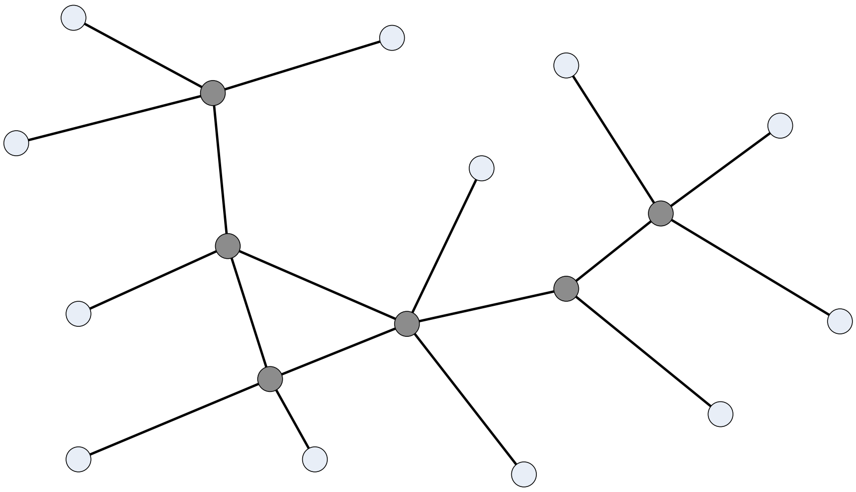


Figure 3-7: Restricting the topology by using a backbone [2].

3.4.2 Clustering

Another approach to hierarchical topology control is that of clustering. Some nodes in the network are marked as having a special role such as monitoring other nodes. Groups of nodes known as **clusters** are formed around a nodes with a special role known as **clusterheads**. Clustering has the same benefits as with dominating sets but also focuses on the arbitration of local resources, shielding of higher networking layers to the dynamics present in the network and making upper layer protocols more scalable [2]. Because of their role clusterheads are a natural choice for a place to perform network functions such as data aggregation and sensor fusion. Given a graph $G = (V, E)$, clustering is the identification of a set of subsets of nodes $V_i, i = 1, \dots, n$ such that $\cup_{i=1,\dots,n} V_i = V$. The dense network of Figure 3-1 is shown in Figure 3-8 where a dominating set has been used to control the network topology.

Protocols

A topology control protocol based on clustering is Low Energy Adaptive Clustering Hierarchy (LEACH) [9]. This protocol is targeted at WSNs with a known number of nodes, a known area and a dedicated node to which all data is sent. The introduction of clusterheads is motivated by the ability of data to be aggregated. The clusterheads collect data from members of their cluster and transmit it in one hop to the data sink. The role of clusterheads is rotated in order to conserve the energy of nodes which is significantly reduced in sending data to the sink. A simple and lightweight procedure for the selection and rotation of clusterheads is employed where nodes independently decide to act as clusterheads and communicate this to their neighbours. LEACH brings together the ideas of energy-efficient cluster based routing and media access and application specific data aggregation to achieve good performance in terms of system lifetime, latency and application perceived quality.

Hybrid Energy Efficient Distributed Clustering (HEED) [8] is based on the assumption that there are multiple power levels that can be used for communication. HEED selects nodes as clusterheads based on a hybrid of node residual energy and a second parameter which may be the node degree or proximity to a neighbour.

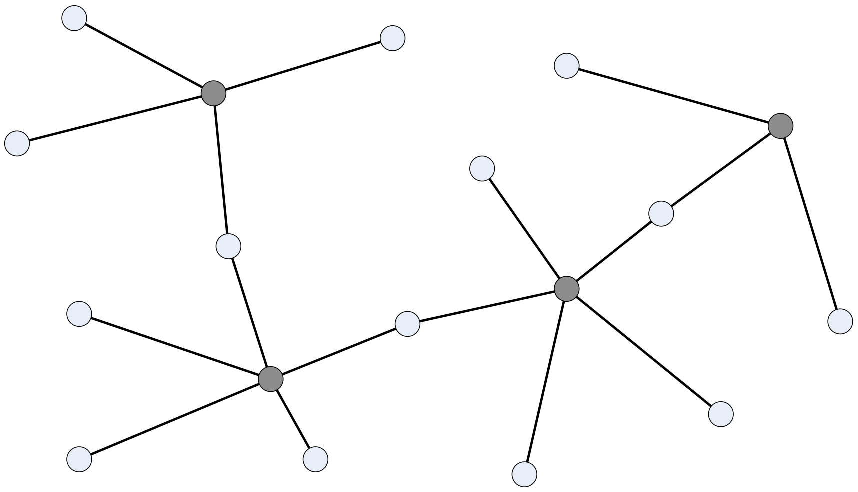


Figure 3-8: Restricting the topology by using clusters [2].

3.5 HYBRID METHODS

There are some approaches to topology control that integrate power control with hierarchy control. These hybrid methods include pilot based power control [42], Ad hoc Network Design Algorithm (ANDA) [43] and CLUSTERPOW [10]. Pilot based power control is presented as stable, dynamic, distributed clustering for energy-efficient networking. Once an initial cluster has been setup, clusterheads use power control on pilot signals on normal data packets. The power control is done in a way similar to cellular networks. Power control on data packets ensures sufficiently low error on far away nodes and efficient transmission for nearby nodes.

The use of clusterheads to control cluster size using power control is also employed in ANDA. This protocol is suited to scenarios where clusterheads are chosen a priori and the network topology is either stationary or slowly changing. ANDA seeks to maximise network lifetime while providing total coverage of network nodes. In order to maximise network lifetime the lifetime of the clusterheads is maximised as they are critical network elements in terms of energy.

CLUSTERPOW was developed to overcome some of the shortcomings of COMPOW mainly that COMPOW is not well suited to scenarios where node distribution is non homogeneous; when there is even a single outlying node this causes every node to use a high transmitter power. In CLUSTERPOW a discrete set of power levels are assumed and clusters are formed at each power level and separate routing tables are formed for each power level. The lowest power level that will ensure that the destination is reachable is used for packet transmissions. Once a packet enters a cluster of a lower power level then the power level is reduced.

Other approaches to topology control are based on the adaptive activity of nodes such as when nodes should be turned on or off and the needs of ongoing communications. Such approaches include Geographic Adaptive Fidelity (GAF) [44] and Adaptive Self-Configuring sEnsor Networks’ Topologies (ASCENT) [45].

3.6 MOBILE NETWORKS

Most of the topology control techniques highlighted are for stationary networks with some being adaptable to mobile networks. Mobility in networks affects topology in a number of ways as follows [4].

1. *Increased message overhead* – In stationary networks the topology control is generally executed once at the beginning of the network operational time, and then at regular intervals to cater for nodes joining or leaving the network. The emphasis in stationary network is more on the quality of the topology control rather than on efficiency of computation. In mobile networks however, efficiency is of great importance as the mobility of nodes makes it necessary to perform topology control on a frequent basis in order to cater for the new node positions. Reducing the

message overhead of the topology control algorithm is a primary requirement in mobile networks even if it means reducing the quality of the resultant topology.

2. *Non uniform node spatial distribution* – Non uniform node spatial distribution may occur with some mobility patterns. This should be taken into account at the design stage when setting important network parameters such as the critical transmitting range.

CHAPTER 4

DESIGN

4.1 OBJECTIVES

There were two design objectives in developing the envisaged topology control technique for WSNs. The first objective was that it should be energy efficient and the second was that it should have low interference. Performance measures were used to determine how well these objectives were met. The relative performance of the new technique compared to other well known approaches to topology control was also used to evaluate how well these objectives were met.

These objectives, however are competing as improving energy efficiency, as measured through the energy stretch factor of a generated topology, increases the level of interference in the network as measured by the maximum and average node degree of the generated topology. In addition to this, topology control involves a compromise between energy conservation and network connectivity (Figure 4-1). In meeting the set out objectives, the topology control technique that was developed was designed to produce a Pareto optimal result using certain heuristics.

Figure 4-1: Compromises in topology control [46].

4.2 REQUIREMENTS

To meet the set out design objectives, the routing sub-graph *T* produced by the topology control technique from the original graph *G* had to meet certain requirements. A number of the requirements were for minimum energy unicast (section 3.3.2); these are:

1. Constant power stretch factor, i.e. the graph should be a power spanner of *G*.
2. Linear number of edges, i.e. the graph must be sparse.

3. Easy computation in a distributed and localised way.

In addition to this, the sub-graph *T* had to be:

4. Connected with high probability if the original graph *G* is connected.
5. Planar, meaning that no two edges in the graph cross each other. This will enable some localised routing algorithms to work with the generated topology such as Greedy Face Routing (GFR), Greedy Perimeter Stateless Routing (GPSR), Adaptive Face Routing (AFR) and Greedy Other Adaptive Face Routing (GOAFR) [47].

4.3 METRICS

Metrics were used to evaluate the efficiency and quality of the topology control technique. The quality measures which were selected are:

- Graph connectivity
- Hop stretch factor
- Node degree
- Edge length

The hop stretch factor and edge length metrics were used to evaluate performance in terms of energy efficiency, whereas the node degree was used to evaluate performance in terms of interference. The topology control technique was not designed for mobile networks and therefore robustness to mobility was not under consideration. The same holds for the throughput quality measure as measuring throughput did not help in meeting the set out design objectives.

In order to better evaluate the performance of the topology control technique in terms of interference, a distinction was made between the physical and the logical node degree. The *physical node degree* refers to the number of neighbour nodes that are within the transmitter range of a given node. The *logical node degree* refers to the number of neighbour nodes that a given node is linked to. This is illustrated in Figure 4-2.

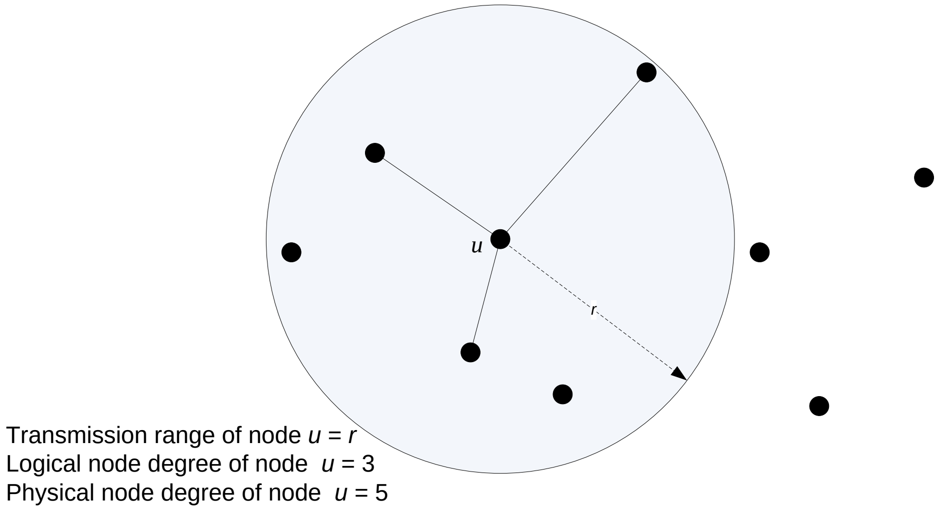


Figure 4-2: Logical and physical node degree.

The node degree is defined per node; an alternative interference measure that is defined per edge is the edge *coverage*. The edge *coverage* for an undirected edge *e* between two nodes *u* and *v* in a topology controlled graph *T*, formed from the original graph *G*, is the number of nodes within the transmission region of both *u* and *v*. Denoting *D* (*u*, *r*) as the disk centred at node *u* with radius *r* and requiring edge symmetry, the coverage of edge *e* is defined as [46]:

$$\mathrm{Cov}(e) := |\{w \in V, w \text{ is covered by} D(u, uv)\} \cup \{w \in V, w \text{ is covered by} D(v, vu)\}| \; . \tag{4.1}$$

The nodes that contribute to calculating the edge coverage for a link (*u*, *v*) are shown in Figure 4-3 below.

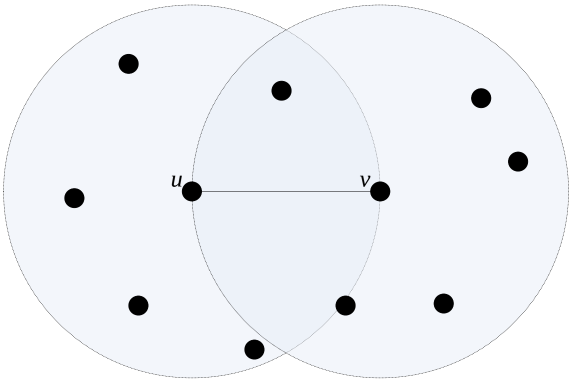


Figure 4-3: Nodes covered by a communication link [46].

From the edge coverage interference metric, a graph interference metric *I* can be calculated for graph *T*. The graph interference is defined as:

$$I(T) \coloneqq \max_{u,v \in V} \mathrm{Cov}(e). \tag{4.2}$$

4.4 OPTIONS

There were a number of options for how the reduced topology graph could be determined. The options were as follows:

Processing architecture	Centralised, distributed or hybrid.
Approach	Power control or hierarchy control.
Power levels	Homogeneous or non-homogeneous.
Protocol stack extent	Layers of the protocol stack involved in performing the topology control.
Node information used	Position information, direction information or neighbour information.

4.5 CHOICES

Processing architecture – The processing architecture that was chosen is distributed architecture. This option was chosen because WSNs usually consist of devices with similar processing capabilities. In addition to this, the design requirements called for the topology control method to be distributed and to use local information.

Approach – The approach that was selected was a power control approach. This option was selected because hierarchical methods, by either clustering or dominating sets, have a high communication overhead for setup. In addition to this, as evidenced by previous hierarchy control studies the focus is not on reducing power levels, but on creating graphs that will result in efficient routing and in network processing of data. This does not help in reducing interference, hence the choice to use a power control approach to topology control – as this could meet the set out objectives of enhancing energy efficiency and reducing interference.

Power levels – The choice was made to go for a non homogeneous approach as this is where greater reductions in interference can be obtained. If the same transmitter power is assigned to all the nodes as in homogeneous topology control, then selection of a large transmitter power to cater for just one remote node will mean there will be unnecessarily high interference in areas of high node density. A non-homogeneous approach is therefore more favourable.

Protocol stack extent – Topology control is a cross layer design problem. Layers affected by topology control include the physical layer, since it determines the quality of the received signal, the network layer and routing, since it affects the transmitting range, the transport layer since interference causes congestion as well as the MAC layer since contention is dependent on transmitting range. Several layers are affected, but the basic functioning of topology control is performed at the data link and network layers of the protocol stack. In this research the topology control technique was designed to operate at the data-link and networking layers as the required performance measures that were identified are available at these layers.

Node information used – The choice of information to use in computing topology controlled graphs was node position. From the node position the direction of neighbours could be calculated and neighbour node information such as node ID can be obtained by piggybacking on packets used to determine position. Node position provides the greatest flexibility and has the highest information content. This also meant that the graph produced by the topology control technique would be a proximity graph.

4.6 TOPOLOGY CONTROL TECHNIQUE

4.6.1 Yao-Gabriel Graph with Smart Boundaries

In order to develop a technique that produced a network topology that met the objectives that have been set out and that adhered to the identified requirements and conformed to the choices made, it was decided to create a graph algorithm that is a hybrid of different proximity graph algorithms. The algorithm is a mixture of the Gabriel graph algorithm and the Yao graph algorithm, with the use of smart region boundaries. The algorithm is referred to as the Smart Boundary Yao Gabriel Graph (SBYaoGG). The topology is generated by first computing the Gabriel graph from the Uniform Disk Graph (UDG) at maximum transmitter power and then computing the Yao graph on the reduced topology to produce the final topology.

By computing the Gabriel graph from the UDG some of the requirements for the final topology are met:

- The graph produced is planar.
- The graph has a linear number of edges.

After computing the Yao graph from the Gabriel graph some other requirements for the final topology are met:

- The graph is connected. This is because both the Gabriel graph and the Yao graph are connected if the original graph is connected.
- The graph is a power spanner of the original UDG. This is because both the Yao graph and the Gabriel graph are power spanners.

In addition to this:

- The final graph is easily computable in a distributed and localised way. The algorithm uses node position information which can be obtained from neighbour nodes. The edges are then computed locally by using only the neighbour position information.

Therefore, all of the requirements for the topology control technique were met. This contributed to meeting the objectives of the final graph in that it is energy efficient and has low interference. A low physical node degree necessary for minimal interference and a low power stretch factor necessary for high energy efficiency are two opposing goals, as has been noted. As an example, the minimum spanning tree of a network has the lowest node degree but it also has the highest power stretch factor when compared with other proximity graphs. The UDG on the other hand, has the lowest power stretch factor but has the highest node degree when compared to other proximity graphs.

Therefore it was desirable for the generated topology to lie somewhere in between the MST and the UDG. The MST is a sub-graph of the RNG, which in turn is a sub-graph of the Gabriel graph. The Gabriel graph is a sub-graph of the Delaunay graph, which in turn is a sub-graph of the UDG. By calculating the reduced topology using the hybrid method, the final topology is a sub-graph of the Gabriel graph. The step that calculates the Yao graph on the reduced topology prunes the edges of the Gabriel Graph and the final topology lies somewhere in between the Gabriel graph and the RNG. How close to the Gabriel graph or the RNG the final topology lies depends on the deployment of the network and the number of regions used in computing the Yao graph, which is a settable parameter.

4.6.2 Pruning the Edges of the Gabriel Graph

The Gabriel graph computed on the UDG has its edges pruned by computing the Yao graph on the reduced topology. This, in effect, generates the previously developed YaoGabriel graph. In order to achieve low interference, it is desirable to reduce the node degree as much as possible whilst maintaining the power spanner properties of the Gabriel graph. The YaoGabriel graph can achieve this. However, further reduction in interference levels can be obtained by variable selection of the axes of the cones for each region of the Yao graph.

The procedure employed to reduce interference was as follows:

- Prune the edges of the Gabriel graph using the Yao graph.
- Use large regions in computing the Yao graph.
- Select the axes of cones for each region of the Yao graph using heuristics.
- Reduce the transmitter power of each node to the lowest level so that it allows it to reach its furthest neighbour in the final topology.

4.6.3 Determining the Region Boundaries of the Yao Graph

A heuristic that was used whilst forming the reduced topology graph was to align the axis of the first cone used in the Yao graph computation to the region where nodes are most densely deployed. This can be accomplished by obtaining the unit direction vectors of all the neighbouring nodes and then calculating the average direction vector. The average direction vector is then used as the axis of the cone for the first Yao graph region. The neighbour direction vectors and the average direction vector are illustrated in Figure 4-4.

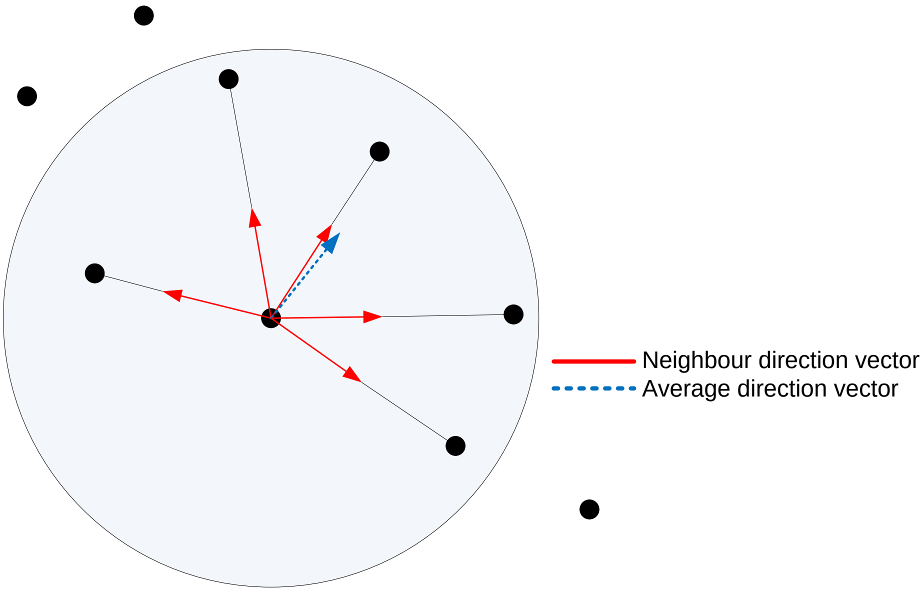


Figure 4-4: Neighbour direction vectors and the average direction vector.

The cones of the Yao graph are as shown in Figure 4-5. In the case of Figure 4-5 α = 120°, corresponding to a Yao graph with 3 cones. It can be seen that aligning the axis of one of the cones to the average direction vector, results in a cone where a high number of neighbour nodes fall into. It is possible that in certain arrangements all the neighbours will fall into this cone, which will mean that the number of edges calculated during topology control will be reduced.

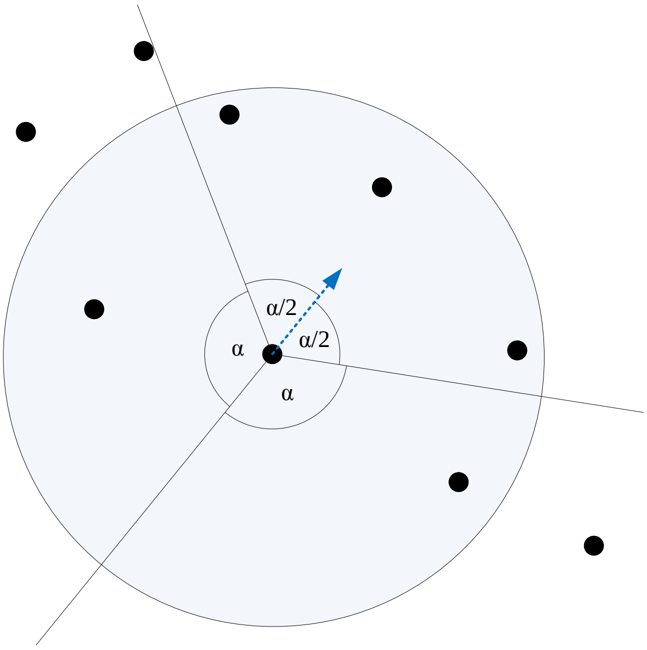


Figure 4-5: Yao graph boundaries using an average direction vector.

An option was to use the neighbour centroid, for the following reason: Opposed to the average direction vector, the centroid has the drawback that neighbours that are further away will have coordinates that dominate over closer neighbour coordinates. The average of unit direction vectors overcomes this drawback. Selection of $\alpha \leq \frac{5\pi}{6}$ is necessary to maintain connectivity [37]. The largest value of $\alpha = \frac{5\pi}{6}$ was used in simulations when setting the boundaries of the Yao graph, in order to reduce the node degree as much as possible whilst maintaining connectivity.

4.6.4 Optimisations

Once the edges of the Gabriel graph are pruned, there will be some asymmetric edges. One optimisation that was used was to make all the edges symmetric by adding the reverse edge of any asymmetric link where $u, v \in E$ but $v, u \notin E$. If a node u has a link to a node v, but node v does not have a link to node u, then node v adds a link to node u. This reduces the power stretch factor of the final graph and ensures that there are no asymmetric links which can pose a burden to a MAC protocol.

4.6.5 Algorithm

The following algorithm describes how to construct the SBYaoGG, detailing the steps each node in the network goes through.

Algorithm: Construction of SBYaoGG

1. The node discovers its neighbour nodes by broadcasting at maximum power.
2. The Gabriel graph is constructed locally.
3. The unit direction vectors of neighbour nodes in the Gabriel graph are computed.
4. The average direction vector is computed.
5. The axis of the cone of the first region to use in computing the Yao graph is set to correspond to the average direction vector.
6. The Yao graph is computed from the Gabriel graph, producing the reduced topology.

The final step in obtaining the SBYaoGG is to optimise the reduced topology in order to ensure low interference and good power spanner properties. Two optimisations were made:

1. All edges are made symmetric by adding the reverse edge for any asymmetric link.
2. Transmitter power levels are set to the lowest level that will allow each node to reach all the nodes with which it has an edge.

After this the SBYaoGG is fully formed and can be used as input to a routing algorithm.

CHAPTER 5

IMPLEMENTATION

5.1 SIMULATORS

Topology control has been studied extensively and several algorithms and protocols have been developed yet there are no well-known and accepted simulator tools used by the network research community that include these protocols and algorithms. An attempt that was made to solve this problem was the Atarraya simulator program [48]. Atarraya is a discrete event simulation tool designed to test and implement topology control protocols for wireless sensor networks. The functional components of Atarraya are shown in Figure 5-1.

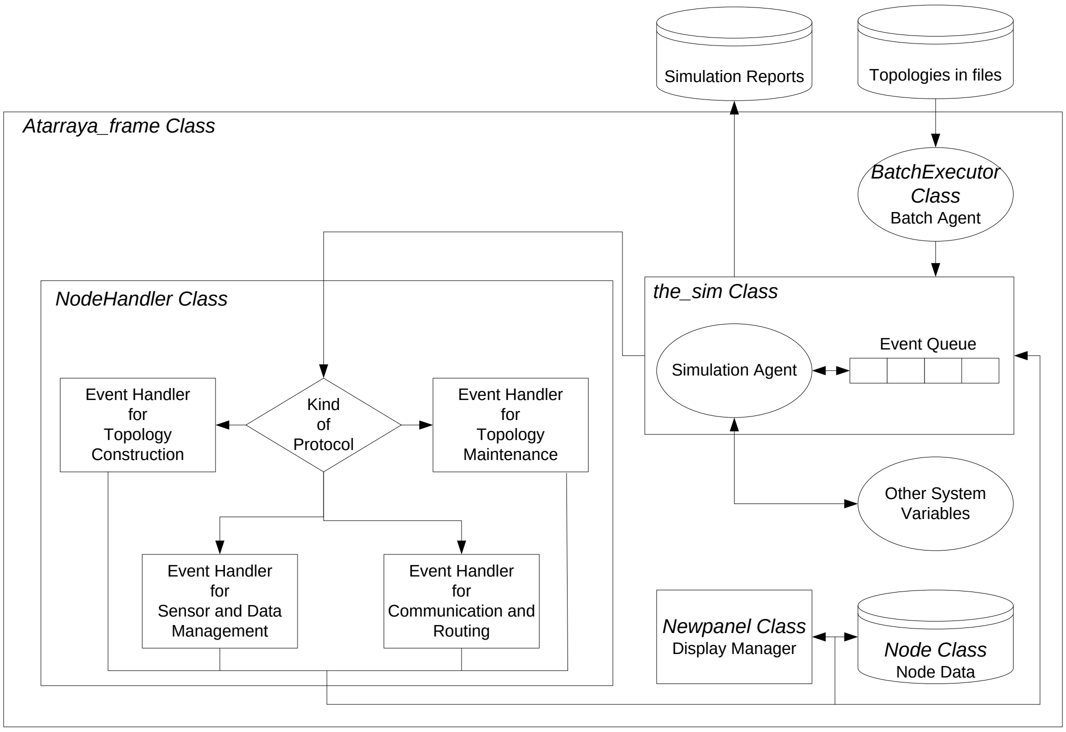


Figure 5-1: Atarraya's functional components [48].

The Atarraya tool includes structures for designing protocols for both topology control construction and topology control maintenance. Atarraya has a graphical user interface and has implementations of several popular algorithms and applications. It can be used for research and teaching.

5.2 SIMULATION ENVIRONMENT

Popular network simulator tools such as ns2 and Omnet++ are simulators that include all the major communication protocols in the OSI and TCP/IP protocol stacks. They do not, however, include topology control protocols and algorithms that have been developed over the years. This is complicated by the fact that it is not clearly defined where topology control sits in the communication protocol stacks. They can be used to simulate topology control with some effort; however, the sort of data that is required and the nature of the experiments that were planned did not necessitate the use of these simulators.

Atarraya, on the other hand, was a more viable option. The problem, however, was that it does not include implementations of some proximity graphs that were under study, such as the YaoGabriel graph and it does not provide some of the performance measures that were needed, such as the physical node degree.

It was decided to write a proprietary simulation program. This was motivated by the fact that it is not necessary to simulate the entire communication protocol stack to get the required information. In addition to this, the algorithms to set up the reduced topology proximity graphs for comparison purposes were readily available.

5.3 CHALLENGES

The decision to write a proprietary custom simulator tool was the first challenge. The second challenge was to implement well-known topology control algorithms in the simulator program correctly. The collection and serialisation of data was another challenge as was ensuring that the techniques employed were calculated in a distributed fashion, using local information. It was necessary to equip the simulator tool with the necessary functionality to create network deployments, view network deployments and evaluate topology controlled networks. It was also necessary to provide functionality to run custom operations on created network topologies and to perform batch simulations.

5.4 SIMULATION SETUP

5.4.1 Node Deployment

Nodes were distributed in a two-dimensional unit square region according to a uniform random point process. A uniform random point process χ_n in a region Ω is one that consists of n independent points, each of which is uniformly and independently distributed over Ω [47]. Nodes initially have a transmitter power large enough for them to reach all their neighbours resulting in the unit disk graph being connected. Figure 5-2 shows example output of the node deployment described above.

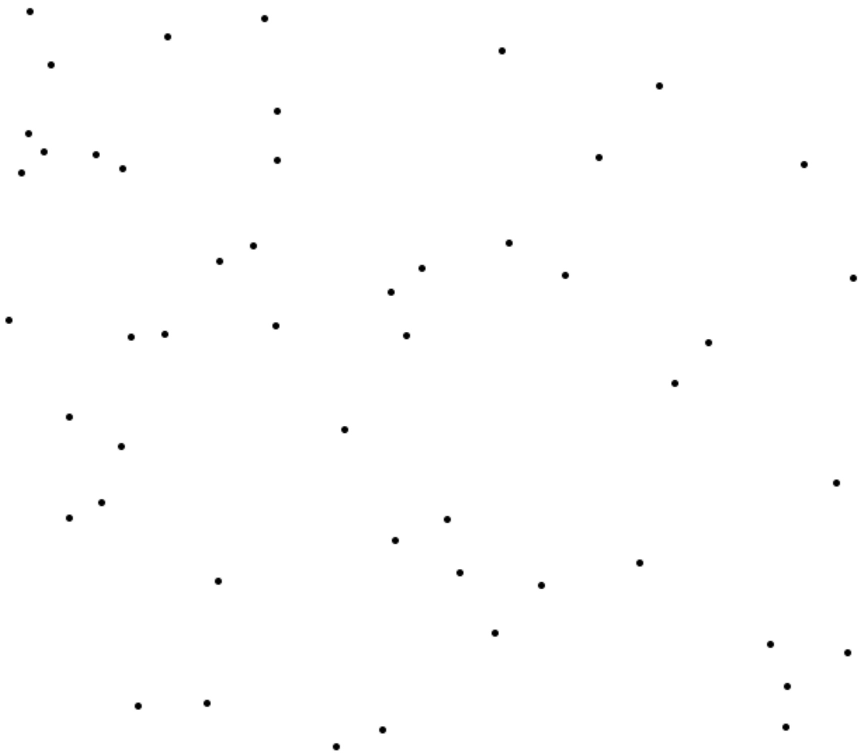


Figure 5-2: Uniform random node distribution over a unit square.

Figure 5-3 shows the unit disk graph of the deployment of Figure 5-2 when a large transmitter power is used so that the graph is connected and all the nodes can reach each other in one hop. Figure 5-4 shows the UDG of Figure 5-2 when a smaller transmitter power is chosen, the transmitter power is too small to keep the UDG connected.

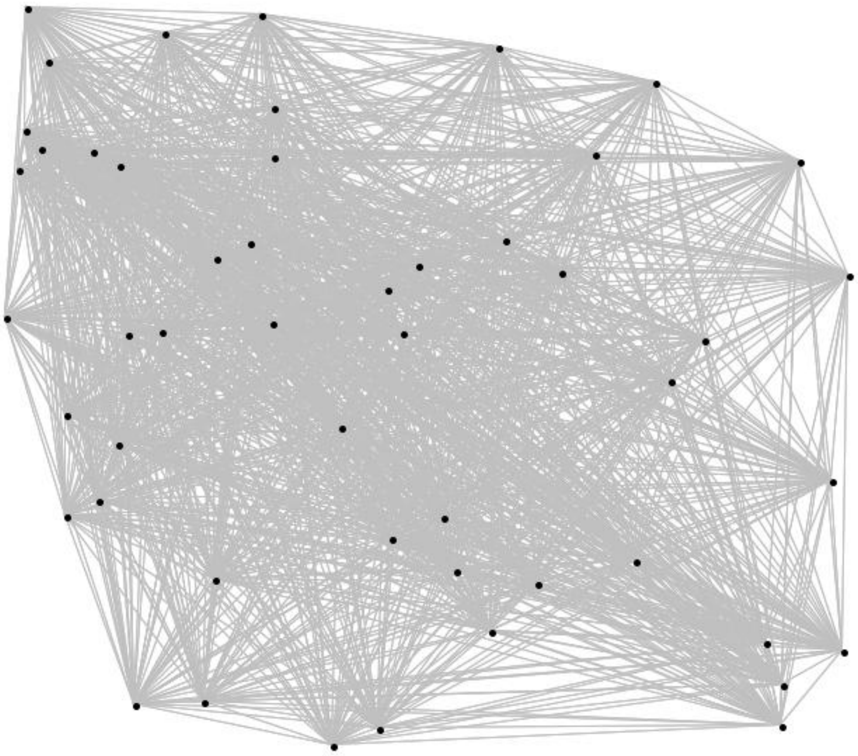


Figure 5-3: UDG with large transmitter power.

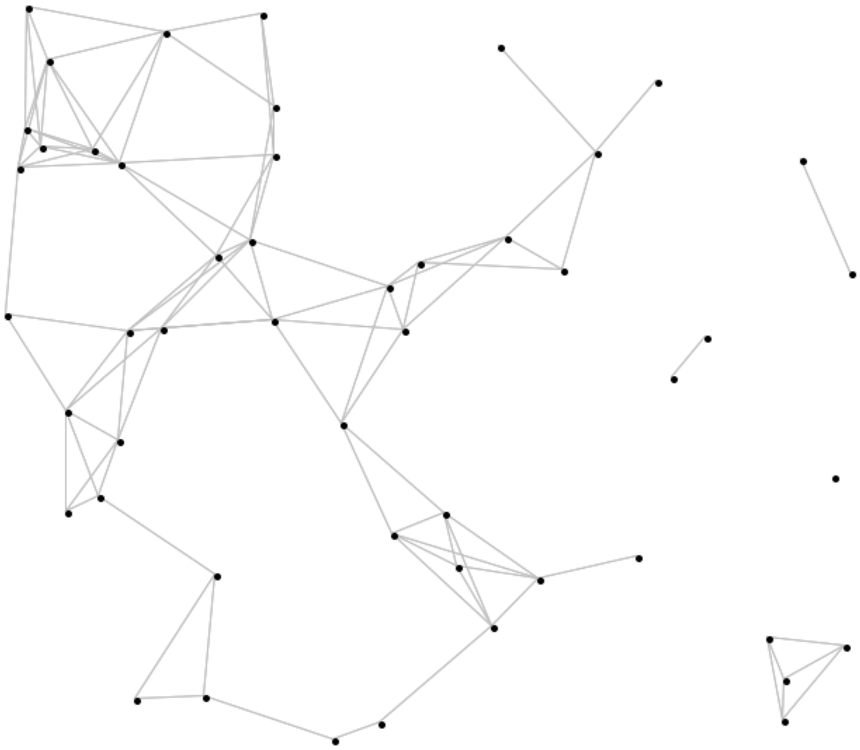


Figure 5-4: UDG with small transmitter power.

5.5 DATA COLLECTION

5.5.1 Setup

Setup data included details on the procedure used for collecting data, the algorithm used to generate the data and the parameters of the algorithm that was used. For example, in the case of running a simulation for evaluating the performance of the SBYaoGG, details that were recorded included the algorithm name, the number and size of networks that were simulated and the size of the axis angles for the region cones used in the algorithm.

5.5.2 Measurements

Standard measurements were taken for each topology control algorithm under consideration. This enabled different algorithms to be compared. The performance measure metrics that were collected are:

- Distance stretch factor.
- Physical node degree.
- Logical node degree.
- Edge length.

The average and worst case values of these metrics were collected.

5.5.3 Statistical Significance

The number of samples to take for each data point was selected so that the results would be statistically significant. In order to get results at a 95% confidence level and a 4% margin of error, 600 samples are needed. It was decided to take 1000 samples which would push the accuracy of results at a 95% confidence level to 3% at a reasonable cost in terms of time and computation.

5.5.4 Randomisation

Randomisation was used to produce random graphs of certain sizes. A Mersenne Twister pseudorandom number generator was used. The Mersenne Twister algorithm provides fast generation of very high quality pseudorandom numbers.

5.6 DATA EXAMINATION

5.6.1 Checking the Data

The data was checked to see if there were any outliers that may be caused by inconsistencies in the simulation setup or in computation. It was important to see the effect of such outliers on the final results. Collecting samples for statistical significance, according to the requirements that were set out, catered for some outliers but a check was still necessary to ensure that the outliers did not compromise the results.

The data collected was also checked to ensure that the results were as expected, by comparing it with theory as well as results of previous studies that have been verified. This also ensured that the simulator setup was correct.

5.6.2 Summary Statistics

One primary summary statistic was calculated on the measured data and this is the sample mean. The sample mean was calculated from samples of each metric for graphs of a certain network size to produce a single data point for each metric.

5.6.3 Plotting the Data

The data was plotted in order to discover any underlying trends that may exist in the data, any interesting grouping of data as well as to see if there was a need to apply any appropriate transformations on the data. Important and unimportant data could then be distinguished by using the plots.

CHAPTER 6

RESULTS

6.1 PREDETERMINED NETWORK DEPLOYMENTS

The SBYaoGG algorithm was run on several random networks in which nodes were distributed in a two-dimensional unit square region. In addition to this, the algorithm was run on predetermined network deployments in order to not only evaluate the general performance of the algorithm, but also its situation-specific performance in networks that pose a challenge in some way in generating a topology with good performance. The predetermined network deployments provide a quick way of comparing the topology control algorithm with other well known algorithms and they help in visualising how it works. Situations in which it is well suited are also made apparent.

6.1.1 Star Deployment

In the star deployment, there are equidistantly placed nodes located on the perimeter of a circle with one node at the centre of the circle. This deployment can be used to test if the algorithm is degree-bounded. The topologies produced by different topology control algorithms for a star network with 21 nodes are shown in Figure 6-1. Figure 6-1 (a) shows the topology generated by the Delaunay graph. Figure 6-1 (b) shows the topology created by the SΘGG which is known to be degree-bounded. Figure 6-1 (c) shows the topology produced by the SBYaoGG and Figure 6-1 (d) shows the MST topology for the same deployment.

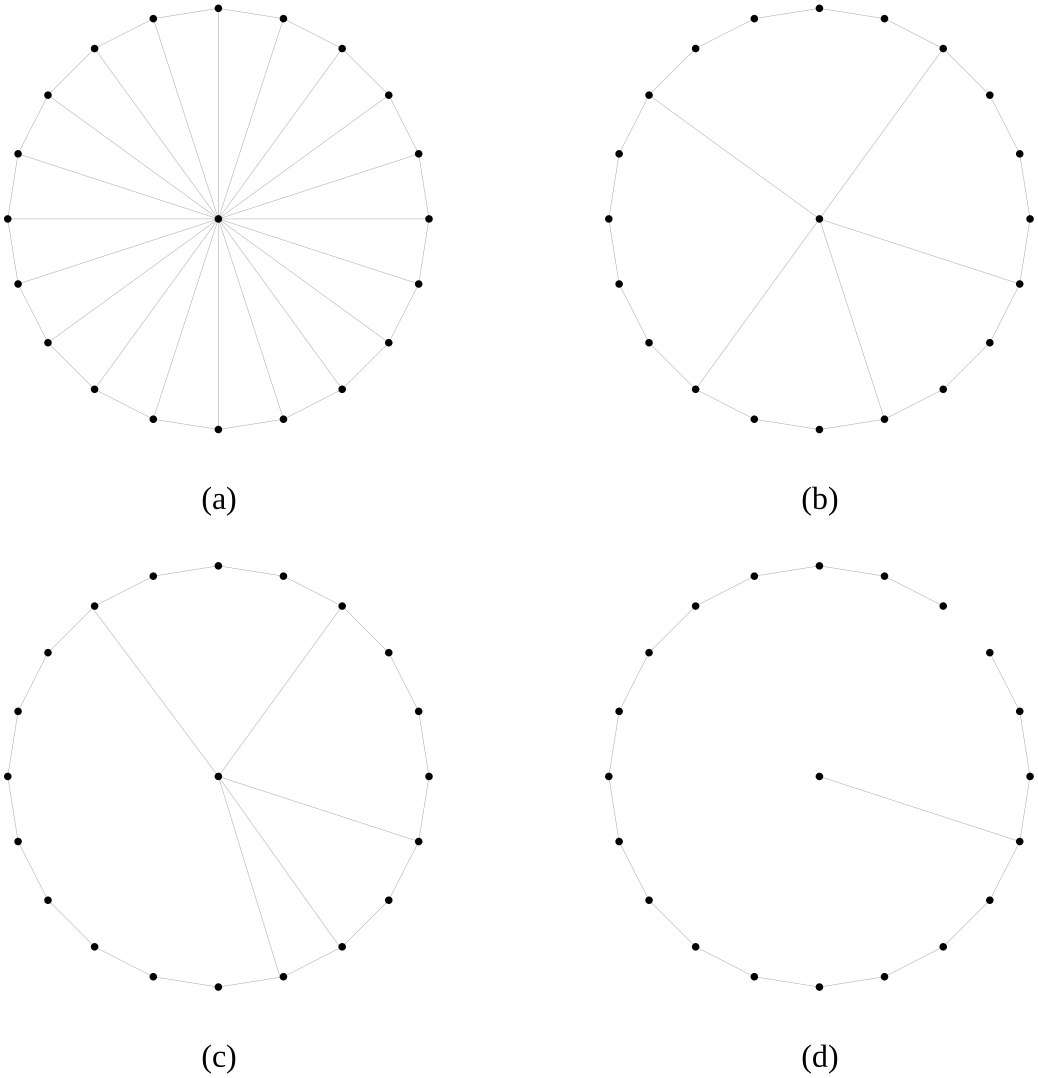
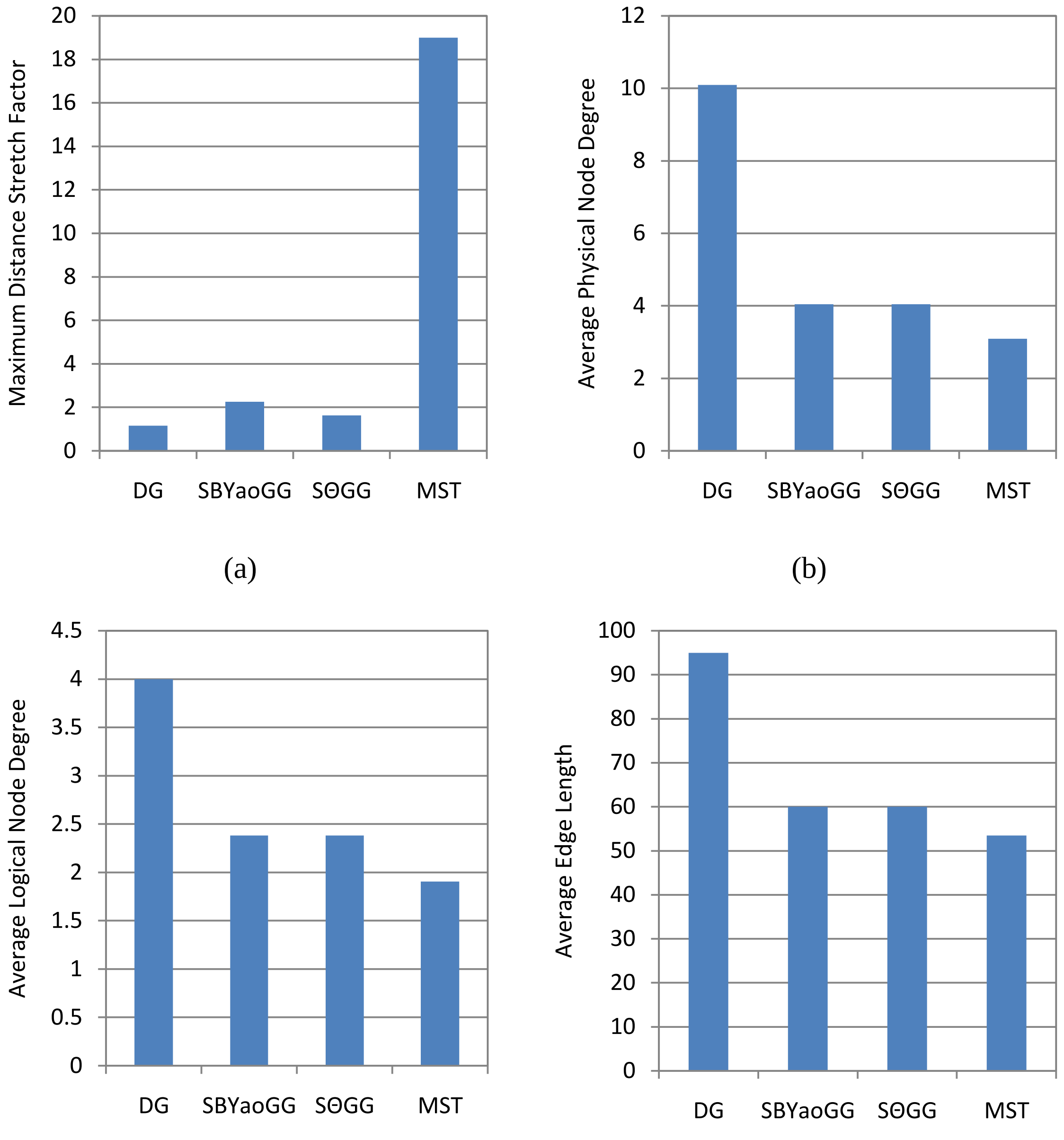

(a) (b)
(c) (d)

Figure 6-1: Topology generated from star network deployment for (a) DG, (b) SΘGG, (c) SBYaoGG graph and (d) MST.

The performance metrics of each of the algorithms for the star deployment described are shown in Figure 6-2. As can be expected, the MST topology has the highest maximum power stretch factor, which means that it is the least energy efficient and has the lowest average physical and logical node degrees as well as the lowest average edge length. As expected, the Delaunay graph is at the opposite extreme, having the highest average edge length and physical and logical node degrees with the lowest distance stretch factor. The SΘGG and SBYaoGG produce similar results except for the power stretch factor where the SΘGG is more power efficient. The higher power efficiency in this case is due to the SΘGG evenly distributing the edges of a node direction-wise.



(a) (b)

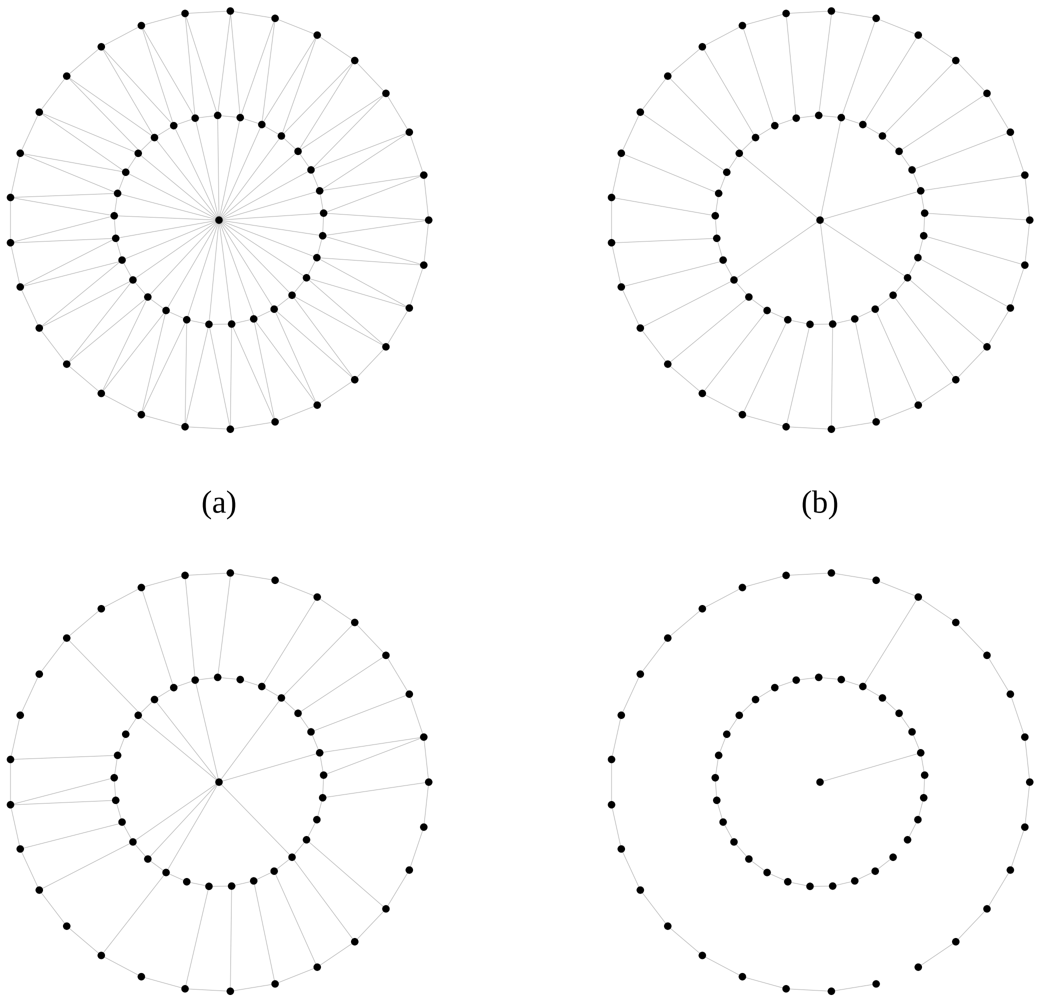
(c) (d)

Figure 6-2: Performance metrics obtained from star network deployment for (a) DG, (b) SΘGG, (c) SBYaoGG graph and (d) MST.

6.1.2 Double Ring Deployment

In the double ring deployment the nodes are evenly distributed on the perimeters of two concentric circles with different radii, with one node located at the centre. This deployment can show topology control algorithms that are not degree-bounded and the energy efficiency of different algorithms. The topologies produced for the Delaunay graph, the

SΘGG, the SBYaoGG and the MST of the double ring network with 61 nodes, are shown in Figure 6-3 (a) to (d) respectively.

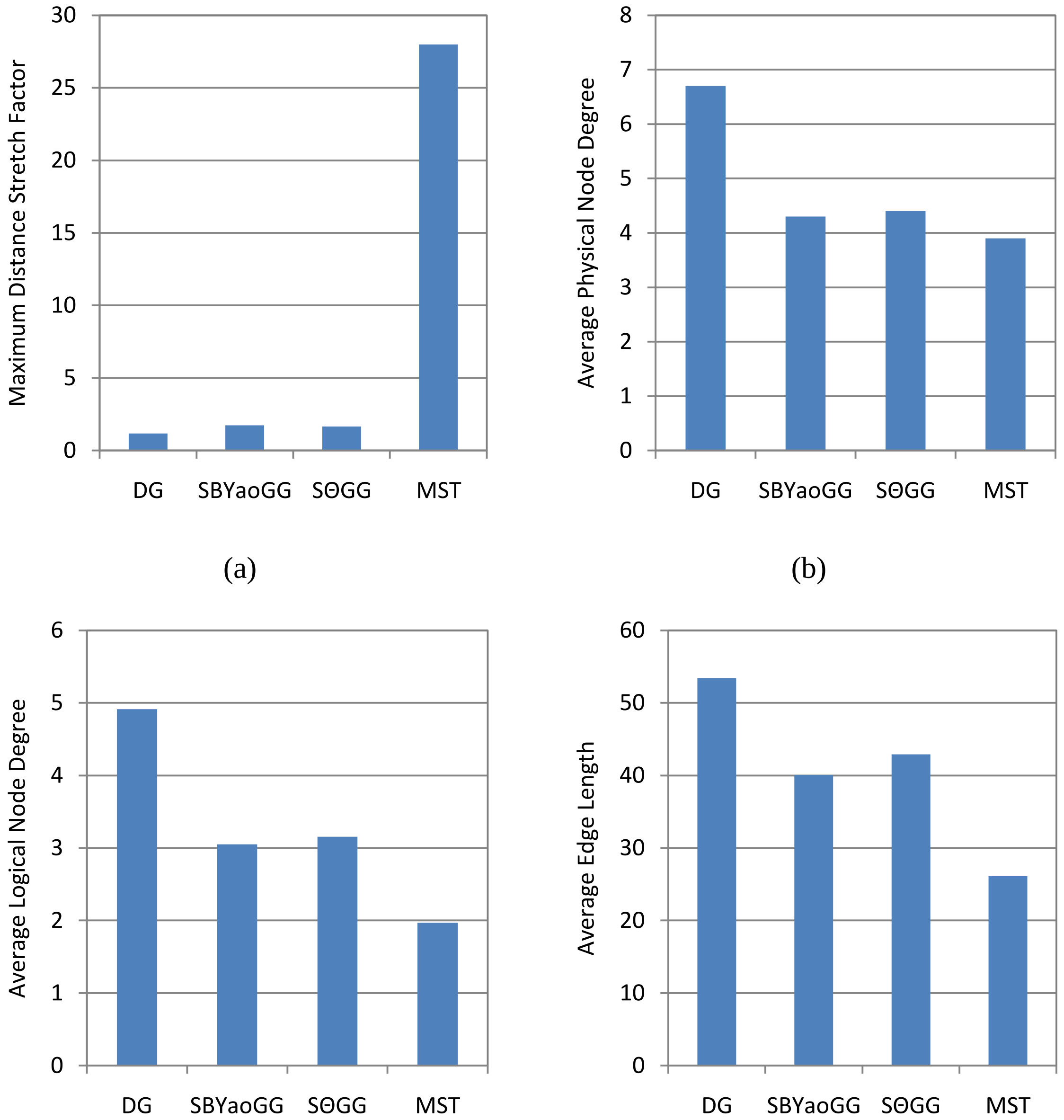


(a) (b)

(c) (d)

Figure 6-3: Topology generated from the double ring network deployment for (a) DG, (b) SΘGG, (c) SBYaoGG graph and (d) MST.

The metrics for each of the algorithms for the double ring network described are shown in Figure 6-4. The MST and the Delaunay graph perform in a similar manner as in the star network with the two algorithms being at opposing extremes for energy efficiency and interference. There is, however, a noticeable difference between the SΘGG and the SBYaoGG in this network as compared to the star network. The SΘGG is still more energy efficient but it becomes increasingly clear that the SBYaoGG has less interference as evidenced by the lower average physical node degree. Considering this is a specific network structure, a general view on performance of the SBYaoGG cannot be formed based on these results, but will become clear in the results from several uniform random networks of varying sizes.



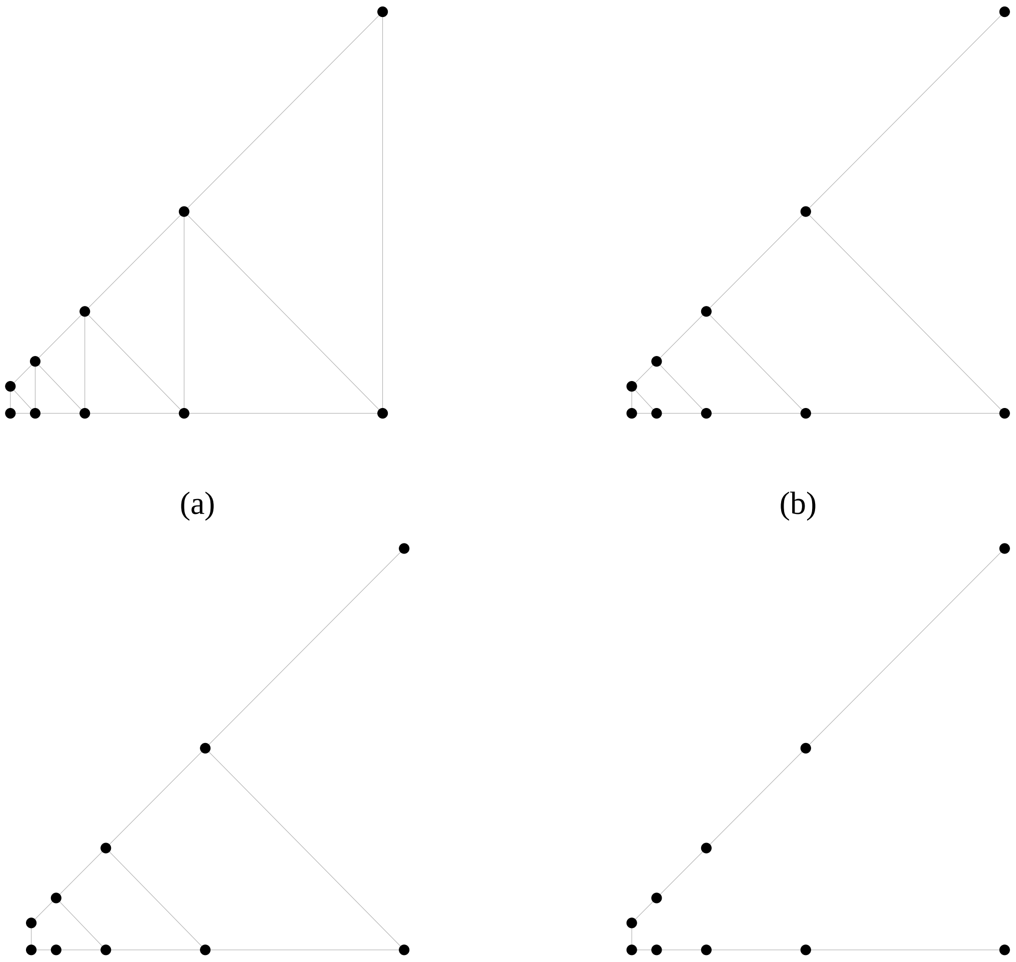
(a) (b)

(c) (d)

Figure 6-4: Performance metrics obtained from double ring network deployment for (a) DG, (b) SΘGG, (c) SBYaoGG graph and (d) MST.

6.1.3 Exponential Node Chain Deployment

The exponential node deployment is a one in which the distance between nodes increases exponentially [46]. This network can be used to compare the interference of different topology control algorithms. The topologies produced for the exponential node chain network with 10 nodes by the Delaunay graph, the SΘGG, the SBYaoGG and the MST are shown in Figure 6-5 (a) to (d) respectively.

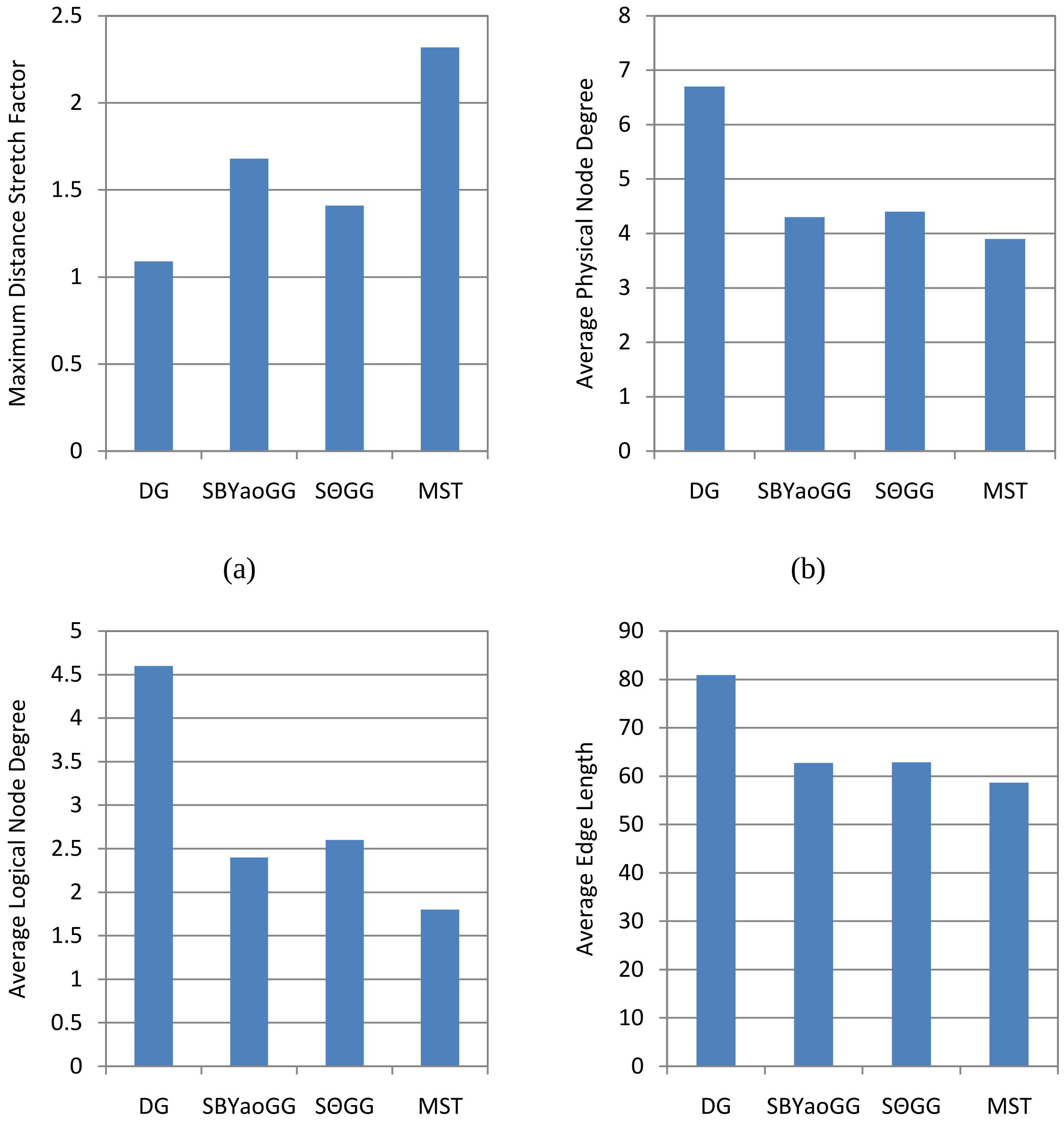


(a) (b)

(c) (d)

Figure 6-5: Topology generated from exponential node chain network deployment for (a) DG, (b) SΘGG, (c) SBYaoGG graph and (d) MST.

The performance metrics obtained for different algorithms on the exponential node chain deployment are shown in Figure 6-6. Notably the SΘGG is more energy efficient than the SBYaoGG as in the star and double ring networks but the SBYaoGG has less interference as was seen in the double ring network.



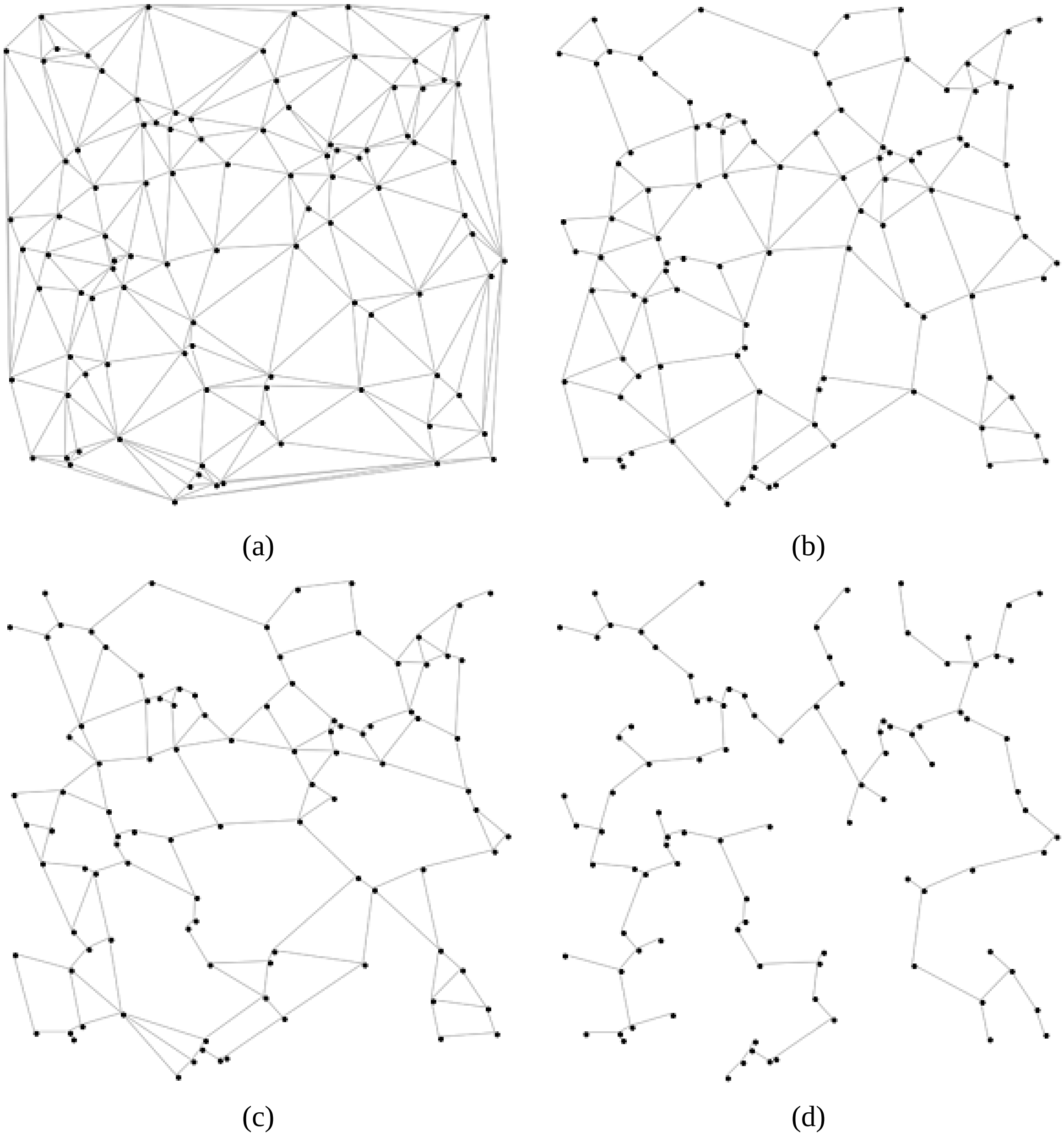
(a) (b)

(c) (d)

Figure 6-6: Performance metrics obtained from exponential node chain network deployment for (a) DG, (b) SΘGG, (c) SBYaoGG graph and (d) MST.

6.2 UNIFORM RANDOM NETWORK DEPLOYMENT

The star, double ring, and exponential node chain network deployments discussed above are useful in evaluating the performance of different topology control algorithms for specific situations that may be boundary cases or cases that reveal a fundamental property of the topology control algorithm. In order to characterise the performance of a topology control algorithm that encompasses all sorts of network deployments it is useful to evaluate the algorithms based on their performance in several uniform random networks. Topologies generated by different topology control algorithms, including the SBYaoGG for the same uniform random network in which nodes are evenly distributed randomly in a two dimensional unit square, are shown in Figure 6-7. The results obtained for several uniform random networks of different sizes are discussed in the next section.


(a) (b)

(c) (d)

Figure 6-7: Topology generated from a uniform random network deployment for (a) DG, (b) SΘGG, (c) SBYaoGG graph and (d) MST.

6.3 COMPARISON WITH SIMILAR ALGORITHMS

The SBYaoGG computes the Yao graph using smart boundaries on the Gabriel graph of a uniform disk graph. The Yao graph has been used to generate sub-graphs in other topology control algorithms, such as the YaoGabriel graph algorithm. The Gabriel graph, on the other hand, has been used as the base graph before a final sub-graph is produced in other algorithms such as the SΘGG and the YaoGabriel graph algorithm. This SBYaoGG therefore bears resemblance to these other algorithms and it is useful to know how it compares with these topology control algorithms before comparing it with other topology algorithms.

6.3.1 Power Spanning Ratio

The maximum and average distance stretch factors of the SBYaoGG compared with the Yao graph, the YaoGabriel graph and the SΘGG are shown in Figure 6-8 and Figure 6-9 respectively. The SΘGG is shown to be the most energy efficient, followed by the Yao graph, the YaoGabriel graph and then the SBYaoGG. This refers to energy efficiency in terms of end to end communication from source to sink and not from hop to hop, which is represented by the average edge length.

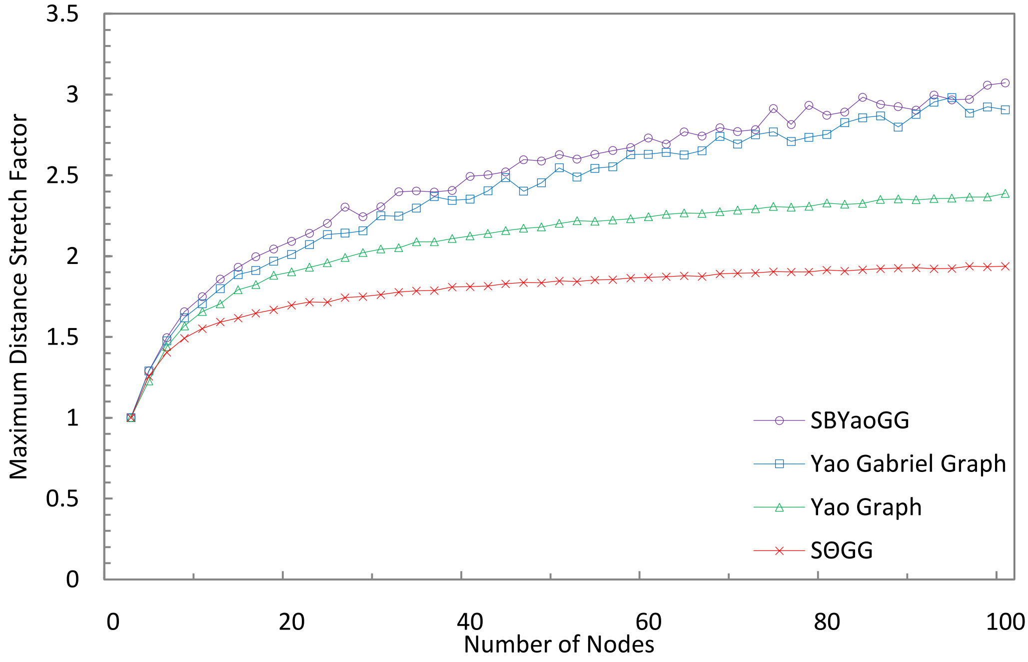


Figure 6-8: Maximum distance stretch factors for the SBYaoGG and similar graphs.

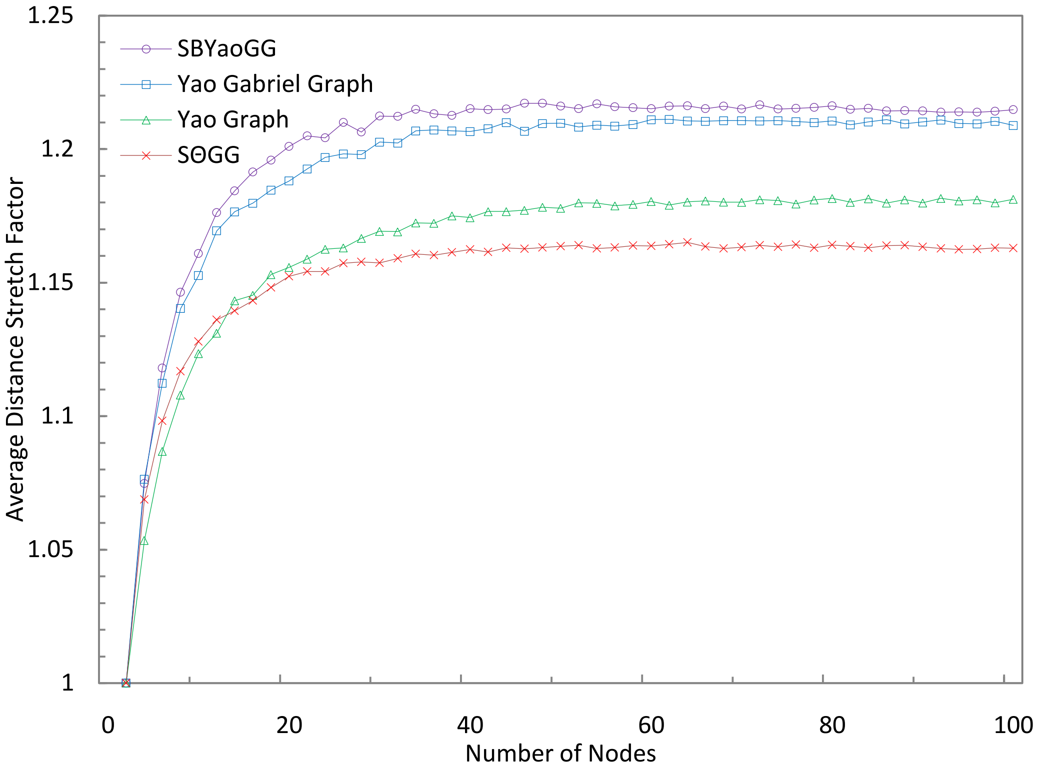


Figure 6-9: Average distance stretch factors for the SBYaoGG and similar graphs.

6.3.2 Logical Node Degree

The maximum and average logical node degree of the SBYaoGG compared with the Yao graph, the YaoGabriel graph and the SΘGG are shown in Figure 6-10 and Figure 6-11 respectively. The SBYaoGG is shown to have the lowest average logical node degree, which means that it will result in smaller routing tables when used as input to routing algorithms. This is followed by the YaoGabriel, then the SΘGG and finally the Yao graph. The SΘGG has the lowest maximum logical edge degree and this is because the algorithm is node-degree-bounded whereas the others, using a parameter of $\alpha = \frac{5\pi}{6}$, are not. The SΘGG can therefore be used as input to a routing algorithm where the maximum number of entries for a particular route can be controlled to be up to a certain guaranteed maximum. It is notable, however, if a parameter of $\alpha \leq \frac{\pi}{2}$ is used for the Yao graph, the YaoGabriel graph and the SBYaoGG will be bounded by a maximum node degree of 6 [49].

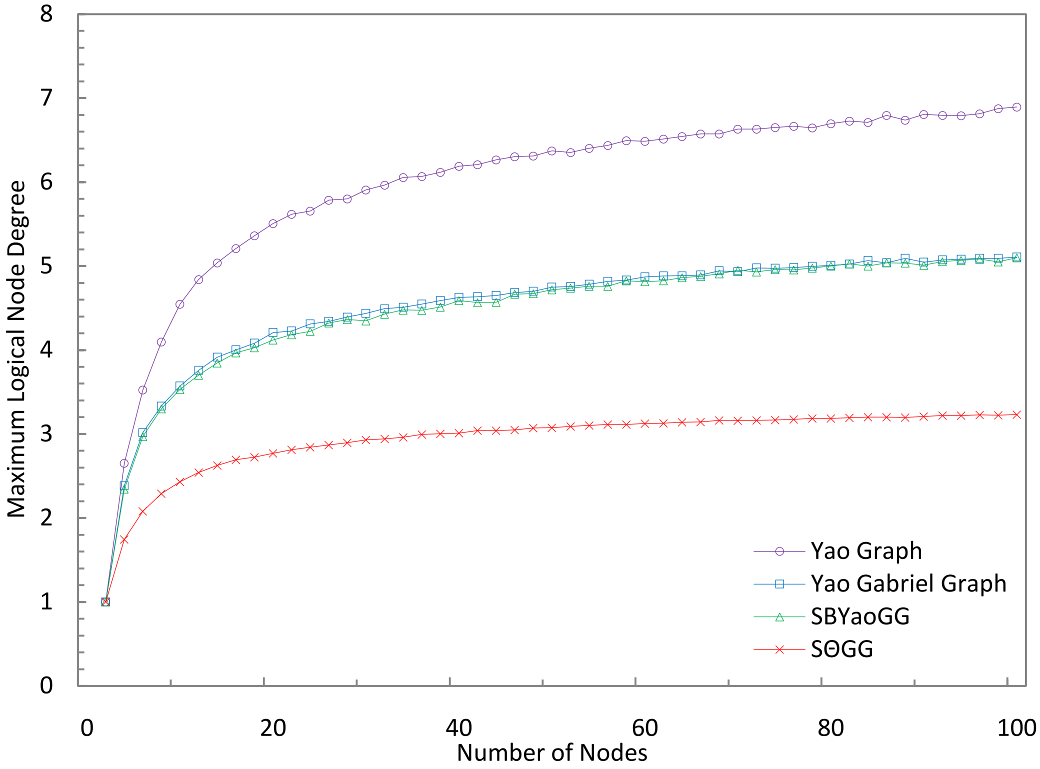


Figure 6-10: Maximum logical node degrees for the SBYaoGG and similar graphs.

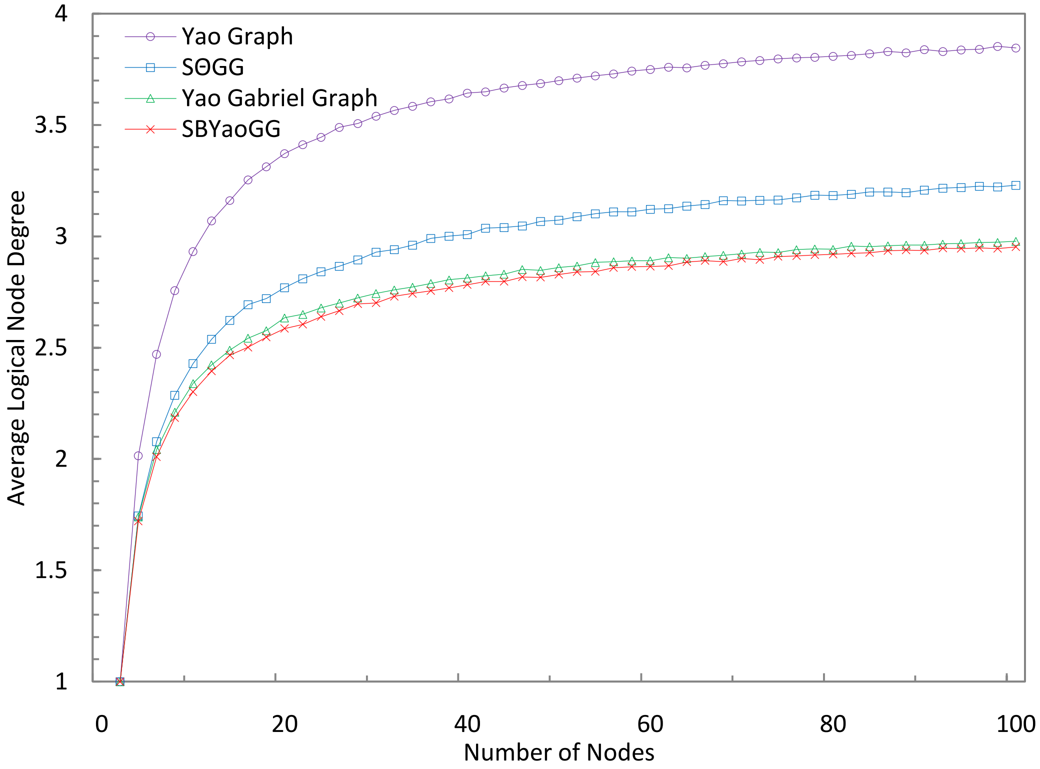


Figure 6-11: Average logical node degrees for the SBYaoGG and similar graphs.

6.3.3 Interference

The maximum and average physical node degree of the SBYaoGG compared with the Yao graph, the YaoGabriel graph and the SΘGG are shown in Figure 6-12 and Figure 6-13 respectively. The SBYaoGG is shown to have the lowest average and maximum physical node degree meaning that it will result in the least interference. This is followed by the YaoGabriel graph, then the SΘGG and finally the Yao graph. It is evident therefore that the fact that the SΘGG is degree-bounded in terms of logical node degree does not help improve its performance in terms of interference.

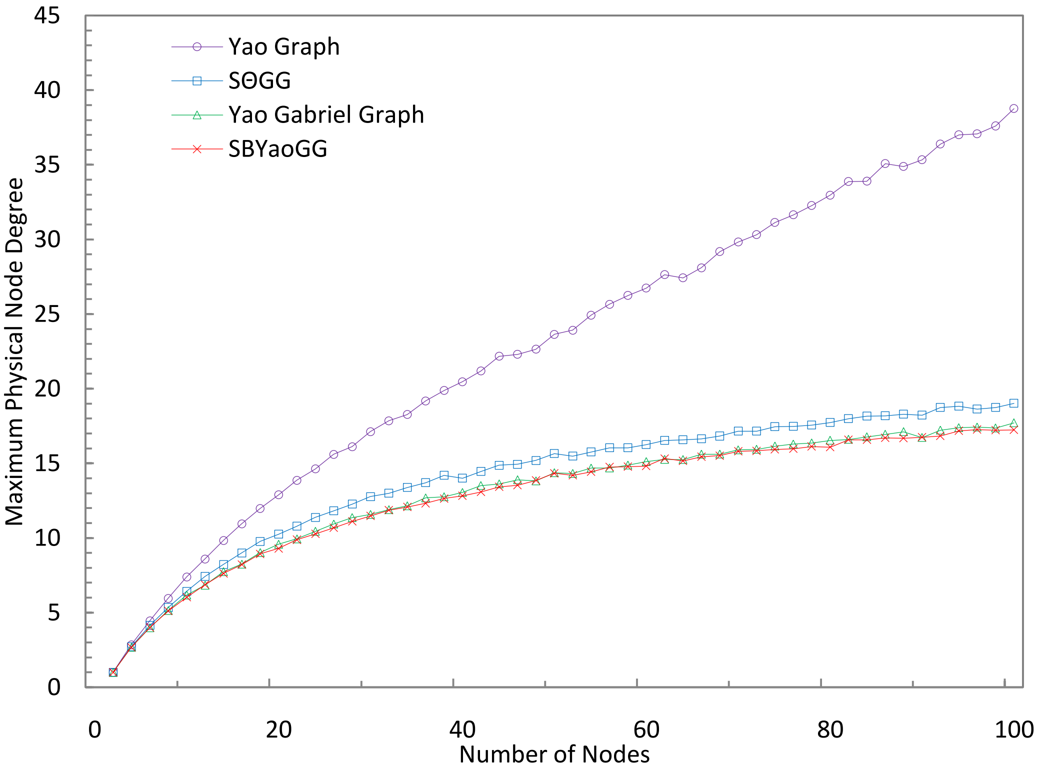


Figure 6-12: Maximum physical node degrees for the SBYaoGG and similar graphs.

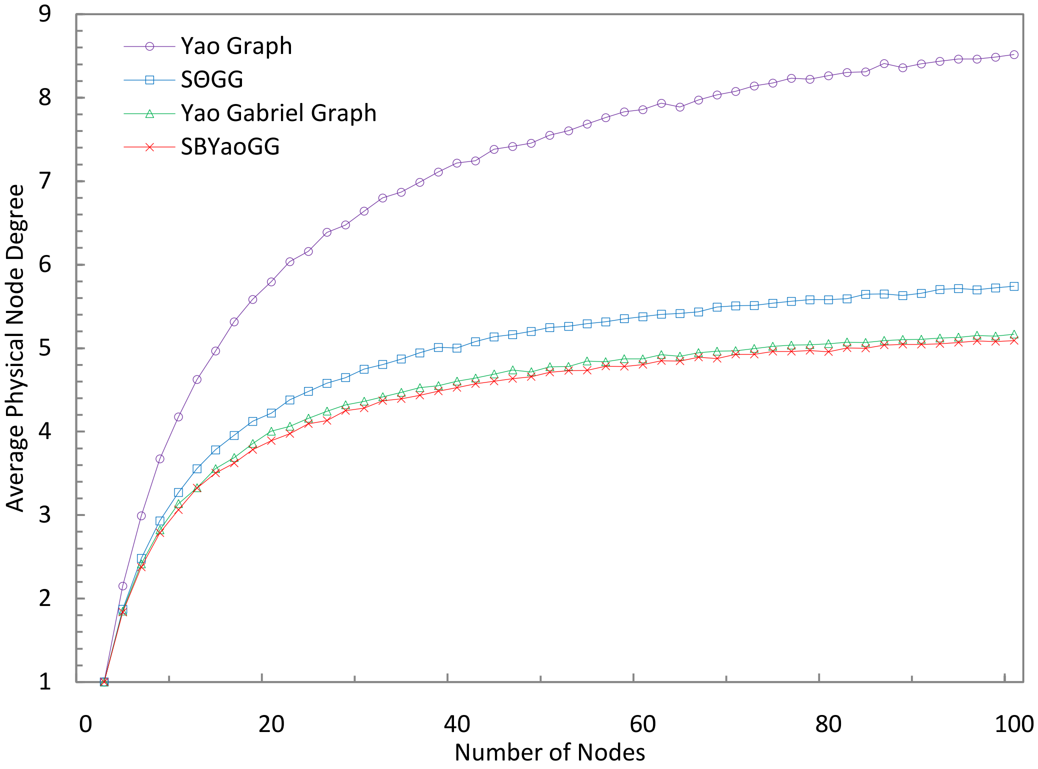


Figure 6-13: Average physical node degrees for the SBYaoGG and similar graphs.

6.3.4 Node Power

The maximum and average edge lengths of the SBYaoGG compared with the Yao graph, as well as the YaoGabriel graph and the SΘGG are shown in Figure 6-14 and Figure 6-15 respectively. The SBYaoGG is shown to have the lowest average and maximum edge lengths, although with the exception of the Yao graph, the performance of the different graphs is very similar. This means that the energy used by a node for a transmission will be less for the SBYaoGG than for the other graphs.

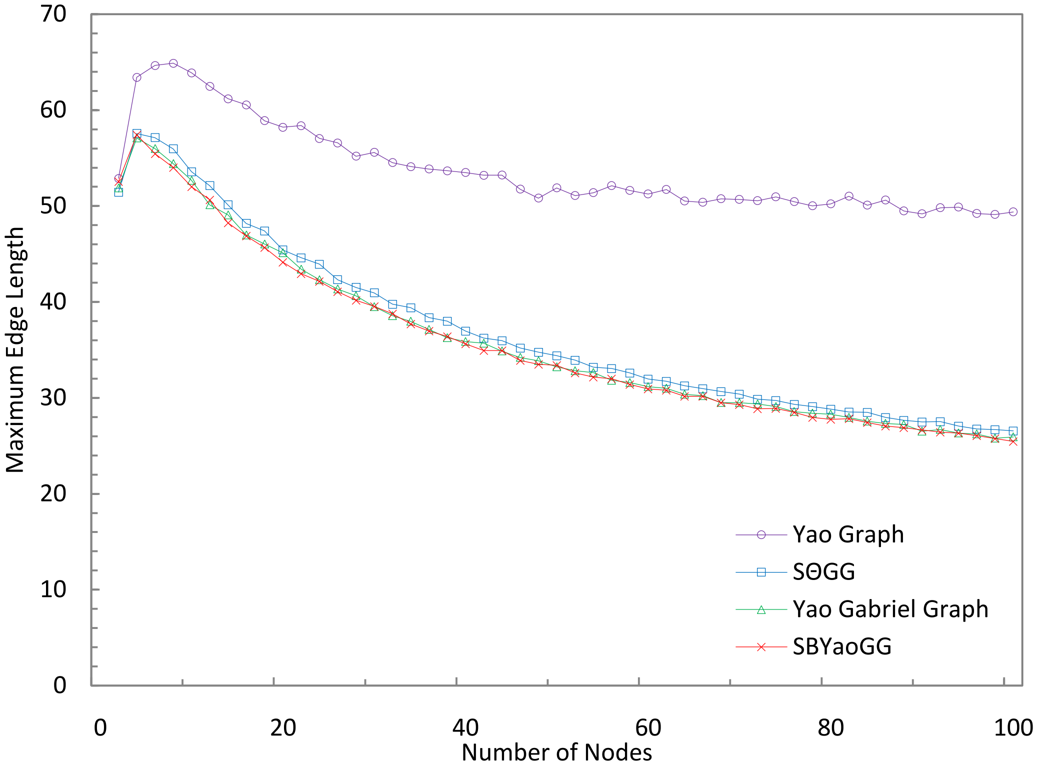


Figure 6-14: Maximum edge lengths for the SBYaoGG and similar graphs.

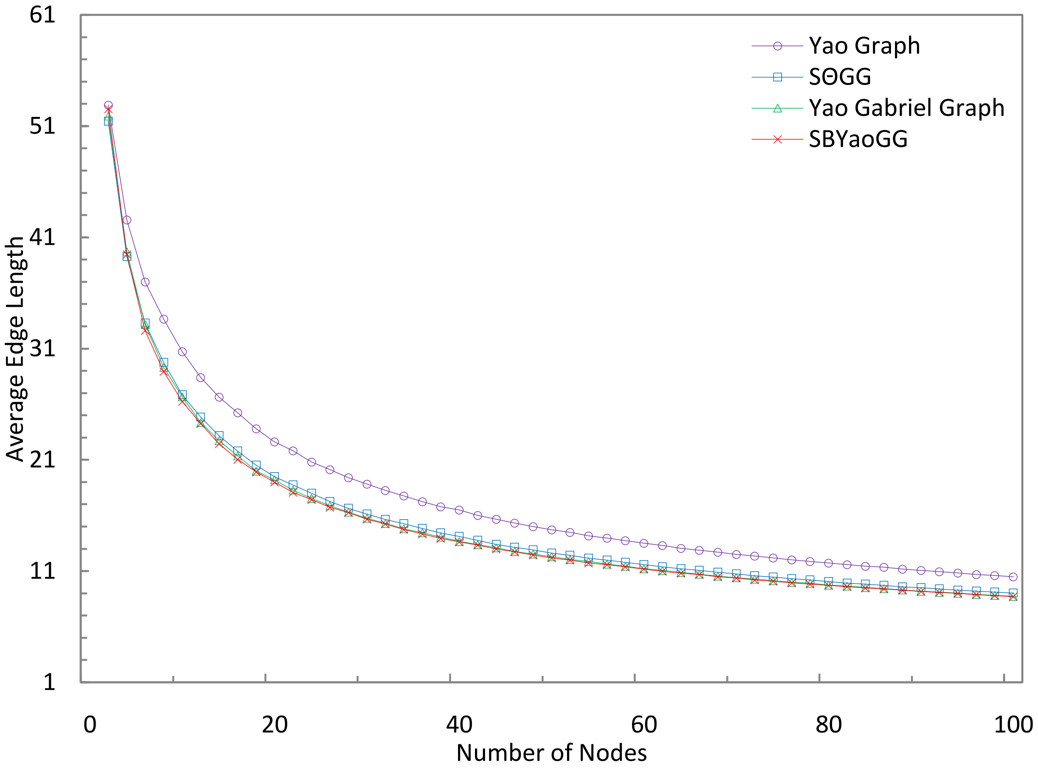


Figure 6-15: Average edge lengths for the SBYaoGG and similar graphs.

6.4 COMPARISON WITH OTHER ALGORITHMS

The previous section compared the SBYaoGG with other similar algorithms for uniform random networks. In this section, the SBYaoGG will be compared to other topology control algorithms where there is a considerable difference in how the topology controlled graphs are computed. The Delaunay graph, the Gabriel graph, the RNG and the MST will be used as comparisons.

6.4.1 Power Spanning Ratio

The maximum and average distance stretch factors of the SBYaoGG compared with the Delaunay graph, the Gabriel graph and the RNG are shown in Figure 6-16 and Figure 6-17 respectively. The Delaunay graph is shown to be the most energy efficient, followed by the Gabriel graph, the SBYaoGG and then the RNG. This refers to energy efficiency in terms of end to end multi-hop communication from source to sink and not from hop to hop, which is represented by the average edge length.

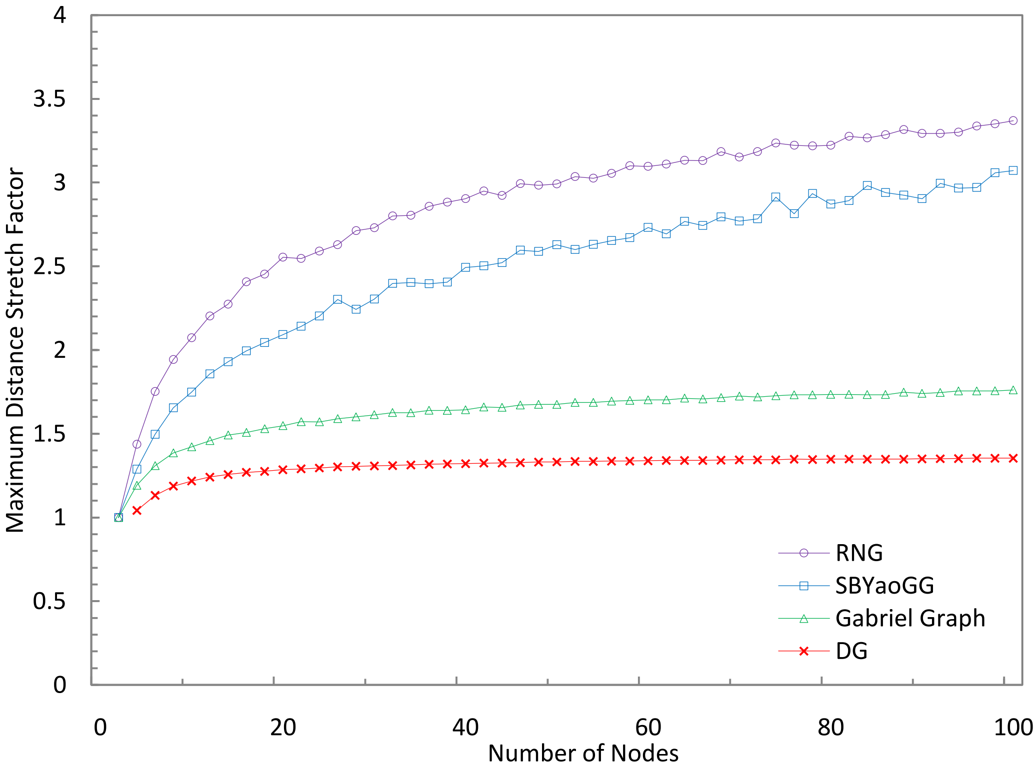


Figure 6-16: Maximum distance stretch factor of different graphs.

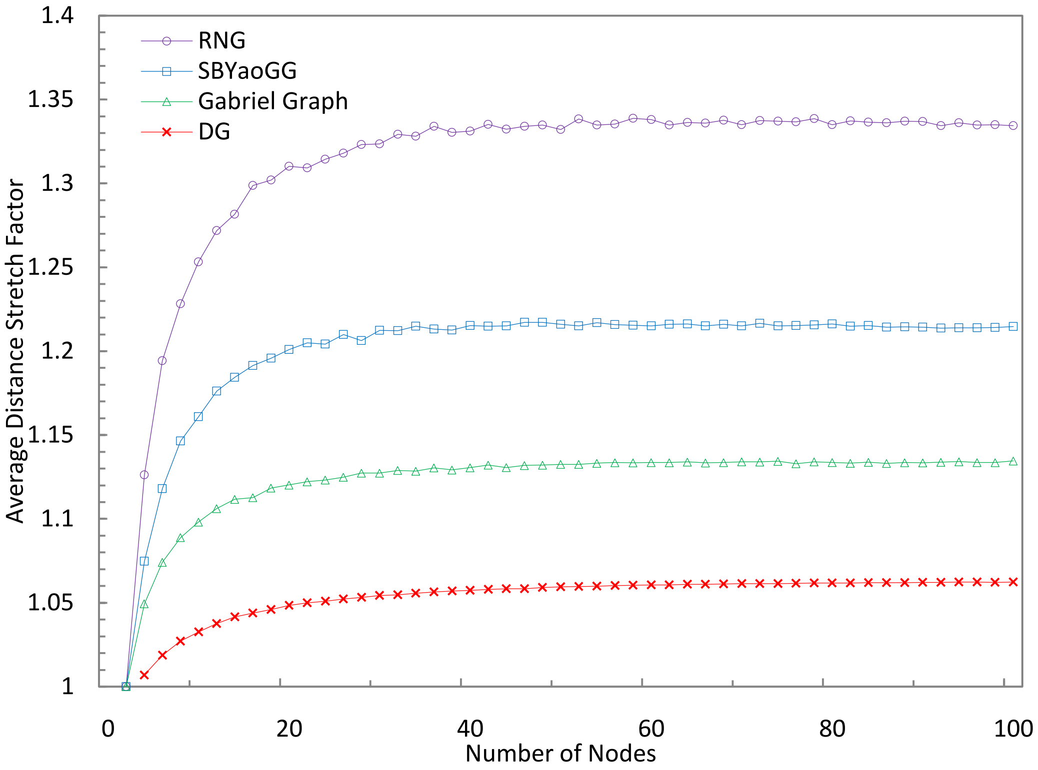


Figure 6-17: Average distance stretch factor of different graphs.

6.4.2 Logical Node Degree

The maximum and average logical node degree of the SBYaoGG compared with the Delaunay graph, the Gabriel graph, the RNG and the MST are shown in Figure 6-18 and Figure 6-19 respectively. As can be expected, the MST has the lowest node degree, followed by the RNG while the Delaunay graph has the highest node degree, followed by the Gabriel graph. The SBYaoGG lies in between the RNG and the Gabriel graph and its node degree is lower than that of the Gabriel graph since it is a sub-graph of the Gabriel graph.

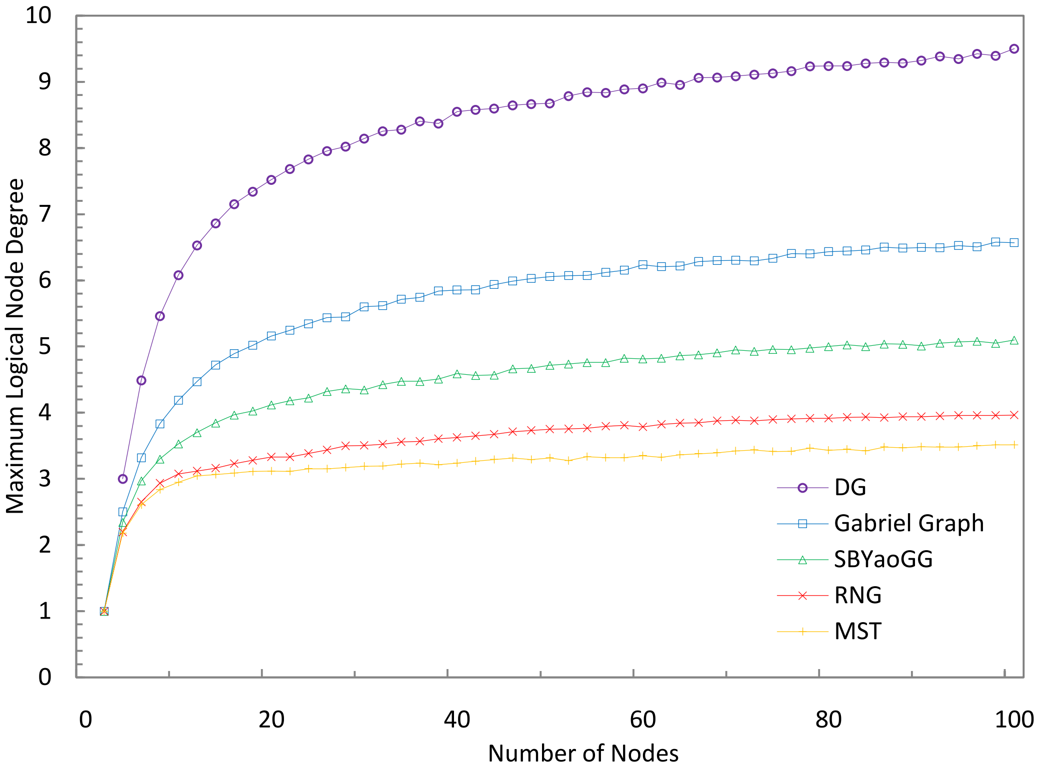


Figure 6-18: Maximum logical node degree of different graphs.

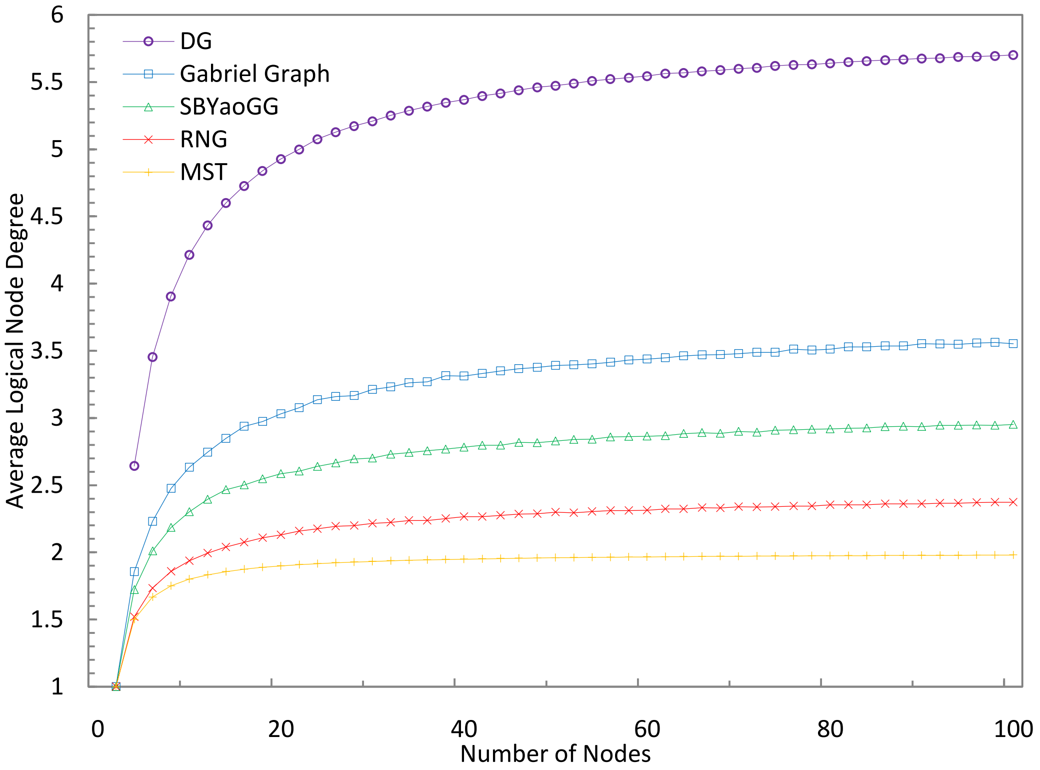


Figure 6-19: Average logical node degree of different graphs.

6.4.3 Interference

The maximum and average physical node degree of the SBYaoGG compared with the Delaunay graph, the Gabriel graph, the RNG and the MST are shown in Figure 6-20 and Figure 6-21 respectively. The results are similar to those for the logical node degree.

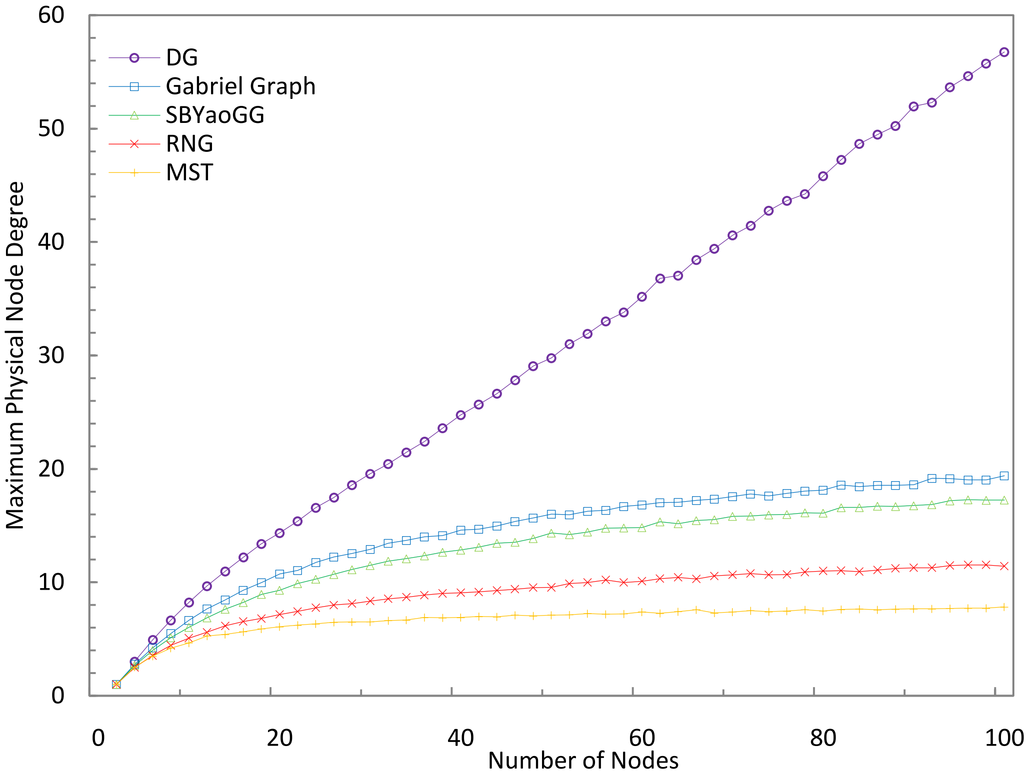


Figure 6-20: Maximum physical node degree of different graphs.

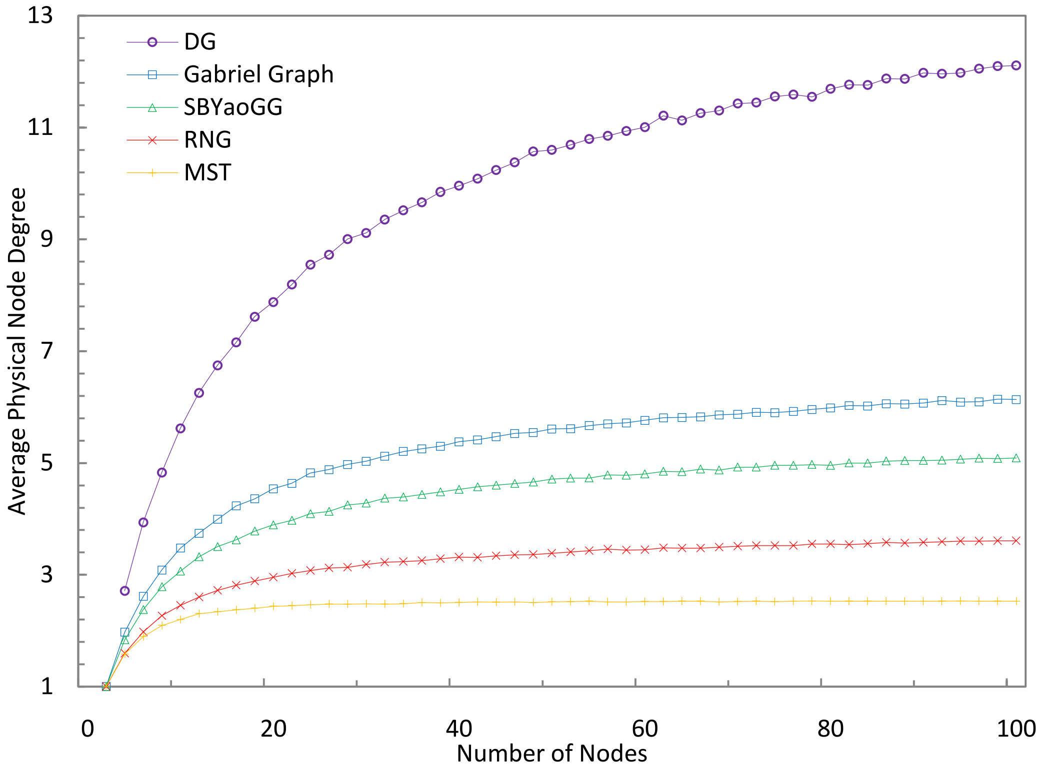


Figure 6-21: Average physical node degree of different graphs.

6.4.4 Node Power

The maximum and average edge length of the SBYaoGG, compared with the Delaunay graph, the Gabriel graph, the RNG and the MST are shown in Figure 6-22 and Figure 6-23 respectively. The order of the results is the same as the results for the physical and logical node degree. This is because the MST is a sub-graph of the RNG, which is a sub-graph of the Gabriel graph, which is in turn a sub graph of the Delaunay graph. Also, the SBYaoGG is a sub-graph of the Gabriel graph.

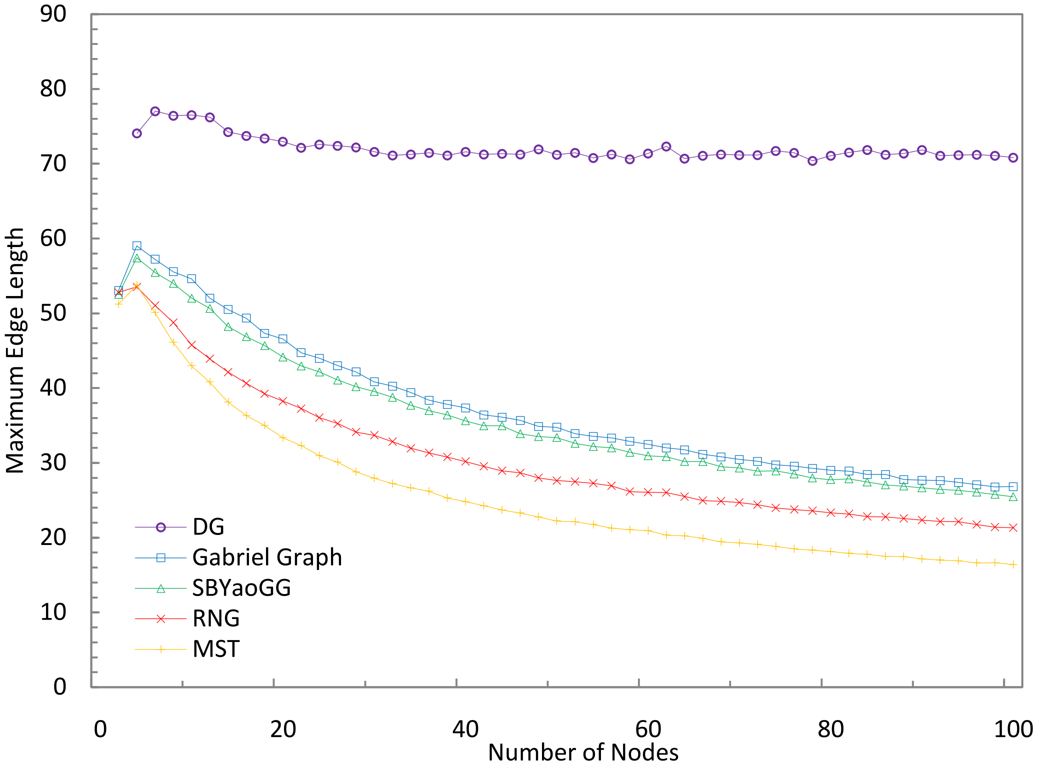


Figure 6-22: Maximum edge length of different graphs.

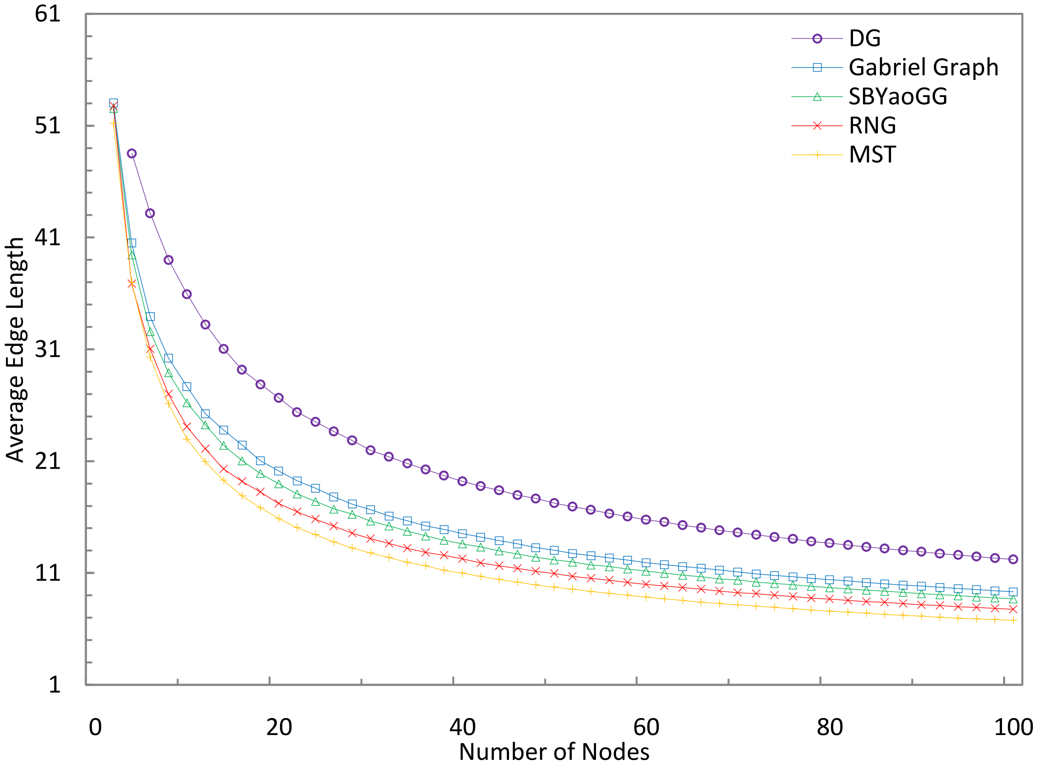


Figure 6-23: Average edge length of different graphs.

CHAPTER 7

CONCLUSION

7.1 SUMMARY OF THE WORK

In this research a technique for energy efficient and low interference topology control in wireless sensor networks was developed in the form of the SBYaoGG algorithm. To achieve this, a literature study was conducted into wireless sensor networks and topology control. Experiments were performed and a design was drafted. The SBYaoGG algorithm was then developed and evaluated using a simulation program.

The SBYaoGG algorithm is a variation of the standard Yao Gabriel graph in which the boundaries of the regions of the Yao graph depend on the distribution of neighbours around a node. The average unit direction vector of the neighbours of a node is used as the axis of the first cone of the Yao graph. The SBYaoGG looks to develop as sparse a topology as possible with good power spanner properties. This is achieved by computing a Gabriel Graph from the original Uniform Disk Graph and then computing the Yao Graph on the Gabriel Graph using smart region boundaries.

There are some heuristics that are used in order to produce as sparse a topology as possible whilst meeting the set out objective of good power efficiency. As few regions as possible were used to maintain connectivity of the graph when computing the Yao graph. Optimisation steps are performed once the basic SBYaoGG is produced. The first step is to ensure that all links in the graph are symmetric by adding the reverse edge of all asymmetric links. This helps to ensure good energy efficiency by keeping the power spanning ratio down. The second optimisation step is to set the transmitter power of each node to the minimum power that is necessary to reach the furthest neighbour with which it has a link in the topology controlled graph.

The performance of the SBYaoGG algorithm was evaluated using several performance metrics and compared with that of other topology control algorithms. The metrics that were chosen were those that measure energy efficiency, interference and the routing efficiency that will be a result of using the topology controlled graph as input to a routing protocol.

7.2 CRITICAL EVALUATION OF THE WORK

The results that were obtained were encouraging in some respects. Firstly, energy efficiency and low interference are conflicting goals in wireless sensor networks. It is desirable to find some Pareto optimality between these goals that produces a good overall performance. The Gabriel graph has good energy-efficiency performance but poor interference performance. The Relative network graph has poor energy-efficiency performance but good interference performance. The SBYaoGG lies somewhere in between the extremes presented by these two graphs and therefore achieves some Pareto optimality of the set out goals.

The SBYaoGG is similar to the Yao Gabriel graph in terms of how the two are calculated. The SBYaoGG can be considered as a refinement of the Yao Gabriel graph in order to meet the set out objectives. In terms of performance they are closely matched, although the SBYaoGG graph clearly has lower interference and lower energy efficiency for end to end communication. The results prove that the heuristics used in the computation of the SBYaoGG, that are not present in the Yao Gabriel graph, are there to sparse the topology as much as possible whilst maintaining connectivity result in performance gains, particularly in terms of lower interference.

A comprehensive survey of different topology control techniques was done. The different techniques were compared with one another and the characteristics of the algorithms were clearly exposed and contrasted. The performance measures of the different algorithms were computed for several different networks of varying sizes and they can be used to determine the most suitable algorithms for certain applications or network deployment scenarios. The breadth and extent of algorithms investigated in this research is a positive outcome.

Another positive outcome is the proprietary simulator program that was developed for the purpose of this research. The program has a library of topology control algorithms and functionality to compute and view network deployment graphs and topology controlled graphs as well as to compute various metrics of the graphs and perform operations such as path searches on the graphs.

One outcome that was somewhat of a disappointment was that there was not as big a difference between the SBYaoGG and the YaoGabriel graph as was hoped. It was hoped that the SBYaoGG would be able to sparse the topology more than it did.

The hypothesis question that was posed at the introduction of this research was: “*Is it possible to develop a lightweight, heterogeneous, symmetric topology control technique that can address performance issues in wireless sensor networks in terms of extending network lifetime, reducing radio interference and lowering energy consumption in a distributed fashion?*”

This question was answered in the affirmative. In addition to this the research objectives were met. A topology control mechanism was developed that results in a topology controlled wireless network that has:

- Low radio interference.
- High energy efficiency.

The topology control mechanism:

- is distributed,
- uses local information,
- produces a connected network and
- produces a sparse network.

7.3 FUTURE WORK

One area for future work that can be done is to port the algorithm onto a simulator that simulates the entire protocol stack. The next step will then be to feed the topology controlled network as input to different routing protocols and introduce different traffic patterns into the network. The effects of the topology control protocol on the routing algorithm and different network applications can then be evaluated.

Another area for future work is to extend the simulator program by adding more topology control algorithms. One possibility is to add hierarchical algorithms that use clustering and dominating sets. Another area of expansion is the addition of different routing protocol implementations to the simulator program and to then inject different traffic patterns into the network.

The algorithm that was developed is focused on stationary networks. The effects of mobility on the algorithm can be studied and perhaps the same research can be done but with a focus on mobile networks.

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