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Performance Analysis of LTR: A Thermal Aware Routing Protocol for WBANs Networks.

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DEDICATIONS

To my dear parents, the source of all kindness, support and strength in my life, may Allah keep them always by my side

To all my brothers and sisters, Amine, Anouar, Hammou, Rahima and all my family members and relatives

To all my classmates, colleagues, SLB IT Team, friends and everyone who supported me through this work

I dedicate this modest work.

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Abstract

With the evolution of technology, WSN became a future renaissance. Even though, it still facing different challenges. Healthcare and in vivo applications have their share of this evolution, within WBANs. Routing in WBANs always represent one of the biggest challenges due to the absence of infrastructure of the networks and the environment unique proprieties. Temperature rise and the heat generated by WBANs affects directly the in vivo environments and can cause serious damages. Thus, researchers proposed LTR, a routing protocol that is thermal-aware, and it is our study case in this work. After implementing the LTR protocol, we worked on adapting it to support Dual Sink architecture, then we ran several tests and simulations using Castalia under OMNeT++ simulator, aiming to enhance LTR performance.

Key terms: WSN, WBAN, LTR, Castalia,OMNeT++, Simulation, Dual Sink, Temperature, in vivo, Routing.

ملخص: مع التقدم الذي تشهده التكنولوجيا، أصبحت شبكات المستشعرات اللاسلكية WSN خطوة نحو نهضة المستقبل، غير أنها لازالت تواجه عدة تحديات. تطبيقات الرعاية الصحية و كل ما يتعلق بالأوساط الحيوية نالت أيضا حصتها من هذا التطور، تحت مسمى شبكات المستشعرات اللاسلكية حول الجسم WBAN. توجيه البيانات في هذه الأخيرة تمثل أحد أكبر التحديات في هذا المجال نظرا لغياب بنية تحتية محددة تشتغل عليها هذه الشبكات، و الخصائص الفريدة للمحيط الذي تشتغل فيه. ان ارتفاع الحرارة المتولد عن تشغيل هذه الشبكات يمثل تهديدا كبيرا على المحيط الحيوي و قد يتسبب في تلفه و تدهوره. من هذا المنطلق، اقترح الباحثون بروتوكول التوجيه LTR و الذي يعنى بمراقبة، تخفيض و موازنة الحرارة في هذه الشبكات، و الذي يمثل موضوع بحثنا. و بعد محاولة تحسين أداء هذا البروتوكول ليدعم نقطتين لتجميع البيانات Dual Sink بدلا من واحدة، قمنا باختبار و محاكاة تطبيق هذا البروتوكول من خلال اجراء عدة تجارب باستخدام مشروع Castalia داخل المحاكي ++OMNeT، أملا في الخروج بنتائج أفضل.

كلمات دلالية: شبكات المستشعرات اللاسلكية WSN، شبكات المستشعرات اللاسلكية حول الجسم WBAN، LTR، بروتوكول التوجيه، الحرارة، نقطتي تجميع البيانات Dual Sink، محاكاة، Castalia، ++OMNeT، المحيط الحيوي.

Résumé : Avec l'évolution technologique, le WSN est devenu une future renaissance. Cependant, ce nouveau type de réseau se trouve face à différents défis. Les soins de santé et les applications in vivo ont leur part de ce progrès au sein des réseaux WBAN. Le routage dans les réseaux WBAN représente toujours l'un des plus grands défis en raison de l'absence de l'infrastructure des réseaux et les propriétés uniques de son environnement. La surchauffe engendrée par ces réseaux endommage directement l'environnement in vivo et peut causer de graves dommages. D'ici, les recherches ont proposé le LTR, le protocole de routage thermique qui est notre sujet d'étude. Après des tentatives d'amélioration du fonctionnement de ce protocole afin de soutenir l'architecture Dual Sink, nous avons effectué plusieurs tests et simulations en utilisant le projet Castalia sous le simulateur OMNeT++, afin d'améliorer la performance du LTR.

Mots-clés: WSN, WBAN, LTR, Castalia, OMNeT++, Simulation, Dual Sink, Température, in vivo, Routage.

General Introduction

With the growth of science and technology of data collecting and processing, in addition to the world growing demands of new efficient systems that can be used in different environments conditions, researchers started to see the future in Wireless Sensor Networks (WSNs) for fulfilling all these requirements and ending up in new era with diverse possibilities.

The main part in these networks are the sensing devices that can collect different type of physical events from the environment such as low sampling rate, seismic, magnetic, thermal, visual, infrared, radar and acoustic, which are clever to monitor a wide range of ambient situations. WSN has numerous applications in real life starting with military, commercial purposes, environmental, house and many others. WSN has many challenges showing up with the advance of the high tech, like the energy limitations, large bandwidth, quality of service (QoS), data processing, security, real-time applications, etc.

Health is one of the leading uses of WSN, under the name Wireless Sensors Body Area Networks (WBANs), including all the applications that are concerned about in-vivo environment. The point behind defining WBAN is to concentrate on the unique specifications of the bodies for example we have temperature sensitivity, Specific Absorption Rate (SAR), the body movements, very small size of the sensors to be used due to body size, multitask devices, sensor lifespan that is up to years maybe with very tiny battery, extreme real-time needs and QoS as we are dealing here with humans lives mostly, and much more detailing consequent to body properties.

In WBAN architecture generally, all the collected data is being transmitted to a Sink, where we aggregate and treat this data to come up with useful information then store them in an accessible server or cloud or send them over the internet, or maybe just store them locally. Data transmission is ensured by routing protocols that are facing different hitches to be handled like the absence of infrastructure (Ad Hoc) and mobility, extremely limited resources such as energy and transmission range. All these obstacles must put in consideration while using a routing protocol.

The heat in the tissue generated due to absorption of radiation while transmitting data by sensor nodes, is an important criterion to consider and should be minimized to reduce the side effects as much as possible. Thus, researches proposed some thermal aware routing protocols.

Least Temperature Routing (LTR) protocol uses a simple algorithm to solve the temperature issue in WBANs. LTR was designed to minify the temperature rise overall the network. This work uses LTR as study case by implementing it then modify the function costs using Dual Sink instead of traditional Single Sink. Afterwards, we run different tests over Single and Dual Sink by simulating the behavior of the two approaches using Castalia in OMNeT++ IDE by varying two important parameters related to LTR protocol, which are: data generation rate and the temperature threshold.

Rest of this work is organized as following: in Part -A- we have the state of art, starting with Chapter one, definition of WSN and related concepts such as topologies, existing components and challenges. Chapter two gives an overview about WBANs and a comparison with WSN, applications of WBAN and some protocols used in WBAN with their classifications. Next we have the Part -B-, which is the contribution part, includes Chapter three that is about LTR protocol with a descriptive algorithm. Chapter four is report of LTR implementation, and how did we accomplish Single and Dual Sink, plus the testing and simulation tools with detailing the obtained results. Last part is a general conclusion to resume all the thesis.

PART A:
-State of Art-

Chapter One:
Wireless Sensor Network

1.1 Introduction:

Wireless sensor networks are increasingly being deployed and considered for diverse environments. The main role of any WSN is to serve as an interface to the real world, providing physical information such as temperature, light, radiation, etc. to a computer system. The major difference between this type of networks and wired networks is their decentralized and specialized nature. In WSN, all its members collaborate towards the common goal of obtaining or deducing certain physical information from their environment. Moreover, WSN is capable of self-organization, thus it can be deployed in a certain context without requiring the existence of a supporting infrastructure[1]. **Fig. 1** represent a general architecture of WSN, where the sensor node can play two main roles: send the sensed data and forward the received data from other sensors.

This network is composed of hundreds or thousands of autonomous and devices called sensor node made of compact microsensors with wireless communication capability. These small devices are relatively cheap with the potential to be disseminated in large quantities.[2]

Sensor nodes capable of gathering information from the surroundings and sending them to the base station or coordinator, but if the destination is out of the radio range of source node, other nodes are used as relay points to reach the base station.

Sink in WSN refers to the base station that performs data fusion based on the accumulated sensory data from multiple sensor nodes and then sending it to data processing center[3]. The link between sink and processing center can be wire or wireless. That is the reason sink node is called the gateway between the sensor nodes and data processing center.

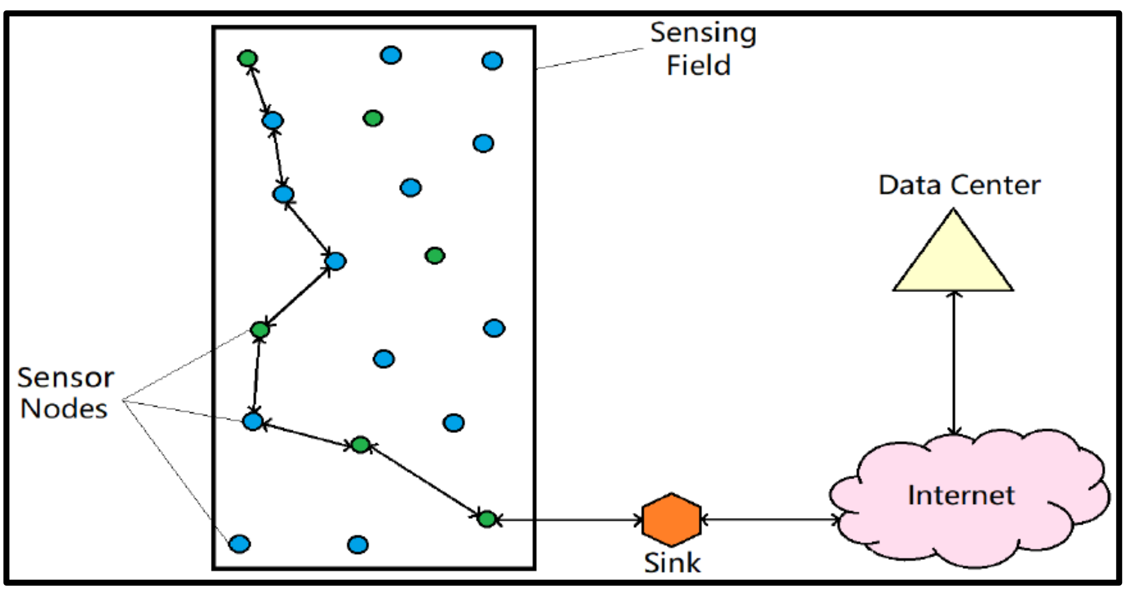


Fig. 1 Communication Architecture.[4]

1.2 The Main Components in a WSN:

As any other network, WSN has many different components, all able to communicate, send and receive data in-between, while the major elements are:

1.2.1 Sensor Node:

Sensor nodes get the physical information of the surroundings using its built-in sensors, process the raw information taking advantage of its computational capabilities, and communicate with other nodes in its surroundings using a wireless channel. All sensor nodes are battery-powered; hence, totally independent and able to operate autonomously, if required. Nevertheless, they can also collaborate with other nodes in pursuing a common goal.[1]

The main constraint about these nodes is limited energy supply, so it is important to deploy the sink at a position with respect to the area of interest; a specific area that is of more interest to the end-user, such that total energy consumption is minimized.[5]

As shown in the **Fig. 2** sensor node is compost of a power unit, processing unit, sensing unit, and communication unit.[2]

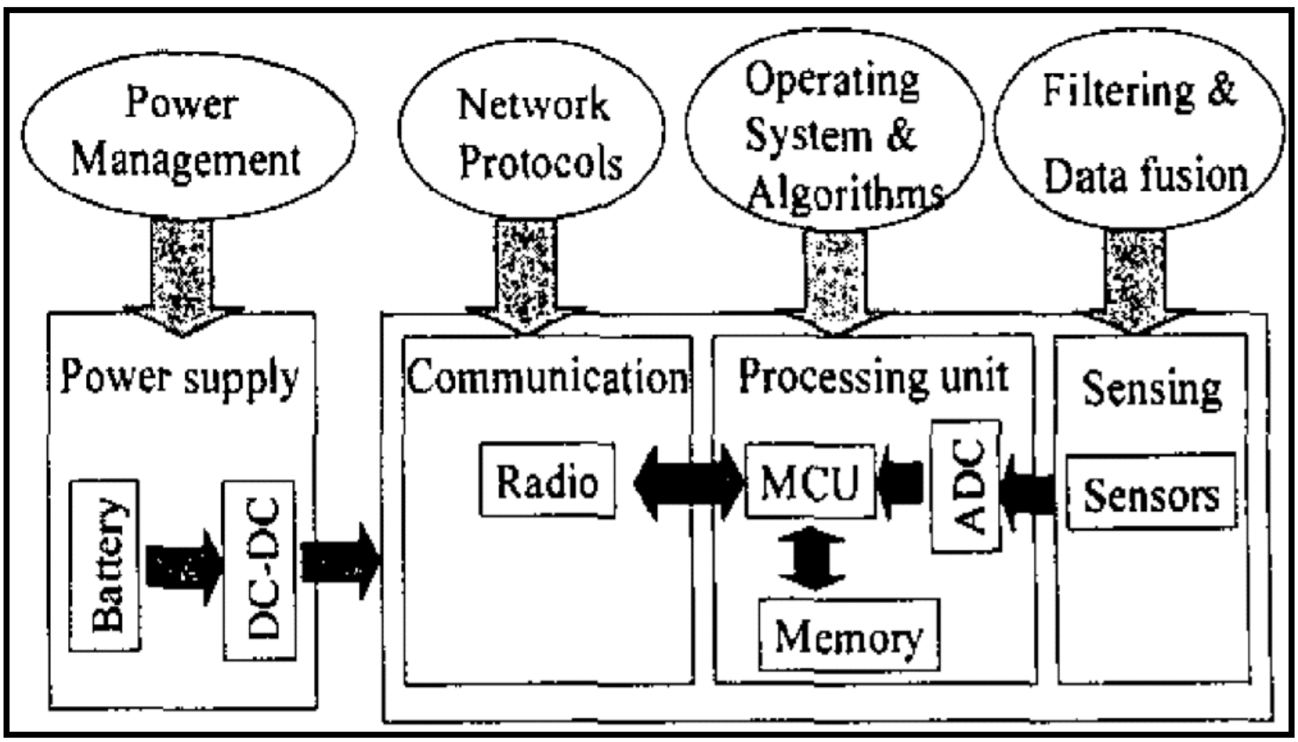


Fig. 2 Sensor node system architecture and challenges.[2]

The processing unit: mostly, it is a microcontroller which is responsible to collect and process signals captured from sensors and transmit them to the network. It combines, generally, a microprocessor that is low power and have low computation capabilities (ranging from 4 to 32 bits microprocessors), running at frequencies in the order of tens of megahertz, and contains also an Analog-to-Digital Converter (ADC). The memory available within this unit is usually also limited, in the range of kilobytes.[6]

The sensing units: they are devices that produce a measurable response to a change in a physical condition like temperature and pressure. A wide range of sensors can be employed to sense data, which is transmitted to other entities through the radio interface.[6]

The communication unit: this part provides a medium to transfer signals from sensors to exterior world or a computer network, and also a mechanism of communication to establish and maintenance of WSN, which is usually ad-hoc. Radio-frequency (RF) based on electromagnetic waves is a common solution in WSN. One of the most important challenges in RF communications devices is antenna size. It is also necessary to reduce energy consumption with modulation, filtering, demodulation, etc. RF communication advantages are its ease of use, integrality, and well established in the commercial marketplace, which make it an ideal testing platform for sensor node. In general, radios can operate in four distinct modes of operation: transmit, receive, idle, and sleep.[2]

The power unit: it provides energy source for sensors is usually battery power; it is and will be the primary metric to design a sensor node. Moreover, sensors are often intended to be deployed in remote or hostile environment, such as a battlefield or desert; it is undesirable or impossible to recharge or replace the battery power of all the sensors. However, long system lifetime is expected by many monitoring applications.[7]

1.2.2 The Sink:

Sink node (or Base Station BS, Coordinator, Gateway) is a connecting link between the preceding and the following, and plays an important role in WSN, which can manage the sensor nodes and communicate with the data center. It is mainly responsible for sending the commands from the data terminal (such as data query, distribution of ID address, etc.), receiving the data from sensor nodes. The sink may also aggregate and analyze the report messages received and decides whether there is an unusual or concerned event occurrence in the deployed area. To sum up, sink node must be with capacity of high-speed processing, large storage, long-distance transmission, connection to the external network, etc.[8] and acts as a gateway between sensor nodes and the end user as its role is to forward data from the WSN to a server. Some sensor networks are not connected to the Internet at all, and their data is simply aggregated and displayed at a local aggregation point, such as a smart phone, PC or Personal Digital Assistant (PDA).[9]

A sink is often AC-powered in case it is a dedicated device but this is not always the case. A smartphone can act as a base station in a Wireless Personal Area Network (WPAN) despite being battery-powered; the smartphone will have significantly more battery power than the sensor nodes in the network and will be regularly charged.[9]

1.3 Architectures and Topologies of WSN:

The infrastructure of WSN can be divided into two parts, the data acquisition network and the data dissemination network, as the **Fig. 3** shows. The data acquisition network contains the sensor network: sensor nodes and sink. Sensor nodes are a collection of small devices with the task of measuring the physical data of its surroundings, and sink are powerful devices in charge of collecting data from the nodes and forwarding control information from the users. On the other hand, the data dissemination network is a combination of wired and wireless networks that provides an interface of the data acquisition network to the end-user.[1]

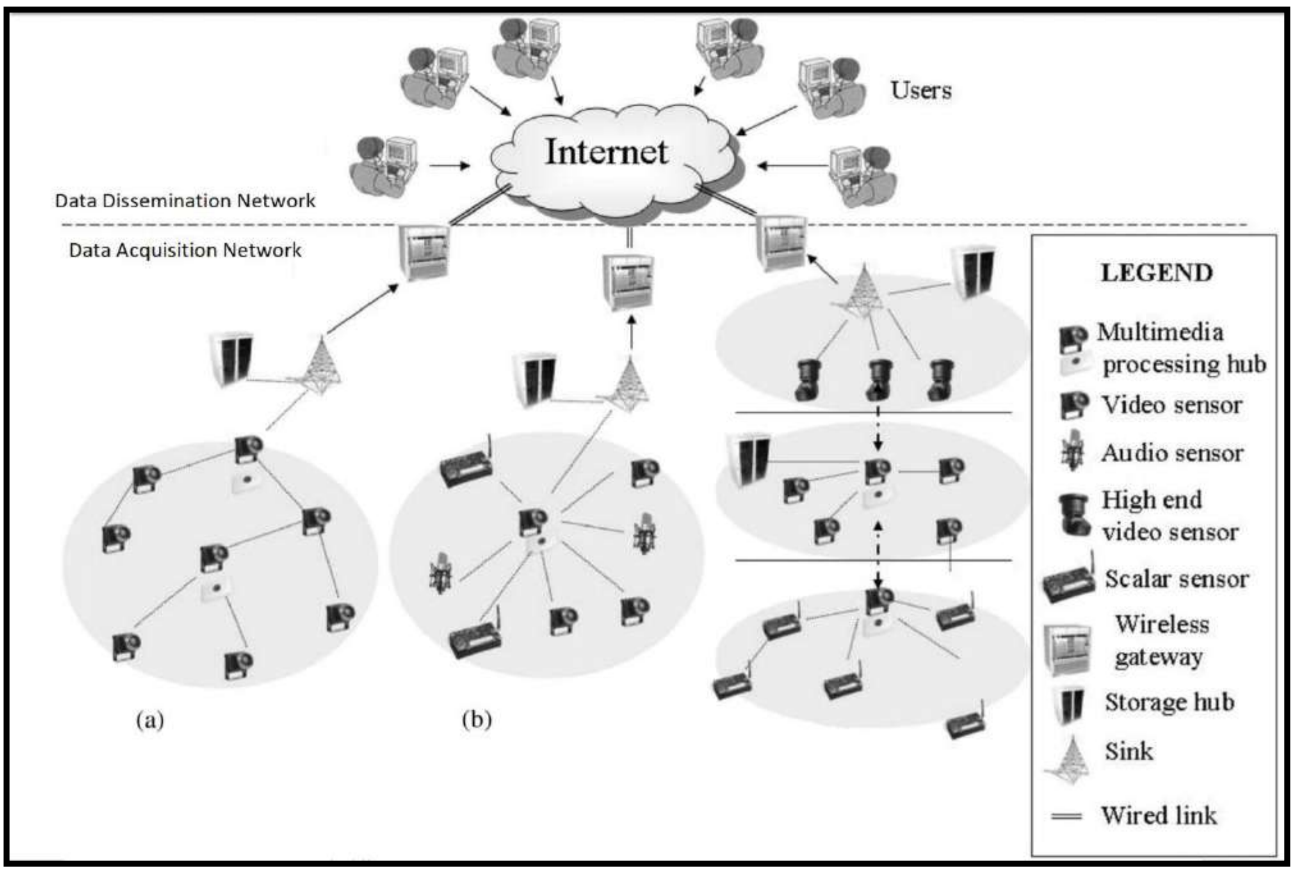


Fig. 3. Reference architecture of a wireless multimedia sensor network[13]

The topology of a WSN refers to how the nodes are arranged within the network. Although wireless sensor networks consist of sensors that are miniaturized, pervasive, and coordinated. The general principles of topology of WSNs are the same as for any other network.[10] These topologies can also be described as having either a flat or hierarchical architecture. In a flat (peer-to-peer) architecture, all nodes in the network has the same computational and communication capabilities. In a hierarchical architecture, the nodes operate in close proximity to their respective cluster heads. Hence, nodes simply capture the required raw data and forward it to their respective cluster heads.[9] Brief details of each of these topologies follow.

1.3.1 Star Topology:

In this topology the nodes are organized in the form of a star with the sink as the hub of the star, as shown in the **Fig. 4 (a)**. Sensor nodes broadcast data through the sink, and cannot directly exchange messages between each other. This topology offers low power usage as compared to other wireless sensor topologies. However, the sink cannot communicate with a node that is out of range. The fact that this topology depends on a single node to manage the network exposes it to a single-point-of-failure weakness, which negatively impacts the overall reliability of the network.[10]

1.3.2 Mesh Topology:

A WSN with a mesh topology (see **Fig. 4 (b)**) has sensor nodes that communicate data through each other. This means that, if a sensor node wishes to send data to an out-of-range node, it can use another node as an intermediate communication resource. One advantage of this topology is that if a sensor node fails, communication is possible with other nodes that are within the communication range. A major disadvantage is that this topology uses more power due to redundant data transmission.[10]

1.3.3 Cluster Tree Topology:

Cluster architecture consist of sensor nodes clusters each governed by cluster head, as the **Fig. 4 (c)** shows. The node in each cluster sends the messages to cluster head and this cluster head sends messages to a higher cluster head or directly to the sink node.[11] The main problem of clustering is nonuniform clustering which leads to high energy dissipation of sensor node, total energy consumption increases, and network connectivity not being guaranteed.[12]

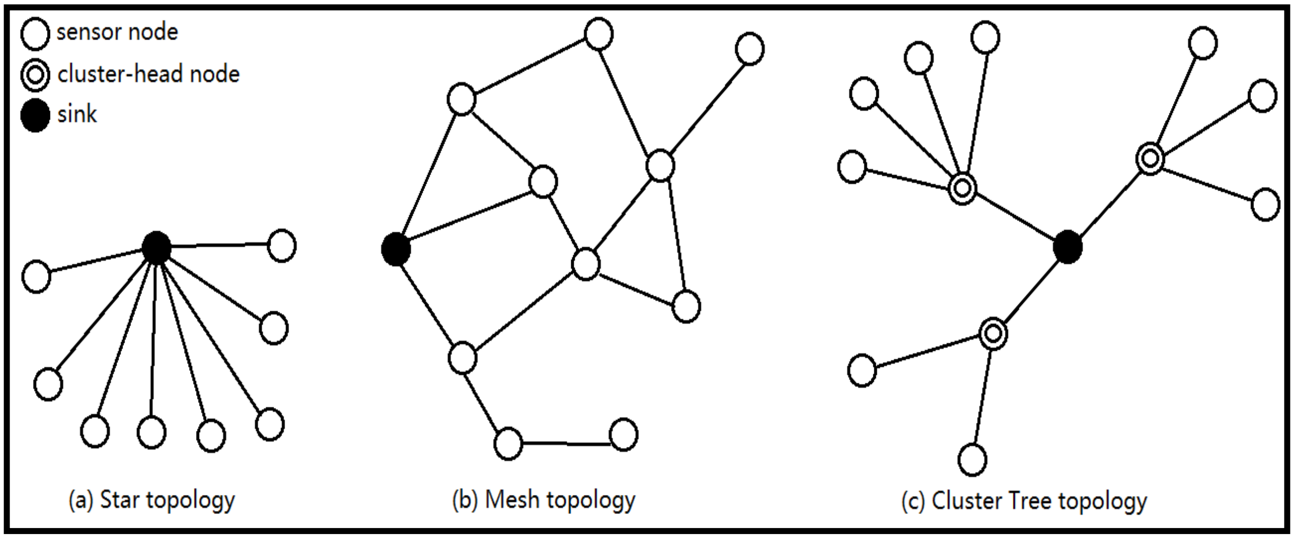


Fig. 4 Star, Mesh and Cluster Tree topologies.

1.3.4 Hybrid Topology:

A hybrid network consists of a combination of star and mesh topologies. This combination results on a star-mesh network that seeks to take advantage of the low power and simplicity of the star topology, as well as the extended range and self-healing nature of a mesh network topology. In this case, nodes serve to sense, extend the range of the network and provide fault tolerance. Since nodes can communicate with multiple other nodes, if a node fails or if a radio link goes down (e.g. due to interferences or lack of battery), the network will reconfigure itself around the remaining nodes.[14]

1.4 WSN Applications:

Regarding the services offered by a WSN, they can be classified into three major categories: monitoring, alerting, and provisioning of information "on-demand". As for the first case, sensor nodes can continuously monitor certain features of their surroundings (e.g. measuring the ambient noise level) and timely send such information to the sink. In the second case, sensors can check whether certain physical circumstances (e.g. a fire) are occurring, alerting the users of the system when an alarm is triggered. In the last case, the network can be queried about the actual levels of a certain feature, providing information "on-demand".[1] The development of wireless sensor networks was originally motivated by military applications such as battlefield surveillance. However, wireless sensor networks are now used in many civilian application areas.[11]

Many other applications fields exploit WSNs as solution to collect data and for the surveillance of any changes that may occur, and deploy this information to build a full view about the previous, current and even future prospects of the situation in the surveilled field. The follows are few examples where a WSN can be integrated.

1.4.1 Military Purpose: it can be an integral part of military command, control, communications, computing, intelligence, surveillance, reconnaissance and targeting systems, detection of mass destruction and explosion and enemy movement, biological, nuclear and chemical attack detection reconnaissance and military situation awareness;

1.4.2 Industry: applications require highly reliable operation in harsh environment, in warehousing, industrial applications, manufacturing monitoring, industrial automation and factory process control;

1.4.3 Environment: these are also widely applied in habitat monitoring, agriculture research includes sensing of pesticide, soil moisture, PH levels, habitat Exploration of Animals, forest Fire and Flood detection, traffic control and ocean monitoring including monitoring of fish;

1.4.4 Home Applications: it will step into our normal life in the future. In home application, sensor node can be embedded into furniture and home appliances, monitoring product quality, managing and monitoring inventory system and automatically control the temperature and airflow of the room;

1.4.5 Healthcare Monitoring and Medical Applications: it is a very hot research topic for industry and academia. The amount of raw data that can be gathered and transported for such application is of the order of 1-10 Mbps. Thus, only useful information is transmitted by using complex algorithms. WSN are also widely used in health care such as monitoring patient physiological data such as blood pressure or heart rate, to control the drug administration, unconsciousness detection, exercise monitoring and noninvasive health monitoring.[15]

1.5 WSN Challenges:

As much as WSNs provide solutions to many problems and it is being used in many different areas, and since the aim is to make it pervasive, a number of difficulties and challenges must be considered. The follows are, not all, but a various of hurdles for WSNs researchers.

1.5.1 Scalable and Flexible Architecture: In the WSNs, the number of sensor nodes deployed may be order of hundred, thousands or millions so that we can easily extend the network size. The communication protocols must be designed in such a manner that deploying many nodes in the network does not affect clustering and routing. In other words, the network must preserve its stability. Introducing more nodes into the network means that additional communication messages will be exchanged, so that these nodes are integrated into the existing network.

1.5.2 Power Consumption: The most important issue to be considered in managing wireless sensors is energy consumption. Replacing or recharging the batteries of sensors is not such an easy task (or might be impossible), in order to achieve efficiency in energy consumption for a longer period; the energy has to be shielded. Nodes are dependent on battery for their power. Hence power conservation and power management are an important issue in wireless sensor network. Due to this reason researchers are focusing on the design of power aware protocols and algorithm for sensors network.

1.5.3 Fault Tolerance and Adaptability: Fault tolerance means to maintain sensor network functionalities without any interruption due to failure of sensor node because in sensor network every node have limited power of energy so the failure of single node doesn't affect the overall task of the sensor network. Adaptable protocols can establish new links in case of node failure or link congestion. Network should be able to adapt by changing its connectivity in case of any fault. In that case, well-efficient routing algorithm is applied to change the overall configuration of network.

1.5.4 Short Range Transmission: In WSNs we should consider the short transmission range in order to reduce the possibility of being eavesdropped. As in long range transmission we need high transmission power due to the point to point transmission between the nodes to reach the destination which increases the chance of being eavesdropped.

1.5.5 Real–Time: Achieving Real-time in WSN is difficult to maintain. It must support maximum bandwidth, minimum delay and several QoS parameters.

1.5.6 Error-Prone Wireless Medium: Since sensor networks can be deployed in different situations, the requirements of each different application may vary significantly. We should consider that the wireless medium can be greatly affected by noisy environments. An attacker interferes knowingly and causes enough noise to affect the communication.[15]

In addition to these hitches, here is a list of few other challenges:

- **Infrastructure.**
- **Production cost.**
- **Hardware design.**
- **Limited computational power and memory size.**
- **Operating environment.**
- **Quality of Service.**
- **Unattended operation.**
- **System Architecture.**
- **Initial connecting process.**
- **Security.[15]**

1.6 Conclusion:

Wireless sensor networks endowed with numerous advantages over traditional wired network, it enables to develop small, low-cost, low power and multi-functional sensing devices. These small sensing devices have the capabilities of sensing, computation, self-organizing and communication and they are used to recognize the phenomena around its environment. This new type of networks is being used in different application scenarios in our life, ranging from daily normal needs to critical applications, such as healthcare and military. Although all these advantages, WSN has to handle serious challenges starting from topology design ending up with different requirements, depending on the applications and use cases.

Chapter Two:
Wireless Sensor Body Area Network

2.1 Introduction:

The advance of civilization and the increased number of elderly populations, especially in large cities and countries, with the appearance of widespread new diseases, also the need of easy and efficient systems in medical sections; all these made the costs of health care exceed the budgets and tighten the noose for patients and even medical services, which also ring the bells about the future prospects.

All these warnings made the scientists and researchers look toward developing new solutions that can respond to the needs of health care, especially with the recent advances in electronics that have enabled the development of small and intelligent (bio-) medical sensors which can be worn on or implanted in the human body. These sensors need to send their data to an external medical server where it can be analyzed and stored. Using a wired connection for this purpose turns out to be too cumbersome and involves a high cost for deployment and maintenance. However, the use of a wireless interface enables an easier application and is more cost efficient[16].

The patient experiences a greater physical mobility and is no longer compelled to stay in a hospital. This process can be considered as the next step in enhancing the personal health care and in coping with the costs of the health care system. Where eHealth (electronic Health) is defined as the health care practice supported by electronic processes and communication, the health care is now going a step further by becoming mobile, this is referred to as mHealth. In order to fully exploit the benefits of wireless technologies in telemedicine and mHealth, a new type of wireless network emerges: a wireless on-body network or a Wireless Body Area Network (WBAN). This term was first coined by Van Dam et al.[17]

A Wireless Body Area Network consists of small, intelligent devices attached on or implanted in the body which are capable of establishing a wireless communication link. These devices provide continuous health monitoring and real-time feedback to the user or medical personnel. Furthermore, the measurements can be recorded over a longer period of time, improving the quality of the measured data.[18]

Mainly, we can arrange the devices in two categories: sensors and actuators. The sensors are used to measure certain parameters of the human body, either externally or internally. Examples include measuring the heartbeat pace and body temperature, etc. The actuators (or actors) on the other hand take some specific actions according to the data they receive from the sensors or through interaction with the user, e.g., an actuator equipped with a built-in reservoir and pump administers the correct dose of insulin to give to diabetics based on the glucose level measurements.[19]

Interaction with the user or other persons is usually handled by a personal device, e.g. a PDA or a smart phone which acts as a sink for data of the wireless devices. In order to realize communication between these devices, techniques from Wireless Sensor Networks (WSNs) and ad hoc networks could be used. However, because of the typical properties of a WBAN, current protocols designed for these networks are not always well suited to support a WBAN.[19]

2.2 WBAN and WSN:

The WBAN as well as the WSN both consists of sensor nodes but the number of nodes in WSN are larger than the number of nodes in the WBAN. Moreover, the area covered by the WSN is larger as in WBAN nodes are implanted near by the body[20]. **Fig. 5** demonstrate the WBAN among other wireless networks.

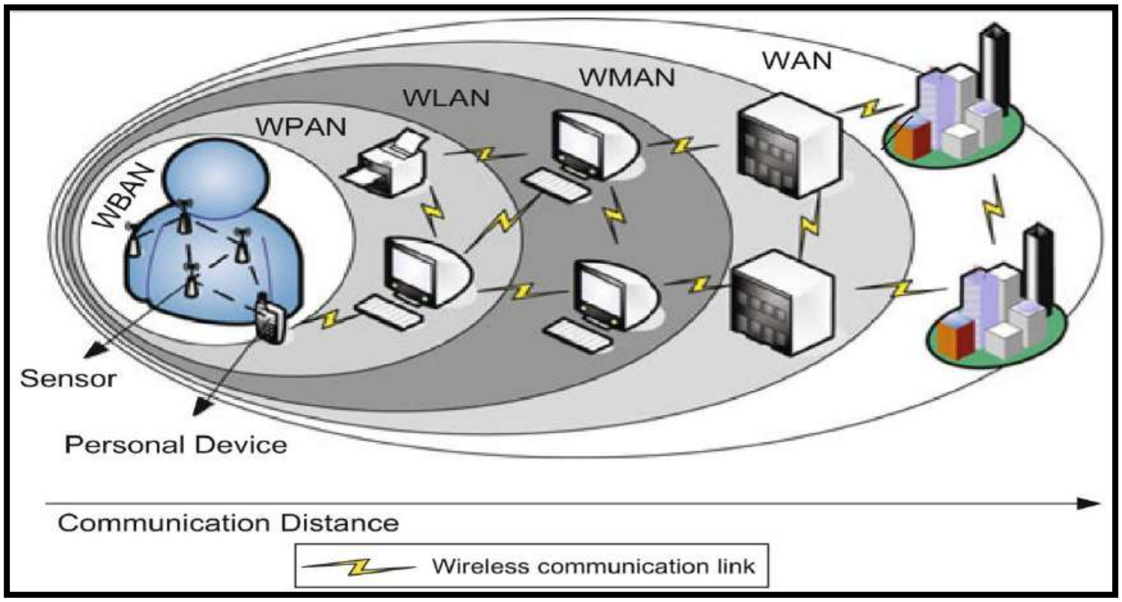


Fig. 5 Positioning of a Wireless Body Area Network in the realm of wireless networks. [19]

Challenges	WSN	WBAN
Node Type	Same i.e. Homogeneous network	Different i.e. Heterogeneous
Area covered	From few m to km	From few cm to m
Number of Nodes	Hundreds to thousands	Tens to hundred
Node Task	Single or dedicate task	Multiple task
End to End delay	Higher Delay	Low delay
Node Replacement	Easily replaceable	Difficult to replace
Node Lifetime	Long Life time	Smaller battery with very long lifetime
Security	Lesser needed	High security required
Data Loss	Tolerated	Can't affordable
Wireless Technology Standard	802.11.4	802.15.6
Mobility	Generally stationary	Mobile (body mobile)

Table. 1 WSN VS WBAN [20]

The **Table. 1** represent few main challenges in networks of wireless sensors and WBANs. The tabular comparison shows that the WBAN is the limited edition of the WSN, and the more constrained, which make it more difficult in the aspect of implementing small electronic devices and suitable algorithms and protocols, that can reduce the energy consumption and build a reliable and efficient network.

2.3 Applications of WBAN:

In order to standardize, enable the pervasion and the ease of use of WBAN advantages, defining the applications of WBAN and classify them was a subject for organizations and researchers worldwide.

2.3.1 The IEEE 802.15.6 (Task Group 6) Classifications:

IEEE 802.15.6 also known as Task Group 6 (or TG6) was formed in November 2007 to address the issues and standardize WBAN. The standard intends to address both medical/healthcare applications and other non-medical applications with diverse requirements. The standard aims to support a low complexity, low cost, ultra-low power and highly reliable wireless communication for use in close proximity to, or inside, a human body (but not limited to humans) to satisfy an evolutionary set of entertainment and healthcare products and services. A typical WBAN structure is shown in **Fig. 6**.[21]

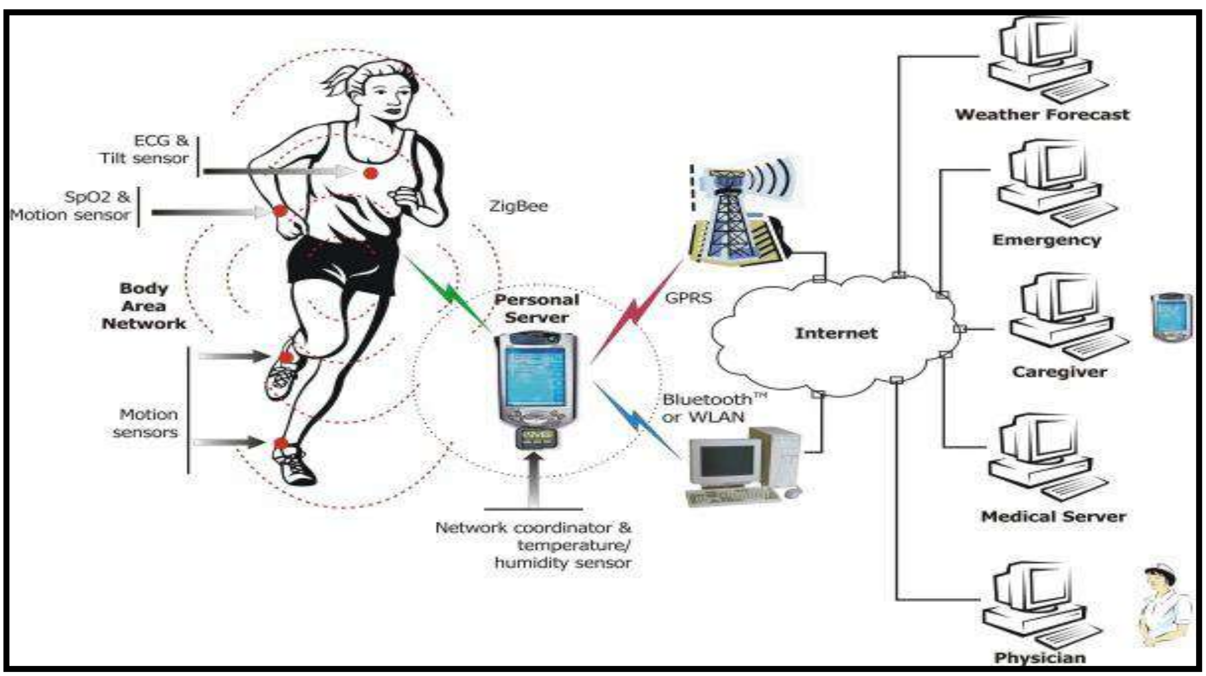


Fig. 6 Typical WBAN structure [21]

The WBAN applications targeted by the IEEE 802.15.6 standard are divided into medical and non-medical applications as given in **Table. 2**.

Category	Type	Application
Medical	Monitoring	Vital signs monitoring
		Respiration monitoring
		Electroencephalogram (ECG)
		pH monitor
		Glucose monitor
	Assistance	Disability assistance
		Blind
		Speech disability
		Artificial hands
Non-medical	\	Video streaming
		Data file transfer
		Sports
		3D videos
		Forgotten things monitor
		Gaming and entertainment
		Social networking

Table. 2 WBAN applications categories with examples [22]

2.3.1.1 Medical Applications:

Medical applications include collecting vital information of a patient continuously and forward it to a remote monitoring station for further analysis. This huge amount of data can be used to prevent the occurrence of myocardial infarction and treat various diseases such as gastrointestinal tract, cancer, asthma, and neurological disorder. WBAN can also be used to help people with disabilities. For example, retina prosthesis chips can be implanted in the human eye to see at an adequate level.[22]

a- Remote Patient Monitoring — This application consists of monitoring a patient’s vital signs, commonly from a hospital or healthcare setting, to provide medical personnel with advice on the patient’s health condition. Traditional patient monitoring devices include electrocardiography (ECG) and blood pressure sensors to monitor heart conditions, electroencephalogram (EEG) to monitor cognitive abilities, respiration and skin temperature sensors to track infections (e.g., fever) or accelerometers to track patient mobility.[23]

b- Patient Rehabilitation — WBANs are important to monitor physical exercises and activities performed by the patient in order to: avoid improper exercises, update exercise complexity, monitor recovery, compare different treatment protocols, enable telerehabilitation. Commonly, the goal of WBANs in rehabilitation is to capture the movements and posture of patients during motor exercise. To this end, accelerometers, gyroscopes, and magnetometers are traditionally used to measure velocity and acceleration of limbs and joints. Those tools have been used predominantly for gait analysis.[23]

c- Biofeedback — According to the Association for Applied Psychophysiology and Biofeedback, biofeedback is the process of using precise instruments to measure physiological activity, and “feed” this biological information “back” to the user, thus allowing the individual to learn how to better control or change this physiological activity in order to improve health and performance. Biofeedback devices can include those that monitor breathing, heart function, muscle activity, and brainwaves.[23]

d- Assisted Living — Assisted living facilities have emerged as an alternative housing facility for people with disabilities (and elderly) who are not considered “independent” but do not need around-the-clock medical care, as in nursing or retirement homes. As such, assisted living promotes independence and dignity (aging in place) whilst reducing medical costs.[23]

2.3.1.2 Non-medical Applications:

Non-medical applications include monitoring forgotten things, data file transfer, gaming, and social networking applications. In gaming, sensors in WBAN can collect coordinates movements of different parts of the body and subsequently make the movement of a character in the game, e.g., moving soccer player or capturing the intensity of a ball in table tennis. Using WBAN in social networking allows people to exchange digital profile or business card only by shaking hands.[22]

a- Fitness, Performance, and Wellness Monitoring — Performance and fitness monitoring tools allow athletes and military personnel to optimize training protocols, thus improving endurance and outcomes and putting them in front of the competition or enemy, respectively. The demand for reliable fitness and wellness monitoring tools has resulted in the burgeoning of wireless devices available in the market.[22]

b- Biometrics — While personal authentication is a topic widely discussed within WBAN medical applications (e.g., encrypt patient data for privacy purposes), here we place emphasis on the use of WBAN-based biometrics for nonmedical purposes, such as banking, accessing secure information/services, or even unlocking a smart phone. Bio-signals such as the ECG (electroencephalogram), EEG (electrocardiogram), and electrodermal activity provide unique biometric signatures which are hard (if not impossible) to steal, copy, forge, or lose. Authentication schemes based on biological signals measured via WBANs are commonly termed “cognitive biometrics.”[22]

c- Serious Gaming — A serious game is defined as a (video) game designed with a primary purpose that is beyond pure entertainment and has the goal of promoting behavioral changes. Serious games have been developed for a plethora of applications in health, education, advertising (also known as advergames), and more recently to promote exercise (known as exergames).[22]

2.3.2 Sensors Classification:

WBANs have great potential for several applications including remote medical diagnosis, interactive gaming, and military applications. **Table. 3** shows some of the in-body and on-body applications [24].

Application Type	Sensor Node	Data Rate	Duty Cycle (per device)% per time	Power Consumption	(Sensitive to Latency) QoS	Privacy
In-Body	Glucose Sensor	Few Kbps	< 1%	Extremely Low	Yes	High
	Pacemaker	Few Kbps	< 1%	Low	Yes	High
	Endoscope Capsule	> 2Mbps	< 50%	Low	Yes	Medium
On-Body Medical	ECG	3 Kbps	< 10%	Low	Yes	High
	SpO2	32 bps	< 1%	Low	Yes	High
	Blood Pressure	< 10 bps	< 1%	High	Yes	High
On-Body Non-medical	Music for Headsets	1.4 Mbps	High	Relatively High	Yes	Low
	Forgotten Things Monitor	256 Kbps	Medium	Low	No	Low
	Social Networking	< 200 Kbps	< 1%	Low	No	High

Table. 3 In-Body and On-Body Sensor Networks Applications [24]

In-body applications include monitoring and program changes for pacemakers and implantable cardiac defibrillators, control of bladder function, and restoration of limb movement. On-body medical applications include monitoring heart rate, blood pressure, temperature, and respiration. On-body non-medical applications include monitoring forgotten things, establishing a social network, and assessing soldier fatigue and battle readiness.[24]

2.4 WBAN Topologies:

For the WBAN, there are two mainly considered topologies in most architectures, star topology (Single-hop topology) and multi-hop topology, where:

A star network — is one in which all nodes are directly connected to the sink. In case of using PDA as a sink, all the nodes will transmit sensed data to the PDA directly without any intermediate.

A multi-hop network — is one where the nodes are connected to the access point possibly through other nodes. Note that, a multi-hop network is very general and also includes cluster-based network topology.[25]

Criteria	Single-hop Network	Multi-hop Network
Energy Consumption	Low for the nodes proximately close to the sink. High in case of the further nodes from the sink.	High for the nodes proximately close to the sink (forwarding data require more energy). low for nodes further from sink.
Transmission Delay	The direct link between node and sink decreases the delay.	Least delay for the closest nodes to the sink.
Inter-user Interference	Sensors that are farther away from the sink will have to transmit with higher power, increasing the amount of interference.	Since each node is only transmitting to its neighbor nodes, the energy of transmission is kept low and hence mitigates the effects of interference.
Node Failure	Only the failed node will be affected and the rest of the network can perform as needed.	The part of the network that involves the failed node has to be reconfigured. Overheads are involved

Table. 4 Comparison of Different Architectures [25]

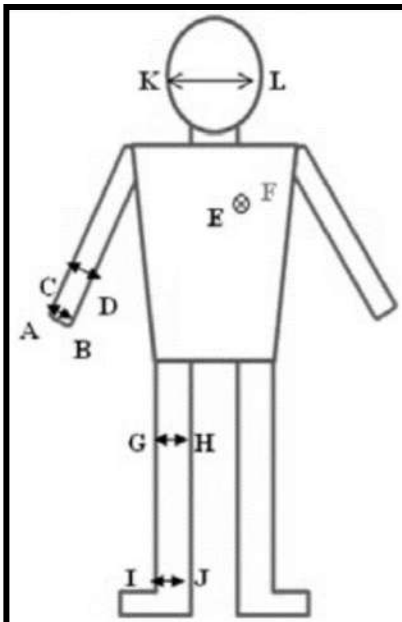
The **Table. 4** giving us a clear comparison between these two topologies in terms of: energy consumption, transmission delay, inter-user interference, node failure.

In the star topology, there are two communication methods: Beacon method, Beacon-less method.

Beacon method — where communication is controlled by the network coordinator, which transmits beacons for device synchronization and network association control. The network coordinator defines the start and end of a super frame by transmitting a periodic beacon. The length of the beacon period and hence the duty cycle of the system can be defined by the user between certain limits.[26]

Beacon-less method — in this case, a network node can send data to the coordinator, by using CSMA/CA if required. To receive the data from the coordinator, the node must power up and poll the coordinator. The advantage of non-beacon mode is that the node's receiver does not have to regularly power-up to receive the beacon. The disadvantage is that the nodes must wake up to receive the beacon and the coordinator cannot communicate at anytime with the node but must wait to be invited by the node to communicate.[26]

In [27], the authors resulted that the path loss between the point inside a human body and the point outside a body is almost the same as the path loss measurements among two points outside the body, by transmitting a signal through some parts of the body as shown in **Fig. 7**.



Link	Description
A - B	Through the hand
C - D	Through the wrist
E - F	Torso, front to back
G - H	Through the thigh
I - J	Through the ankle
K - L	Left ear to right ear

Fig. 7 Typical WBAN structure [27]

2.5 Routing Protocols in WBAN:

2.5.1 Routing Protocols Challenges:

The routing protocols that are used in WSNs have been under study for past few years, these protocols cannot be used for WBANs due to its stringent requirements. For WSNs, the main focus is on minimal routing overhead and maximal throughput than reduced energy consumption. Also, WSNs are mostly homogenous networks, the WBANs are heterogeneous too.[28]

In order to identify the important metrics that have to be considered in WBANs during the design process, a general overview about the routing challenges in WBANs should be studied. The certain routing issues and challenges include network topology, postural body movements, limited resources, quality of service metrics, radiation and interference, global network lifetime, heterogeneous environment, node temperature, etc.[28]

The design challenges of WBANs routing protocols involve many aspects due to diverse characteristics of the WBANs environment. The main aspects are summarized as following[29]:

2.5.1.1 Limited Energy Capacity: Although biosensors can be removed from their operation site to be recharged (hard task and not always applicable), or recharged by external IR radiation, energy consumption is an important constraint for WBANS. Because the frequent recharging of batteries is not a desirable task and the radiation can damage the health of the patient, therefore WBAN routing protocols should be energy aware.

2.5.1.2 Limited Hardware Resources: In addition to the power consumption constraint, biosensor nodes are also constrained by their limited processing and storage capacities. For example, when a large data is transmitted via tiny sensor devices, the network lifetime will rapidly decrease. Therefore, in WBANs, serious problems can occur if the device characteristics are not reflected and considered in the routing algorithm.

2.5.1.3 Operating Environment: Biosensors are worn on or implemented in the human body which may increase the loss medium for propagated waves.

2.5.1.4 Dynamic Network Topology: The WBAN network topology may change frequently because it is very depended to the patient's movement, thus network protocols should treat mobility in their design phase.

2.5.1.5 QoS Requirements: as WBANS are made up out of very heterogonous devices, routing algorithms must support heterogonous traffic and temporally differentiated QoS requirements.

2.5.1.6 Security and Privacy: the forwarded data consists of medical data so routing protocols must ensure data privacy and confidentiality.

Therefore, the most challenging issue is how to combine low duty cycle scheduling and minimum energy route in order to maximize the lifetime of the WBAN network and to satisfy QoS requirements for different WBAN applications.[29]

2.5.2 Routing Protocols Classification:

The classification of routing protocols can be done in different categories that correlate with the routing challenges of WBAN. The existing protocols can be categorized as Cluster-based, Cross layer, Postural aware, quality of services (QoS) aware and Temperature-aware routing algorithms. The **Fig. 8** gives a classification of a number of routing protocols developed for WBAN.[28]

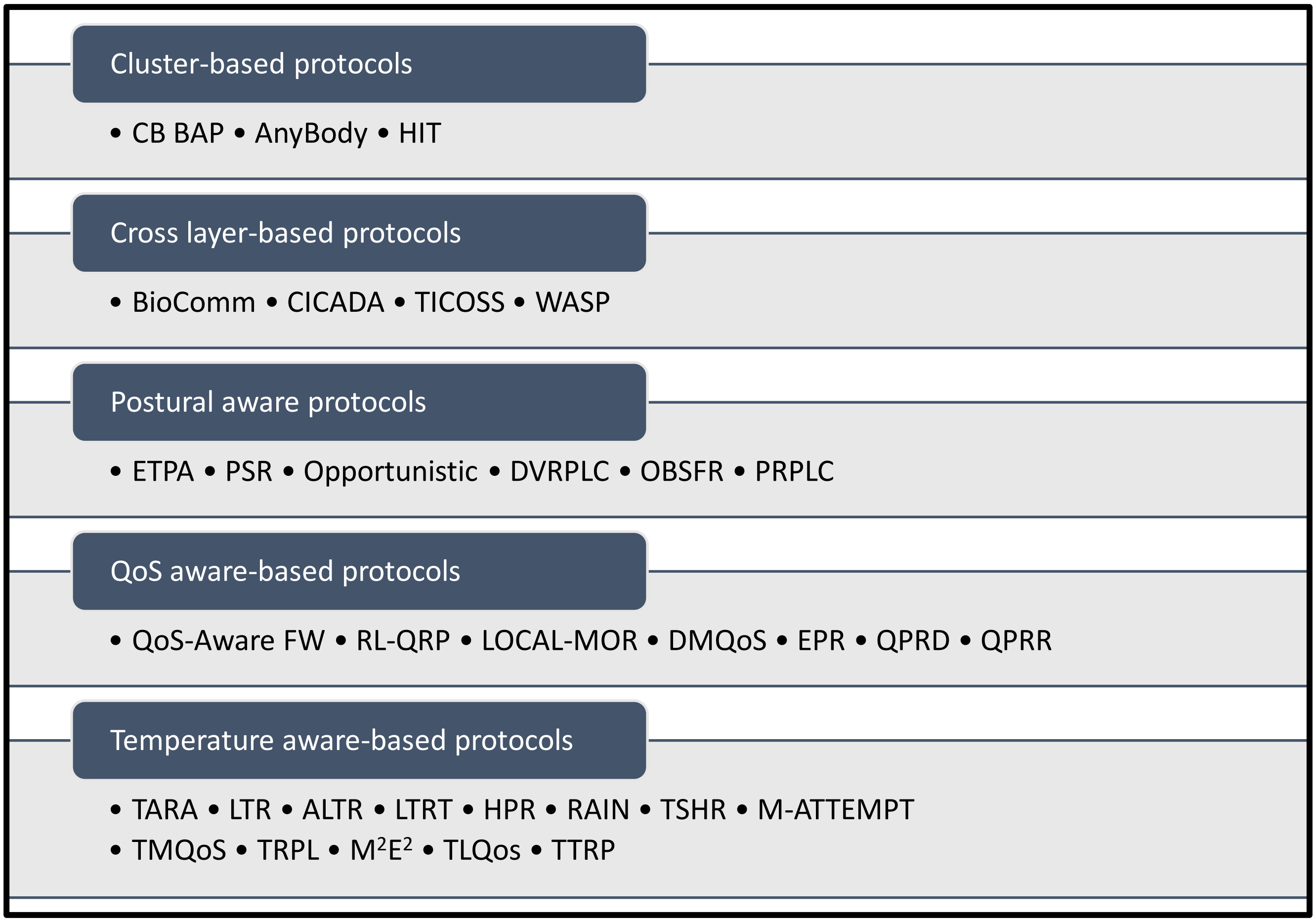


Fig. 8 Classification of well-known routing protocols in WBAN.[30,31]

2.5.2.1 Cluster-based Protocols: In both WSNs and WBANs, the limited energy source is the main constraint to be analyzed. Hence, several efficient cluster-based schemes are proposed for both networks to minimize the power consumption and maximize the network lifetime. The bio-medical sensor nodes or sensing nodes are divided into one or more clusters and different methods are used to select one of nodes of the specific cluster, as a Cluster Head (CH) and the data is sent to the sink (base station) through these CHs to reduce the direct communication between the sensing nodes and the sink.[28,30]

The number of clusters may remain the same if some nodes are added to the network, which is the case of AnyBody[32], or it can increase when new nodes are introduced into the network, such as the LEACH[33] protocol may end up creating new clusters in this case.

2.5.2.2 Cross layer-based Protocols: Protocols like WASP, TICOSS and many other ones, address and try to solve the issue and challenges of both network and MAC layers at the same time where each layer (adjacent or non-adjacent) in the protocol stack shares their information unlike in the strict layered model, thereby we can optimize the overall network performance. Although this topic has gained the attention of WSNs researchers, it is an emerging area of research in WBAN.[28,29,30]

2.5.2.3 Postural Aware Protocols: The network topology of WBSNs or the link between two nodes often faces the problem of partitioning or disconnection because of the body postural movements. In this class of WBSNs routing protocols, different researchers have tried to solve the problem of link disconnection by defining a cost function, which is updated periodically, such as in Opportunistic, OBSFR, PRPLC. These protocols choose routes from the bio-medical sensor nodes to the base station with minimum cost to forward the data packets.[30]

2.5.2.4 QoS Aware Protocols: Presently, there are a number of diverse QoS aware protocols available in WSNs, including QPRR, DMQoS, QPRR or EPR. Yet, these cannot be as such implemented in WBANs, but by considering its unique curbs it can. The common criteria taken into account for achieving QoS are status of the wireless channel, network traffic, effectiveness of each node in terms of transmission and reception of data, priority assigned to data to be transferred and many more. The metrics considered for measuring the effectiveness of a routing protocol are end-to-end delay, packet conveyance proportion and overall power consumed for routing process.

2.5.2.5 Temperature Aware Protocols: Among important issues that should be considered in wireless transmission around and on human body are heating effects on the body and radiation absorption. The antenna radiation, its absorption and interference are the major challenges to be considered while designing a body sensor network, because electric and magnetic fields are generated due to the radio signals used in wireless communication, will result in temperature rise and this will affect temperature sensitive organs of human body by reducing the blood flow, growth of certain tissues, enzymatic reactions and might damage the surrounding tissues if in place for long periods of time.[28,29,30] And for that we have several proposed protocols, like TARA, LTR, ALTR, RAIN.

2.5.2.6 Other classification: because of the diverse criteria, there are specific constraints to be considered while working on network implemented in sensitive environment such as a human body and different metrics used to classify the routing protocols for WBAN application, other classification can be Energy-aware, Link-aware, Mobility-aware, Delay tolerant aware, Medium Access Control, etc.[31,34,35]

2.6 Conclusion:

Concluding this chapter, we have defined the WBANs and stated the needs that led to introduce this concept and how is it different from WSN like the covering area of WBAN. In order to understand the role of WBAN, we have listed a variety of applications and how are they classified to highlight the challenges in WBANs, such as IEEE 802.15.6 and different types of sensors classifications.

One of these challenges is the topology used for the network, where the in vivo environments tend to be unstable and include movements, therefore using star or multi-hop topologies is related to the application needs. Since the routing protocols used in WSN cannot fulfil the requirement, the protocols proposed for WBAN application focus on one or two challenges to work on, we arranged few of them to cluster-based ones, cross-layer, postural-aware, QoS-aware, thermal-aware, and so on.

PART B:
-Contribution-

Chapter Three:
LTR Protocol Implementation, Simulation and Results

3.1 Introduction:

For the WBAN applications the antenna radiations are likely to damage the tissue or the organs because of the heat resulted by wireless communications. Therefore, the temperature produced by the sensors should be listed as an important point to discuss while studying and implementing the routing algorithms and protocols due to radiations generated (RF-Radio Frequency) by the wireless antenna that rise the temperature of the tissue since the body absorb the waves.

First proposed protocol that is thermal-aware was TARA (Thermal Aware Routing Algorithm) in [36]. After that, many other different researchers contributed to come up with more efficient protocols that consider the temperature while routing data, and solve the heating issue.

In order to analyze the thermal-aware routing protocol LTR performance, we intended to use a simulator to test LTR functionality and examining the effectiveness of using Single or Dual Sink. Simulation process helped to come out with clear sight of the results under several applications.

3.2 Least Temperature Routing (LTR) Protocol:

Least Temperature Routing (LTR) was proposed by researchers in [37] as a solution algorithm for routing protocols that are thermal-aware and can be efficient for WBANs. This algorithm is capable of reducing the amount of heat produced in the network. To simplify the idea, the algorithm routes packets to the coolest neighbor without falling in routing loops. The proposed algorithm performs much better in terms of reducing the amount of heat produced, delay and power consumption compared to the other non-thermal aware protocols.

3.2.1 LTR Algorithm Description:

Setup phase:

This is the startup configuration phase, where all the nodes communicate with the neighbors and collect information about their temperature and build a list of neighboring nodes, by sending a HELLO packet that holds the node information, as we can see in the **Fig. 9**.

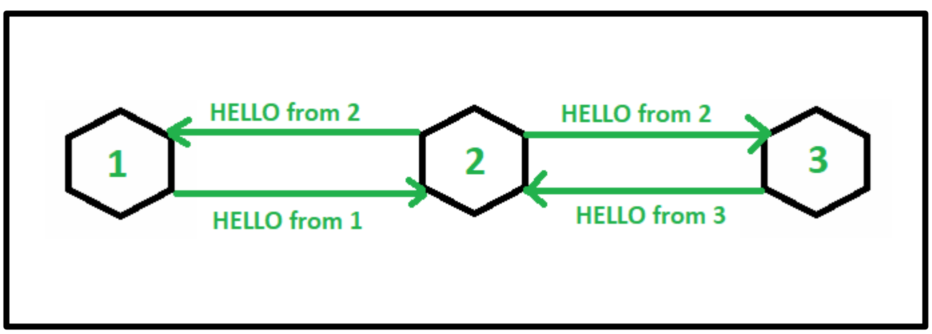


Fig. 9 HELLO packet broadcasting for setup phase

Routing packets:

Each node has to handle two types of packets; those are generated locally due to events sensed by the node itself and the ones received from other nodes. Both types of packets are handled in the same way, If the destination node of the packet is a neighbor node, the packet is forwarded directly to its destination node. Also, we are assuming that each node has the information about its neighboring nodes. So, in case the destination is not a neighboring node, the packet will be forwarded to the node having the least temperature among the neighbors, or “coolest neighbor”.

Packet discard:

All the data packets transmitted in the network maintain a hop-count variable, and it gets incremented each time a node forwards that packet. This hop-count is checked by every node receiving the packet (except for the sink node) then compare it to the threshold value MAX-HOPS, and if it is above that value, the packet is discarded. The value MAX-HOPS is related to the size of the network.

Reducing unnecessary hops and loops:

The packet holds a small list of recently visited nodes and if the next hop (coolest neighbor) is already there in that list, the next hop will become the node having second lowest temperature among the neighboring nodes and so on. Similarly, the same action of choosing the node having the second lowest temperature if the “coolest neighbor” is a leaf node. The list of recently visited nodes should be updated always whenever a node receives that packet before forwarding it again. **Fig. 10** shows the cases when we switch to 2nd coolest neighbor.

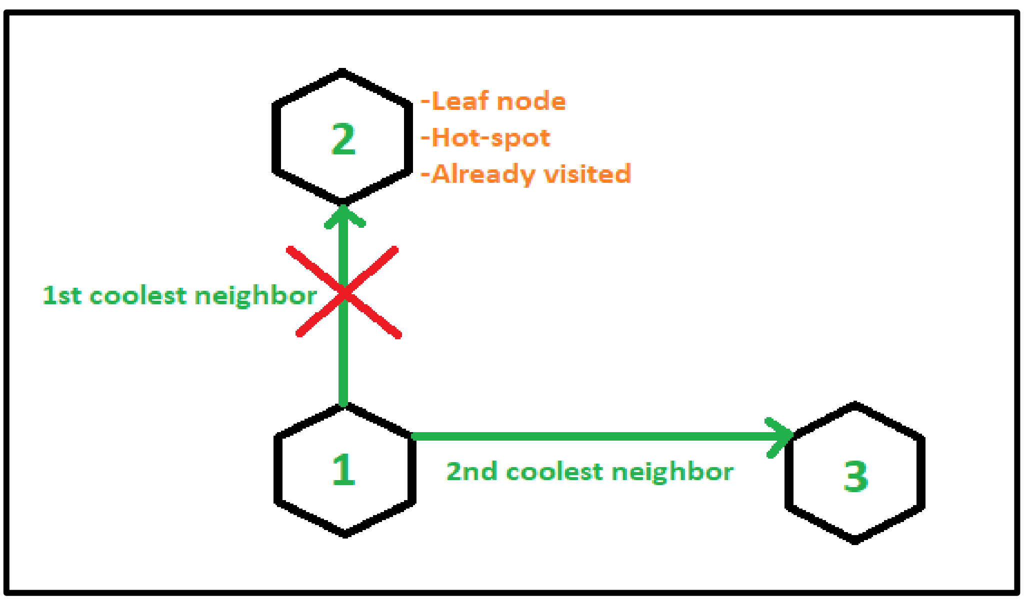


Fig. 10 Cases of choosing the 2nd coolest neighbor

Fig. 11 is a scheme that resume the process of handling a packet within LTR protocol starting from when it is received until it gets transmitted or discarded. It is also shown that the node will check if the destination of the packet is the node itself, and this action is performed only when the node is not the source (generator) of the packet.

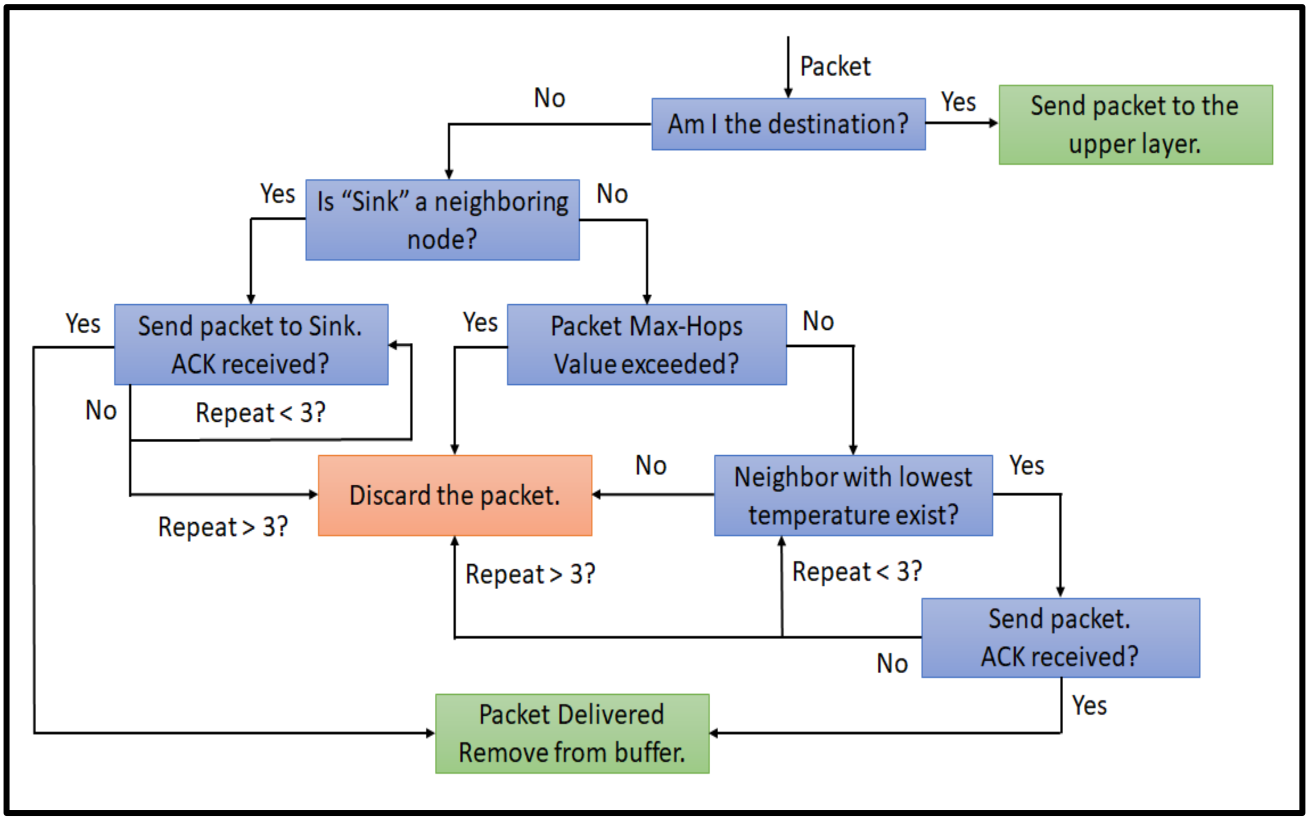


Fig. 11 Scheme of packet handling within LTR protocol

3.3 "Dual Sink" Approach for Performance Enhancement:

In the general scenario, the packet will keep roaming in the network randomly following the path of nodes having less temperature, until it reaches the Sink node or it will be dropped in case the MAX-HOPS exceeded. Therefore, we can conclude that using "Dual Sink" may increase the chances for the packet to reach one of the Sink nodes before reaching the limit of MAX-HOPS and reduce the number of loops, which signify to reducing the heat generated by transmitting the packets as well as saving more energy and extending the network lifespan.

3.4 Simulation Tools:

To run the simulation and test the performance of the LTR protocol, we used Castalia project within OMNeT++ simulator and examined the advantages and downside of using Single Sink or Dual Sink solution.

3.4.1 OMNeT++ 4.6 Outlines:

OMNeT++ is an extensible, modular, component-based C++ object-oriented modular discrete event network simulation framework. It has a generic architecture, so it can be used in various problem domains:

• modeling of wired and wireless communication networks

• protocol modeling

• modeling of queueing networks

• modeling of multiprocessors and other distributed hardware systems

• validating of hardware architectures

• evaluating performance aspects of complex software systems

• in general, modeling and simulation of any system where the discrete event approach is suitable, and can be conveniently mapped into entities communicating by exchanging messages.

Although OMNeT++ is not a network simulator itself, it has gained widespread popularity as a network simulation platform in the scientific community as well as in industrial settings, and building up a large user community, because it provides infrastructure and tools for writing simulations. One of the fundamental ingredients of this infrastructure is a component architecture for simulation models. Models are assembled from reusable components termed modules. Well-written modules are truly reusable, and can be combined in various ways like LEGO blocks. [38]

3.4.2 OMNeT++ 4.6 Modeling Concept:

An OMNeT++ model consists of modules that communicate with message passing. **Fig. 12** represent the UML composite structure diagram of the active modules which are termed simple modules (gray background); they are written in C++, using the simulation class library. Simple modules can be grouped into compound modules and so forth; the number of hierarchy levels is unlimited. The whole model, called network in OMNeT++, is itself a compound module. Messages can be sent either via connections that span modules or directly to other modules (arrows).

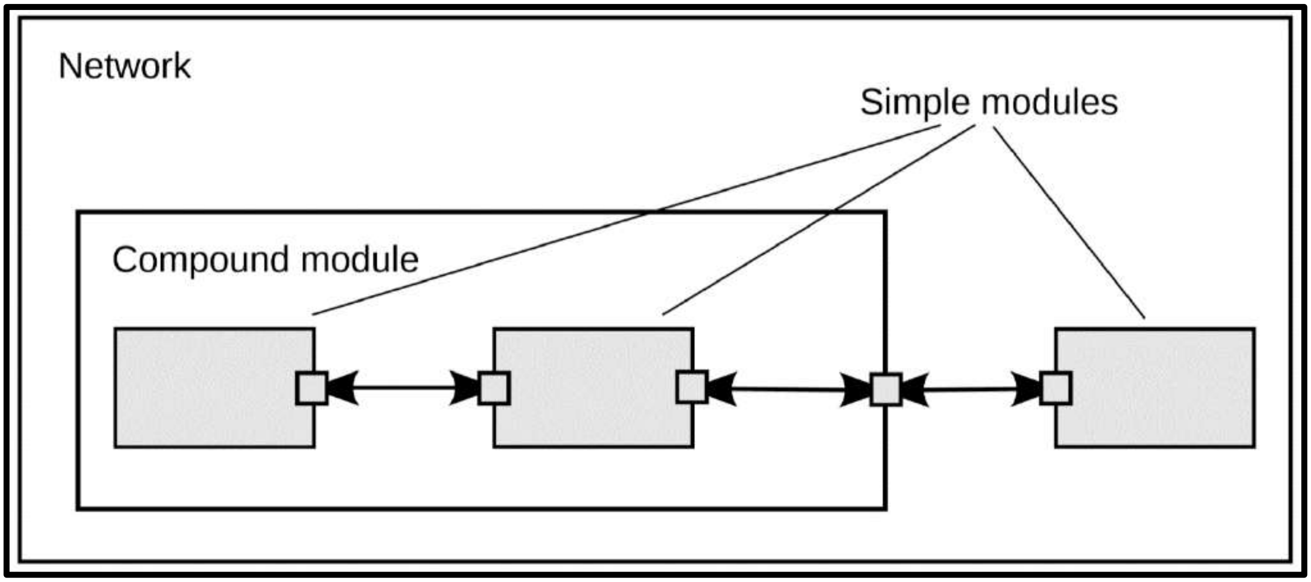


Fig. 12 Simple and compound modules [38]

OMNeT++ provides efficient tools for the user to describe the structure of the actual system. Some of the main features are the following [38]:

- Hierarchically nested modules
- Modules are instances of module types
- Modules communicate with messages through channels
- Flexible module parameters
- Topology description language

3.4.3 Castalia 3.2 Overview:

Castalia is project under OMNeT++ platform and used for the simulation of Wireless Sensor Networks (WSN), Body Area Networks (BAN) and generally networks of low-power embedded devices. It allows the researchers and developers who want to test their distributed algorithms and/or protocols in realistic wireless channel and radio models, with a realistic node behavior especially relating to access of the radio. Castalia can also be used to evaluate different platform characteristics for specific applications, since it is highly parametric, and can simulate a wide range of platforms. Castalia was designed right from the beginning so that the users can easily implement/import their algorithms and protocols into Castalia while making use of the features the simulator is providing.[39]

3.4.4 Castalia's General Structure:

The **Fig. 13** representing Castalia's basic module structure. Notice that the nodes do not connect to each other directly but through the wireless channel module(s). The arrows signify message passing from one module to another. When a node has a packet to send this goes to the wireless channel which then decides which nodes should receive the packet.[39]

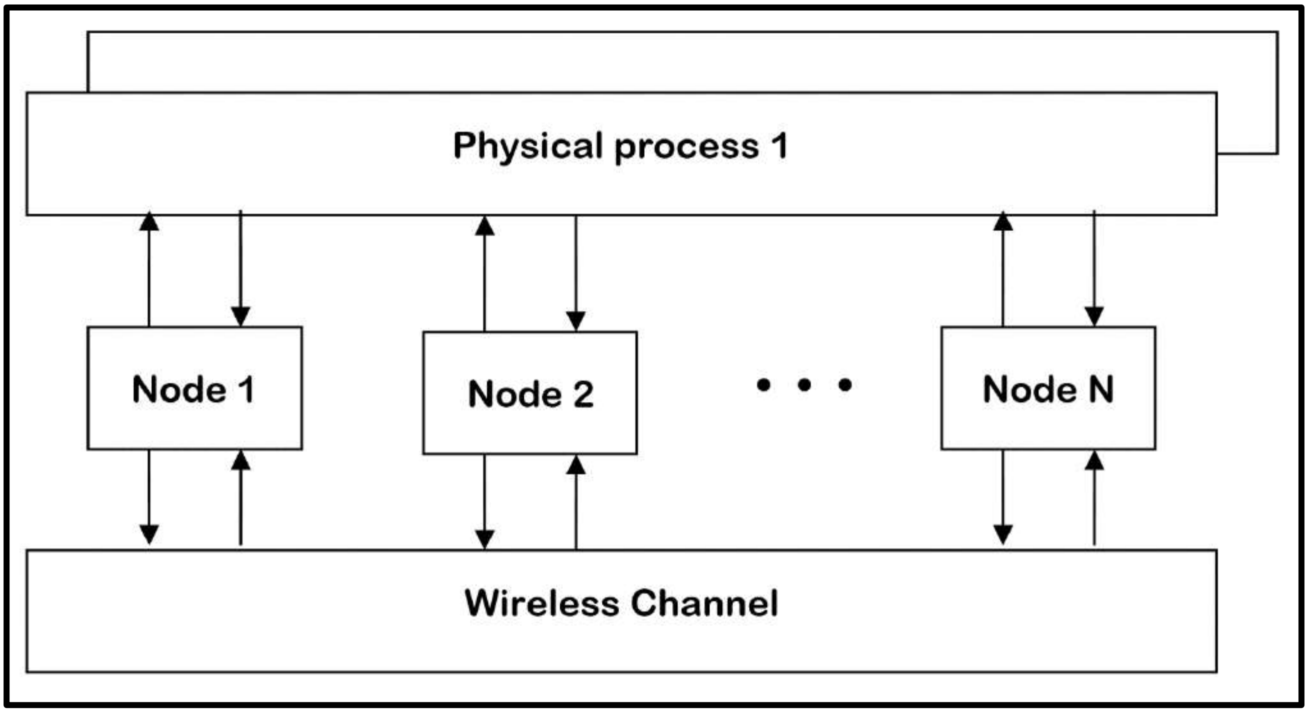


Fig. 13 The modules and their connections in Castalia [39]

3.4.5 The Node Architecture:

The node module is a composite one. **Fig. 14** shows the internal structure of the node composite module. The solid arrows signify message passing and the dashed arrows signify simple function calling. For instance, most of the modules call a function of the resource manager to signal that energy has been consumed. The communications MAC and Routing modules, as well as the Mobility Manager module, are candidates for change by the user, usually by creating a new module to implement a new protocol or mobility pattern. Castalia offers support for building your own protocols, or applications by defining appropriate abstract classes.[39]

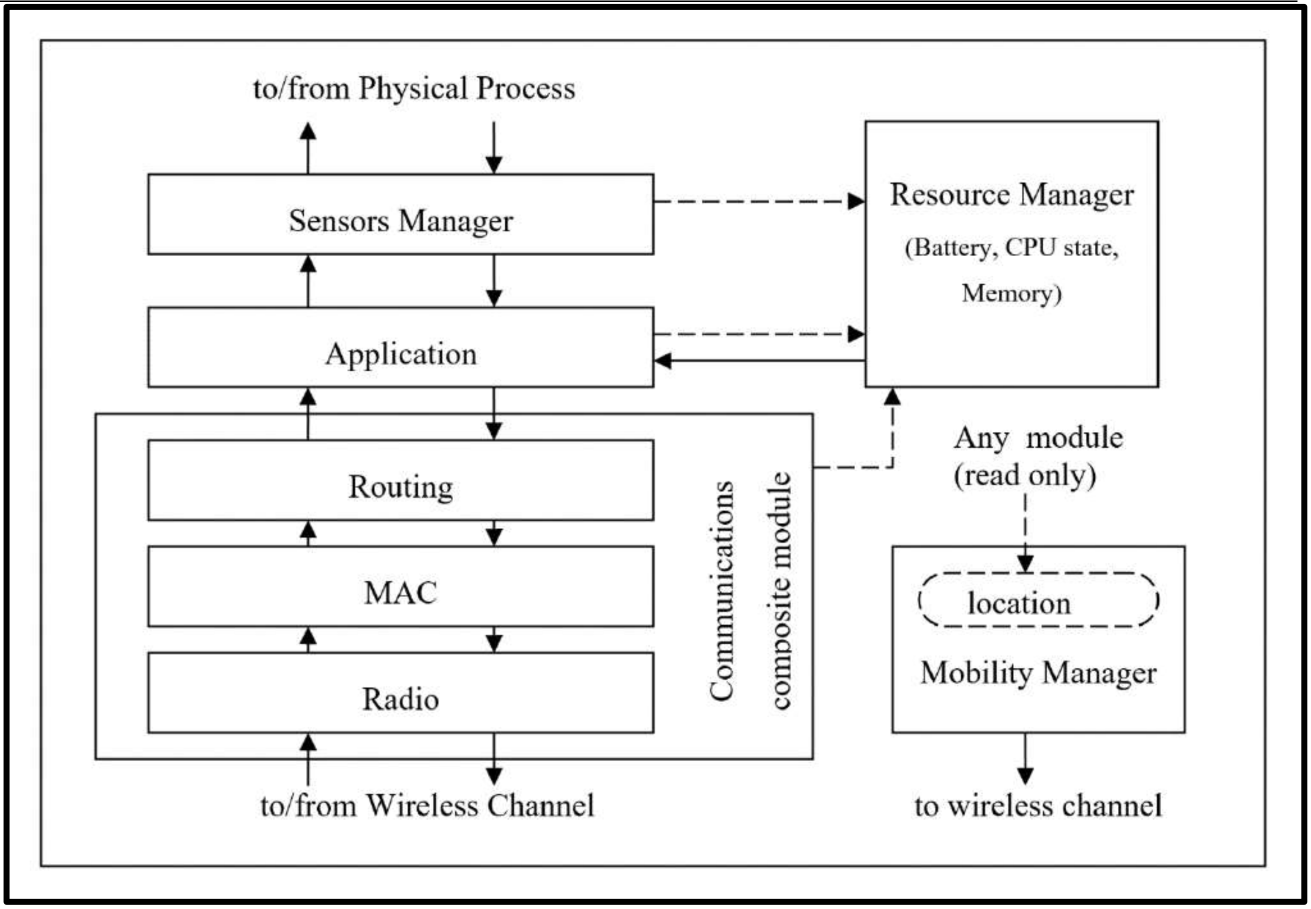


Fig. 14 The node composite module [39]

3.5 LTR Implementation:

In order to simulate the LTR behavior with "Single Sink" and "Dual Sink" we started by implementing the protocol as described in [37], running with a Single Sink, then we made the necessary changes to support Dual Sink. The updates basically were in the Routing and MAC layers (**Fig. 14**) of the Communications composite module, inside the node of Castalia.

3.5.1 Single Sink:

The routing layer of a node module is represented by the folder labelled routing inside communication folder along with mac and radio. Routing folder contains the class *VirtualRouting.cc*, and other available routing protocols, each inside its specific folder, and all the protocols should inherit from *VirtualRouting.cc*, and LTR is not an exception. LTRRouting folder contains the class *LTRRouting.cc*, that store the core functionalities of LTR protocol. Methods of *LTRRouting.cc* are implemented as following:

```
class LTRRouting: public VirtualRouting {
	void startup();
	void fromApplicationLayer(cPacket *, const char *);
	void fromMacLayer(cPacket *, int, double, double);
	void delayedToMacLayer(cPacket *, int, double);
	void timerFiredCallback(int);
	void finish();
	void sendHelloMessage();
	void handleRadioControlMessage(cMessage *);
	void handleNetworkControlCommand(cMessage *);
	void updateNeighborTemperature(int);
	void decreaseNeighborsTemperature();
	void reportLatency(int, double);
	void countReceivedPkt(LTRRoutingPacket *);
	bool isDuplicatedPkt(LTRRoutingPacket *);
	int insertInTheQueue(LTRRoutingDataPacket *);
	NodeTemperature leastTemperatureNeighbor(NodeTemperature,list<NodeTemperature>);
	string firstHop(string);
	string nextHop(vector<string>, string);
	list<NodeTemperature> CreatNotVisitedList(vector<string>);
	bool isDestinationANeighbor(const char*);
	bool neighborExist(int);
	void addNeighbor(int);
	bool isWithdrawnPacket(vector<string>);
}
```

The method **`startup();`** is the first method to be executed. It is where all the variables used in this class are being initiated, such as `list<NodeTemperature> listOfNeighbors {};` this list represents neighboring nodes for each node, along with their temperature. Also, **`startup();`** calls the method **`sendHelloMessage();`** and send a `LTRRoutingHelloPacket` to exchange the initial temperature of nodes and build the neighboring list when the node is activated for the first time. A `LTRRoutingHelloPacket` carry the information whether it is sent by Sink or normal node. Whenever a node receives a HELLO packet made by a Sink, it will forward it again to all the neighboring so all the nodes will know the address of the Sink and store it to make it the destination of all the future data packets.

When a packet is generated a by the node and then received in the routing layer, the method **`fromApplicationLayer`** is the first action to be triggered, and by the help of other methods, it will decide which node is the next hop and if it is the destination (Sink node) is a neighbor then it will be forwarded directly, otherwise it will select a relay node from the neighbors based on the temperature criteria. On the other hand, when a packet is received from another neighboring node, **`fromMacLayer`** is the method that response to this event and we have in this case two possible scenarios: first one is when the receiving node itself is the destination, in other words the Sink, then we just forward it up to the upper layer which is the Application.

In case of the second scenario, and when the receiving node is not the destination, then it will try to forward it to the coolest node form the neighboring list. If all the neighboring nodes are marked as hot-spots, or the node has no neighbors except the sender of the packet, then it will just send it back to the sender, to restart the process of sending the packet again to the node having the second lowest temperature.

For the acknowledge (ACK) mechanism of the packets that are sent by the nodes, we use a passive scheme to reduce the control overhead, that means when a node forwards a packet that is received from the previous node, this forwarding will be the ACK for the previous node. See **Fig. 15.**

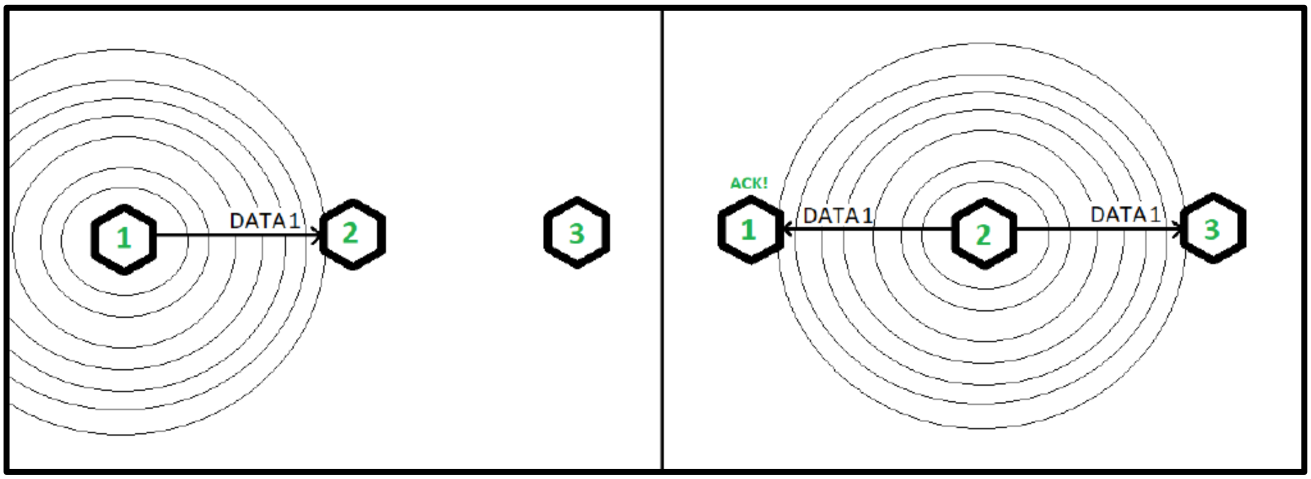


Fig. 15 Passive ACK Mechanism

When a node sends data packet and doesn't receive ACK after a time interval -that is related to the network size-, it will re-forward the packet again after re-selecting the coolest neighbor. And if a node doesn't receive ACK from a neighbor after three attempts, it will take it off the neighbors list, until it receives a packet from that node, that time it will add that neighbor again.

3.5.2 Dual Sink:

In case of Dual Sink approach to be supported, LTR protocol functions almost remain the same, we just make small changes so every node will always store the address of the two sink nodes. The usual way to store the sink address node is using a variable `Sink_ID`. So, in our case we will just add another variable to memorize the both addresses, which is going to be `Sink_1_ID` and `Sink_2_ID`.For all nodes, except the sinks; whenever they receive a packet to forward it, they check in their neighbor lists if any sink node is a neighbor so they just forward it directly, otherwise the usual method of sending the packet to the coolest neighbor form the list of neighbors.

3.6 Simulation Environment Parameters and Testing Metrics:

3.6.1 Environment and Parameters:

As we mentioned before, we used Castalia 3.2 within OMNeT++ 4.6 to simulate the scenarios where we use the LTR protocol and test the performance of LTR with Single or Dual Sink. we simulated with two different setups, where in the first one, as we can see in **Fig. 16** and **Fig. 17,** we have 30 nodes that generates data packets plus a Single Sink or Dual Sink in 8x4 Regular Mesh deployment where each node is connected to all adjacent neighbors.

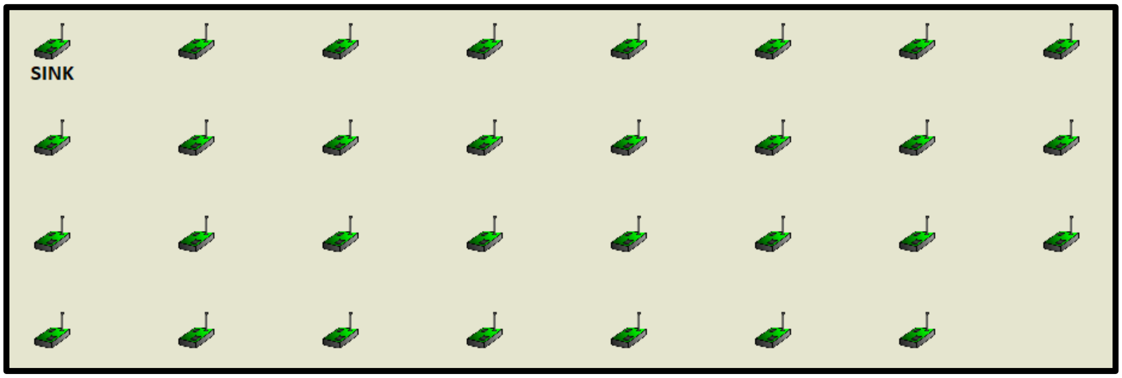


Fig. 16 8x4 Regular Mesh Deployment with Single Sink

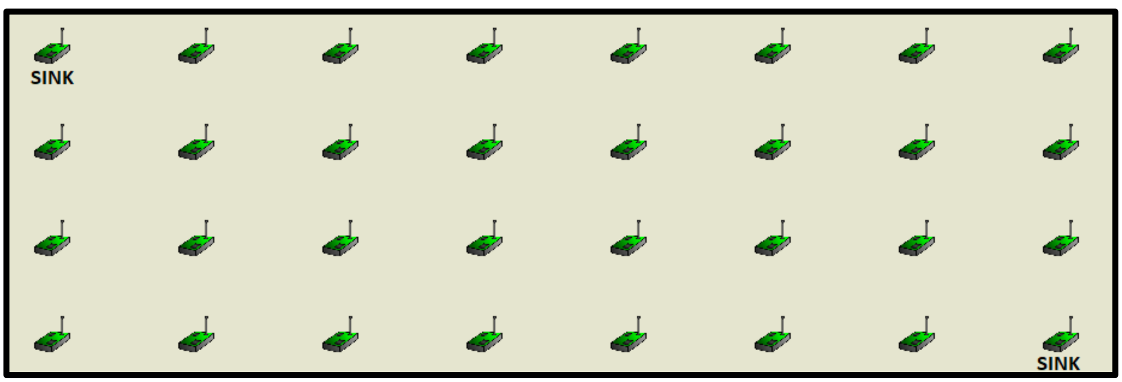


Fig. 17 8x4 Regular Mesh Deployment with Dual Sink

The other two setups have 98 nodes, all distributed randomly in a rectangular field which will help us test the protocol scalability. First setup with Single Sink and the second one has a Dual Sink. **Fig. 18** and **Fig. 19** illustrates these setups for the both configurations, the Sink nodes are positioned in the edges of the field and doesn't sense any data, just receiving data flow from the rest of the nodes.

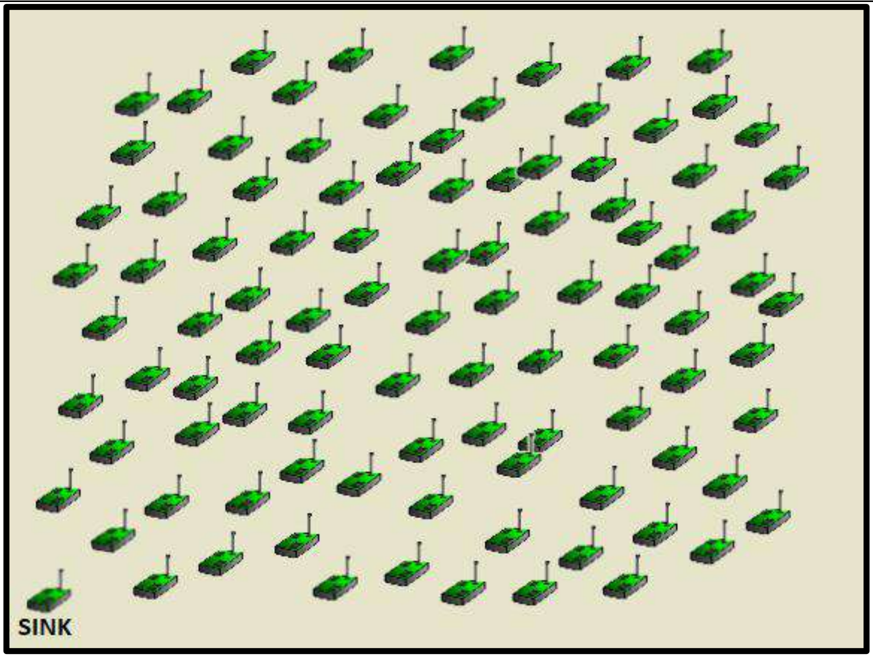


Fig. 18 Random Nodes Deployment with Single Sink

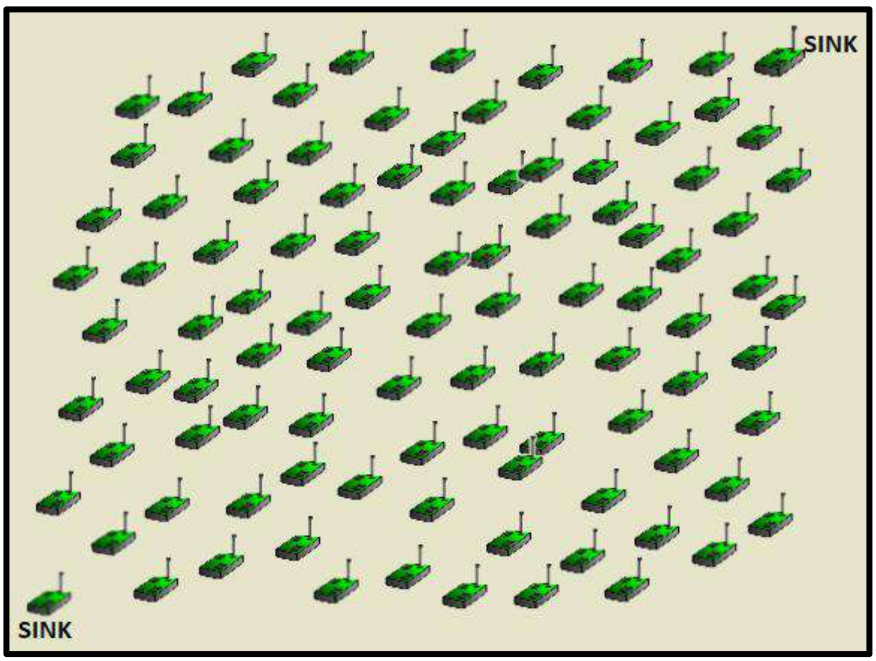


Fig. 19 Random Nodes Deployment with Dual Sink

There are some applications such as sports athletics or movie actors preforming CGI (Computer-generated imagery) characters, or even animals with big body sizes like the blue whale or elephants, where they have to use huge number of sensors. Also, we can mention the Inter-BAN applications, where many bodies are considered as nodes that can transmit data forming a network.

To compare between the efficiency of using Single or Dual Sink, we varied the number of packets generated per second for each node in the network and collected the results from the two different setups, Single and Dual Sink. we did the same for the temperature threshold, we varied the limit of temperature that all nodes should not exceed and examined the results. This both factors can impact the LTR functionality either for better or for worse. In **Table. 5** bellow we resume the rest of the main parameters used for our simulations.

Parameter Name	8x4 Regular Mesh Deployment	Random Deployment
Radio Model	BANRadio	
Power of Tx	-20dBm	
MAX-HOPS	40	
Temperature Threshold	[100 ; 400 ; 800 ; 1300 ; 1750 ; 2000 ; 2300 ; 2750] Packets	
Temperature Rise	1 Temperature Unit for each routed packet	
Node Cooling Rate	1 Temperature Unit / Second	
Routing Power Consumption	2 mJoule / Packet received or transmitted	
Idle Listening Power Use	1 mJoule / Second	
Packets Generating Rate	[0.5 ; 1 ; 1.5 ; 2 ; 2.5 ; 3] / Second	
Number of Sensor Nodes	30	98
Simulation Duration	250 second	130 second
Total Generated Packets	[3750;7500;11250;15000;18750;22500]	[6370;12740;19110;25480;31850;38220]
Field Diameter	16x8 m	25x25 m

Table. 5 Main Parameters Used for the Simulation

3.6.2 Evaluation Metrics:

Several metrics, as listed below; are considered in our testing to evaluate and compare the performance of both settings, Dual and Single Sink:

1- **Average Temperature Rise:** The heat produced by all the nodes in the whole network is measured then calculate the average.
2- **End-to-End Delay:** The necessary time for packets to reach the destination starting from the source. This time is calculated in the routing layer, so application latency is not included.
3- **Average Energy Consumption:** We extracted the value of the energy consumed by all the nodes then we calculated the average of consumption over all the network.
4- **Packet Delivery Ratio:** This metric represents the number of packets received by the Sink from all the nodes in the network.

3.7 Results and Discussions:

3.7.1 8x4 Regular Mesh Deployment:

The main reason of choosing this deployment method, is the fact that minimum number of neighbors will be 3 and maximum will be 8 and also their positions are already known before starting the simulation.

Varying the Samples Interval in 8x4 Regular Mesh Deployment: Generally, the number of packets generated by a node in a time interval, affect the LTR performance. The curves and histogram below giving us a general look to the results we have got from the simulation, where number of packets generated by each node vary between 0.5, 1, 1.5, 2, 2.5, 3 packets per second.

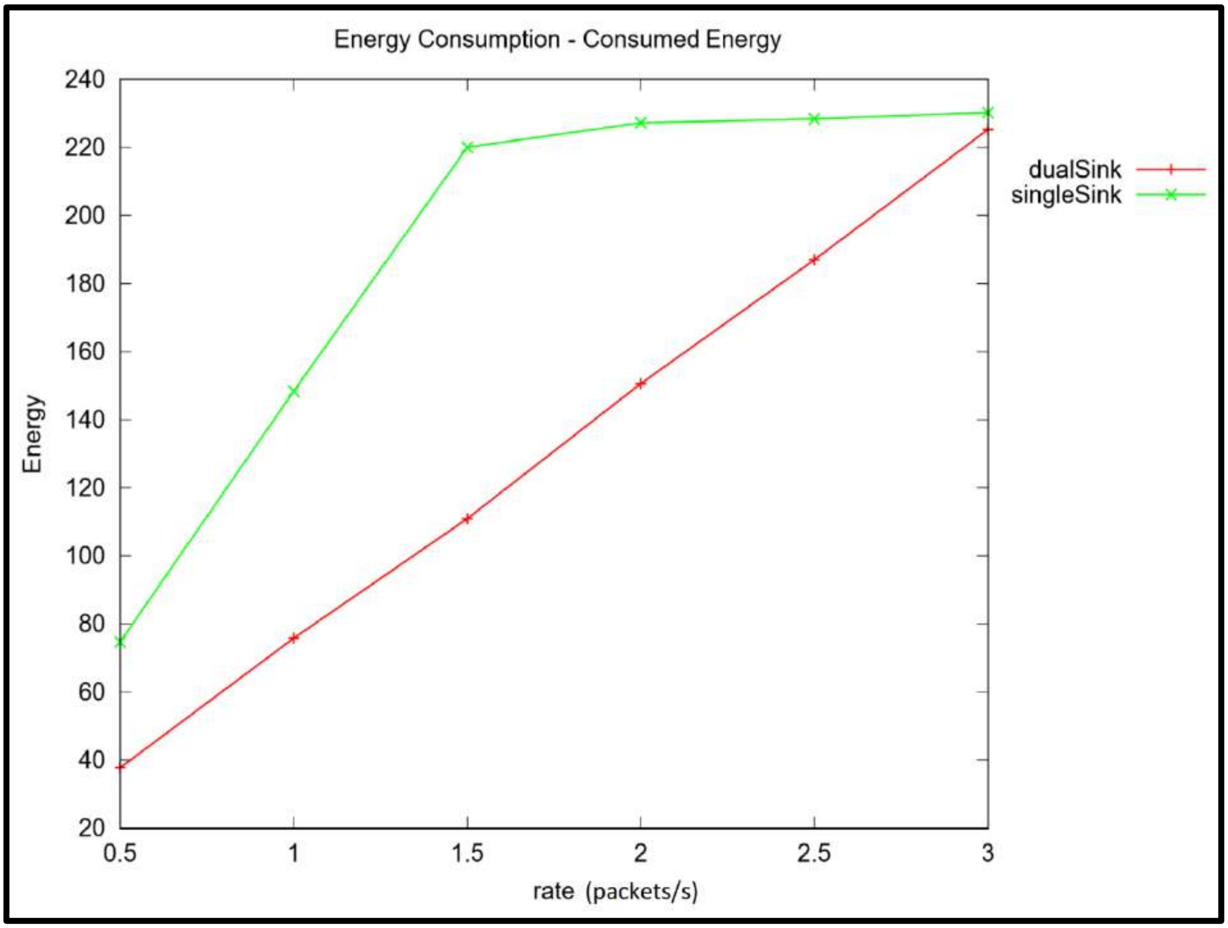


Fig. 20 Average Consumed Energy VS Packets Rate (Regular Mesh)

Fig. 20 represent the energy consumption for both cases, Dual and Single Sink. It is clear that power consumed while using Single Sink is much higher than Dual Sink, and the amount of energy consumed is growing at higher rate.

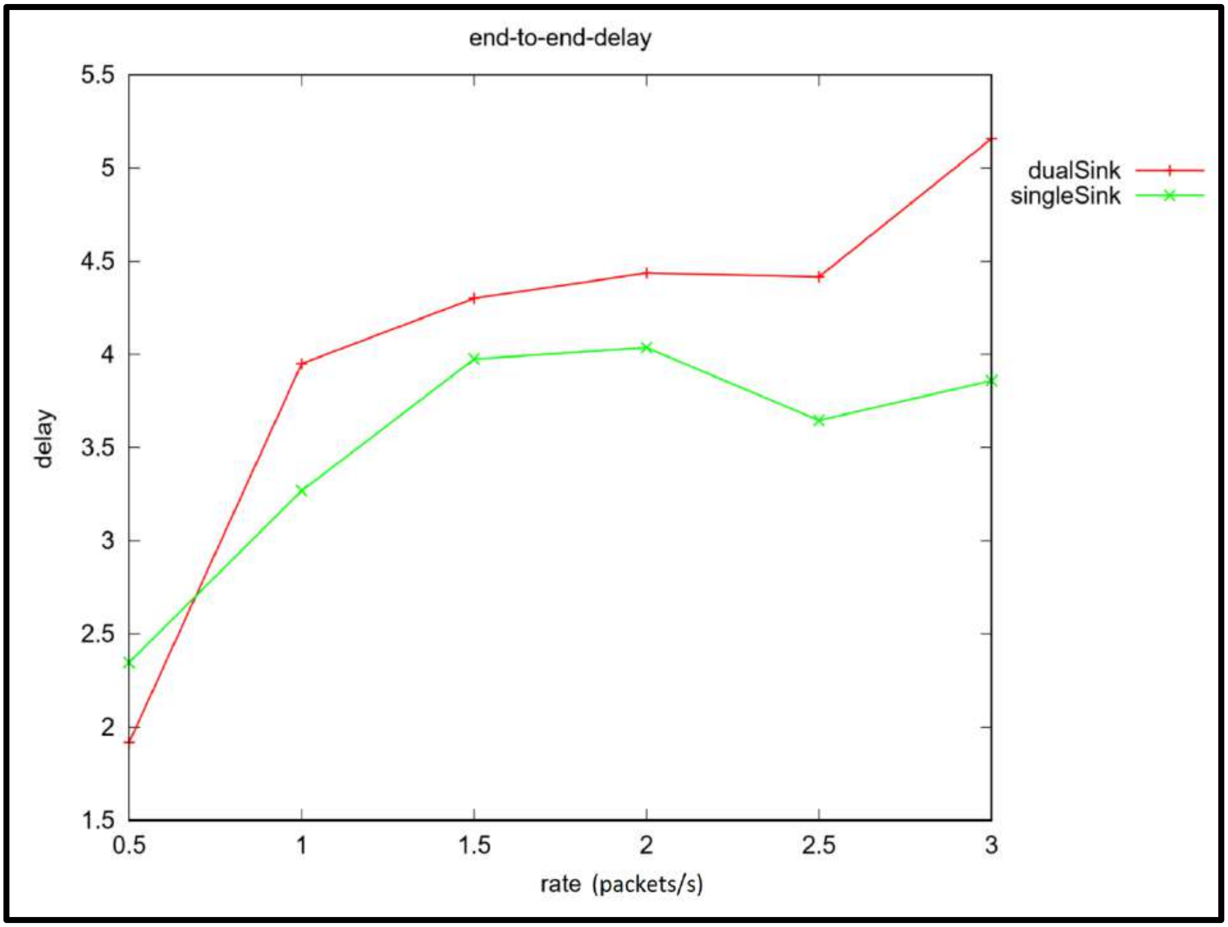


Fig. 21 Average End-to-End Delay VS Packets Generation Rate (Regular Mesh)

From the delay results showed in **Fig. 21**, we can see that Single Sink results are slightly better than Dual Sink. Also, higher results obtained for both, doesn't even reach 5.5 ms while the lower is about 2 ms, meaning that the overall delay results are good in both cases.

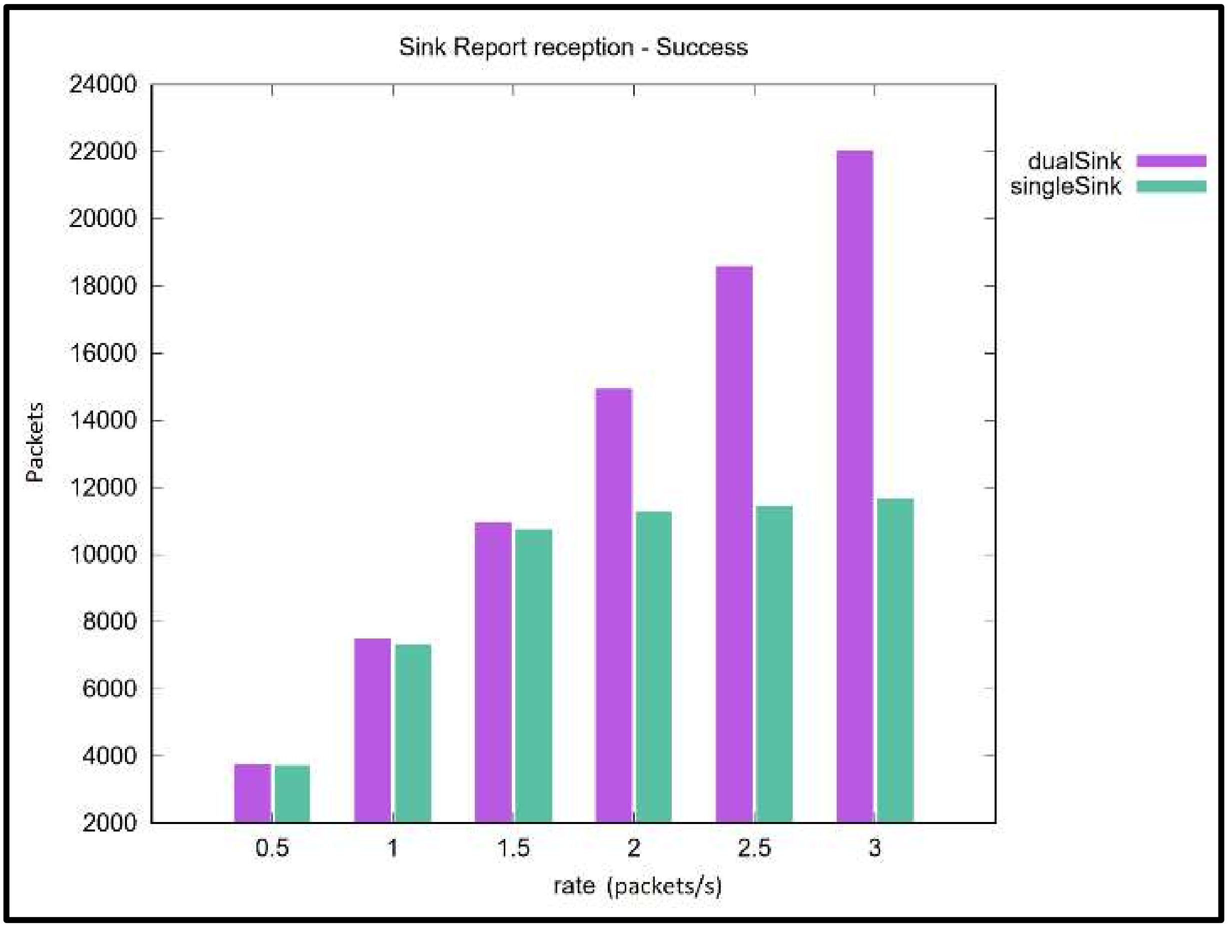


Fig. 22 Packets Received by Sink VS Packets Generation Rate (Regular Mesh)

The number of packets received by sink (PDR) is reported in the **Fig. 22**. As it is shown, in the lower rate of packets generation both Dual Sink and Single results seem to be close. Yet, starting from rate 2 packets per second all the way to 3, we can notice that Dual Sink reporting more packets received, with very large difference between that and Single Sink.

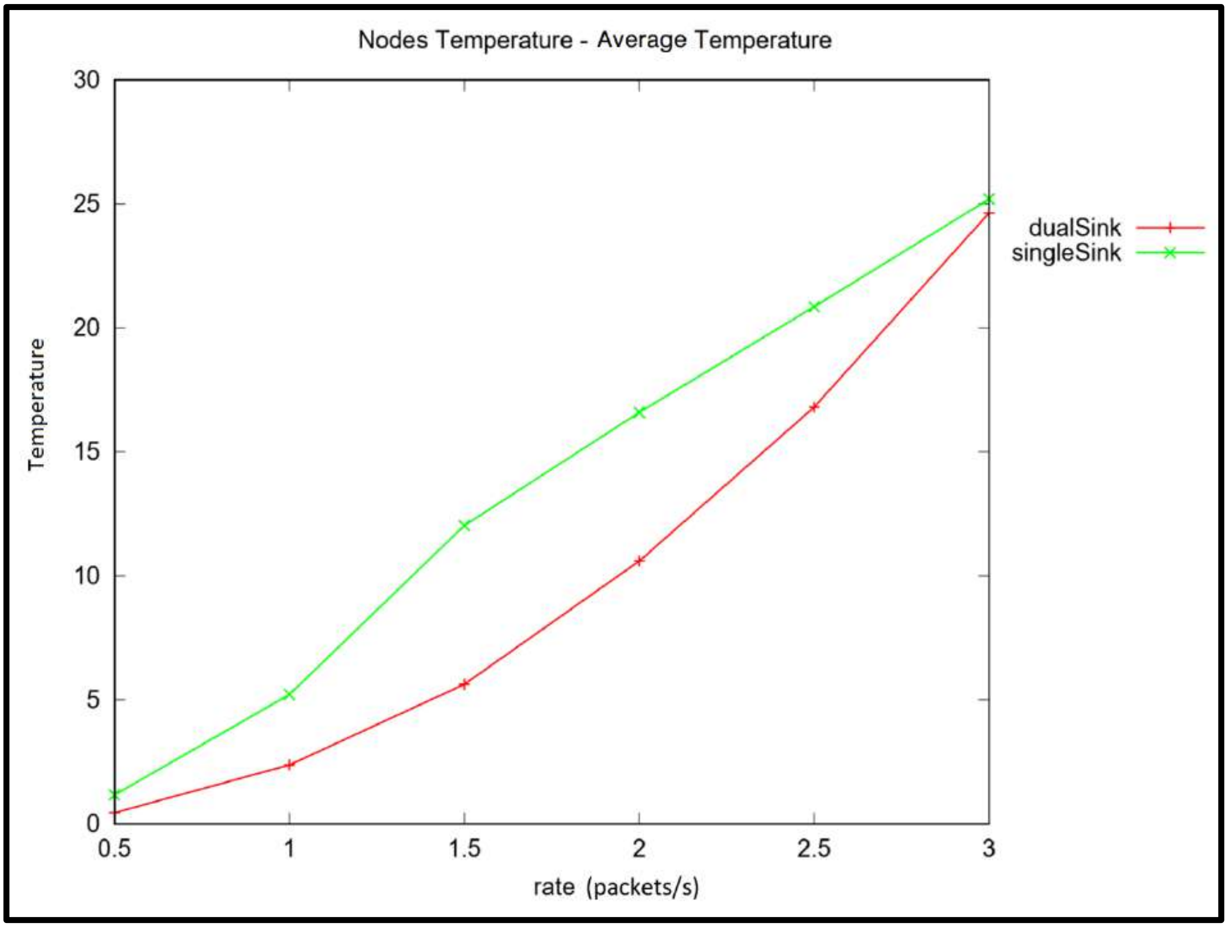


Fig. 23 Average Temperature Rise VS Packets Generation Rate (Regular Mesh)

The average temperature results in the **Fig. 23**, are calculated based on number of routed packets, giving us an estimate of the amount of heat produced by nodes due to wireless communications. The results of Dual Sink in are much better than the ones obtained in Single Sink case, and this can be explained as following. The packets roaming in network and reaching the limit of defined threshold is higher in case of Single Sink, which drive the temperature to increase more than the case of Dual Sink.

Varying the Temperature Threshold in 8x4 Regular Mesh Deployment: Changes in the temperature threshold means the number of packets that can be forwarded by node will increase in time intervals with the threshold value increasing. We made our tests on some selected samples, starting from 100, 400, 800, 1300, 1750, 2000, 2300, 2750. Results we got are shown in the illustrates below.

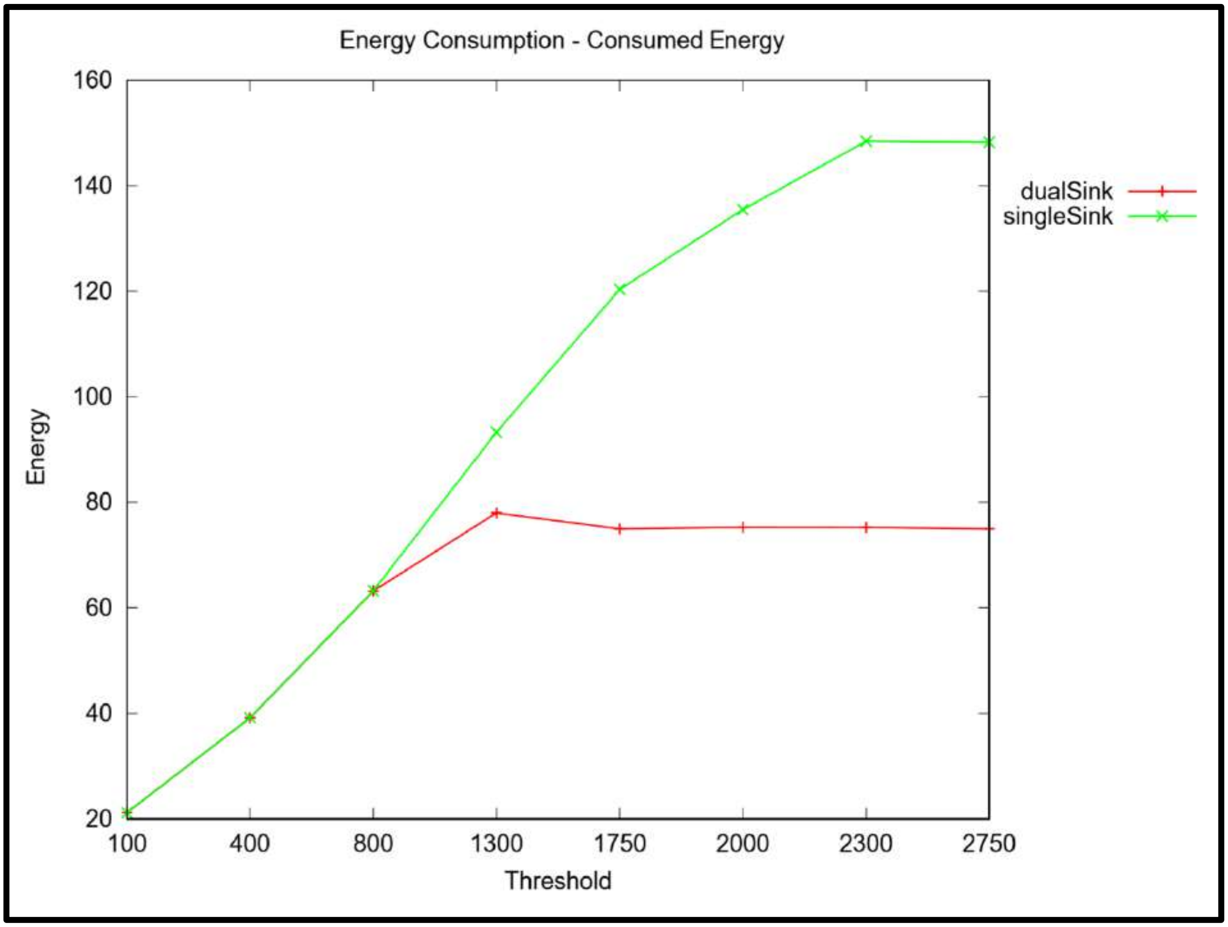


Fig. 24 Average Consumed Energy VS Threshold (Regular Mesh)

The threshold represents the limit that tells if a node is turning into hot spot or still cool node, imply that higher thresholds will allow more packets to be routed. From the **Fig. 24**, it can be observed that using only Single Sink results in more energy to be consumed than using Dual Sink, in the case of higher temperature threshold, where it seems to be stable for Dual Sink starting from threshold 1300.

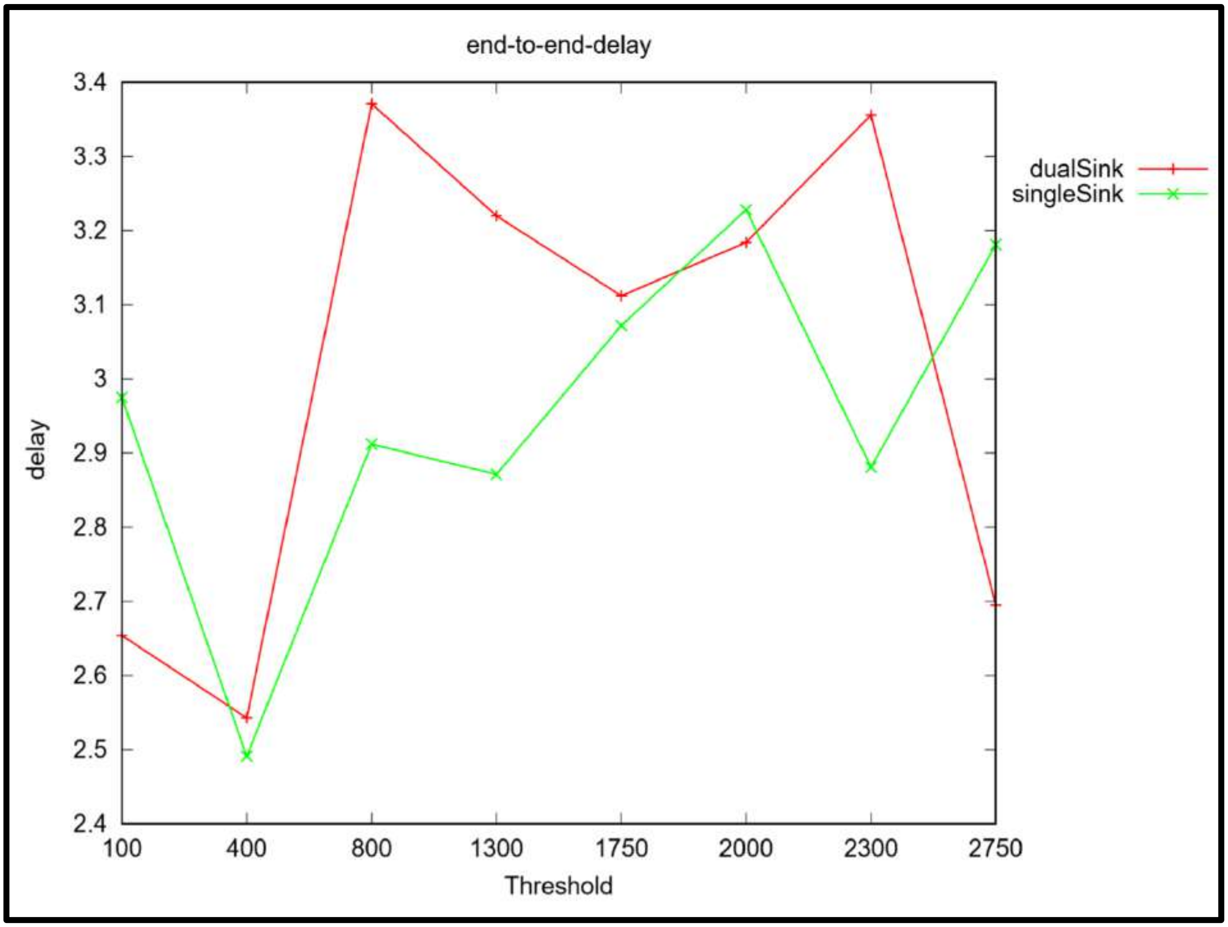


Fig. 25 Average End-to-End Delay VS Threshold (Regular Mesh)

The reason behind these unsettled results in **Fig. 25** is the random generated values that Castalia uses to run simulations. In general, there are 11 distinct random number streams initialized each time before running any simulation, and affect different parts of the simulation [39]. Delay obtained here looks very messy, though we can note that Dual Sink is experiencing a little bit higher delay, more than Sigle Sink. Delay will be always affected, but we can see that delay results are between 2.5 ms and 3.4 ms, which is very acceptable for both cases.

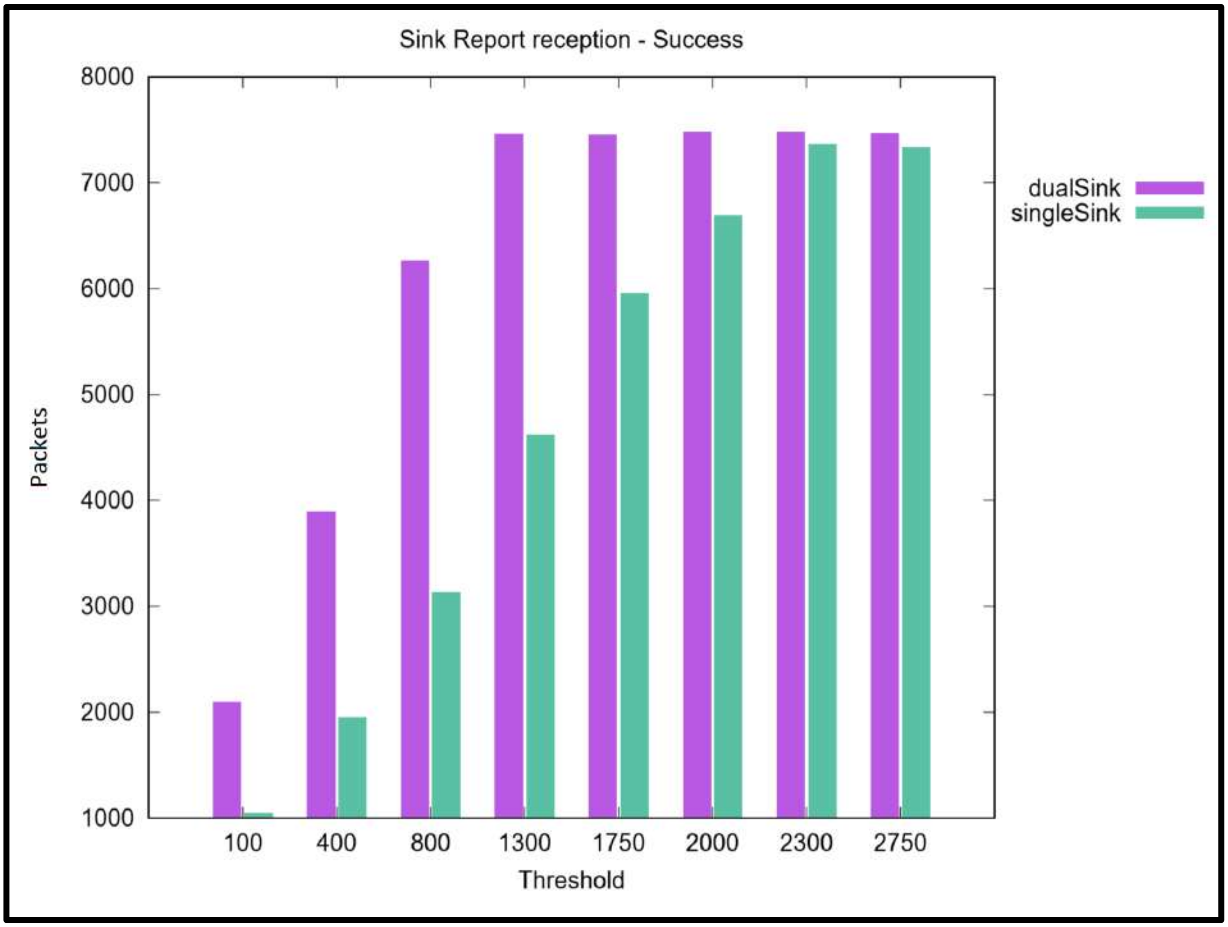


Fig. 26 Packets Received by Sink VS Threshold (Regular Mesh)

In the **Fig. 26** Packet Delivery Ratio (PDR) is observed that for lower values of the temperature threshold, Dual Sink preform way batter than Single Sink using case, and slowly they get almost same results for higher threshold values.

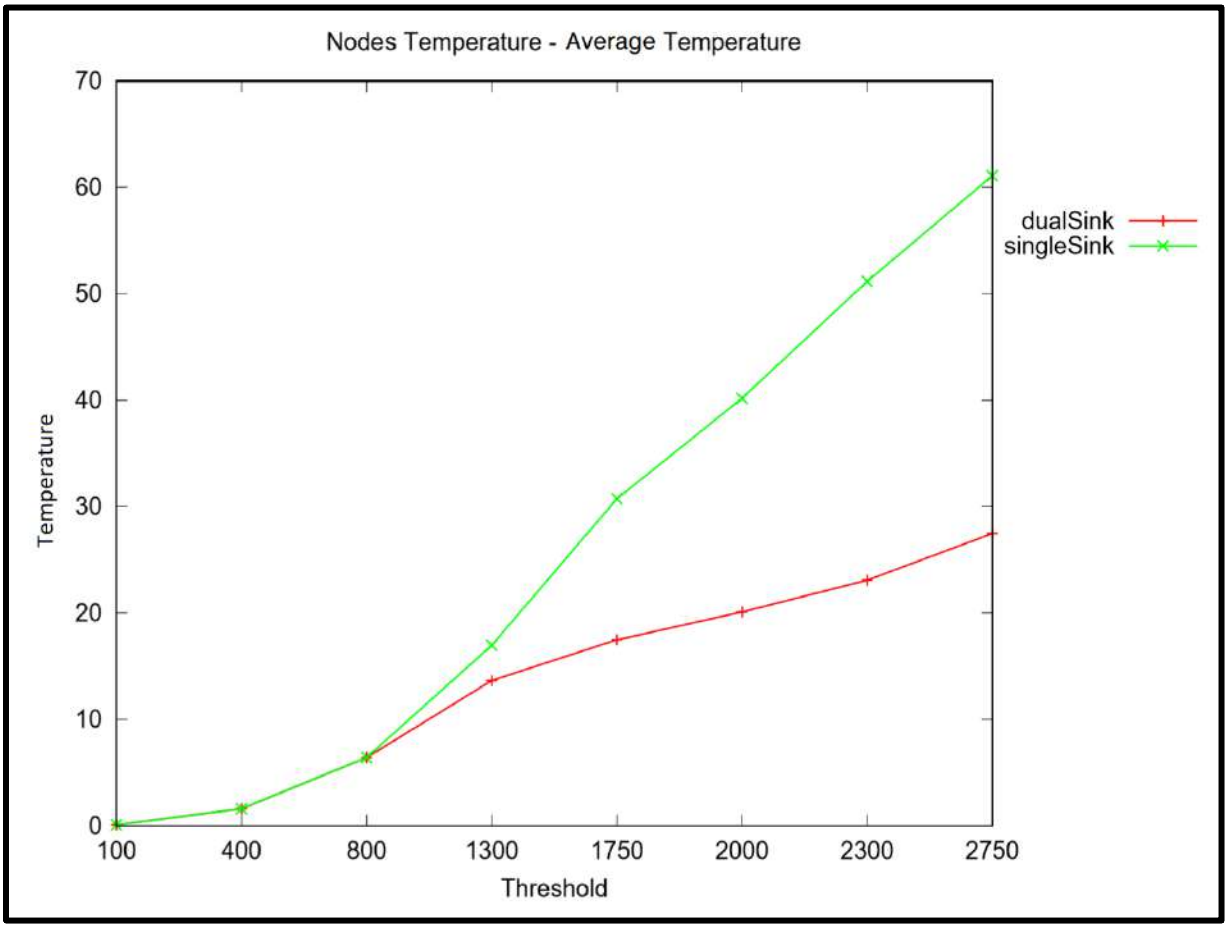


Fig. 27 Average Temperature Rise VS Threshold (Regular Mesh)

Temperature results as represented in **Fig. 27** are proportional with high values of threshold, though Dual Sink temperature values are below the Single Sink ones, meaning we are experiencing preferable results when we use Dual Sink instead of Single one.

3.7.2 Random Deployment:

In this case, we deployed the nodes randomly in a field of 25x25 m. Here, we can't determine for a node how many neighbors it will have. Thus, it will allow us to test the protocol scalability, and the load of data to be forwarded will differ from each node to another. But for the Sink nodes, they are always positioned in the corners of the field.

Varying the Samples Interval in a Field of Random Positioned Nodes: The below figures represent the results obtained from our simulation.

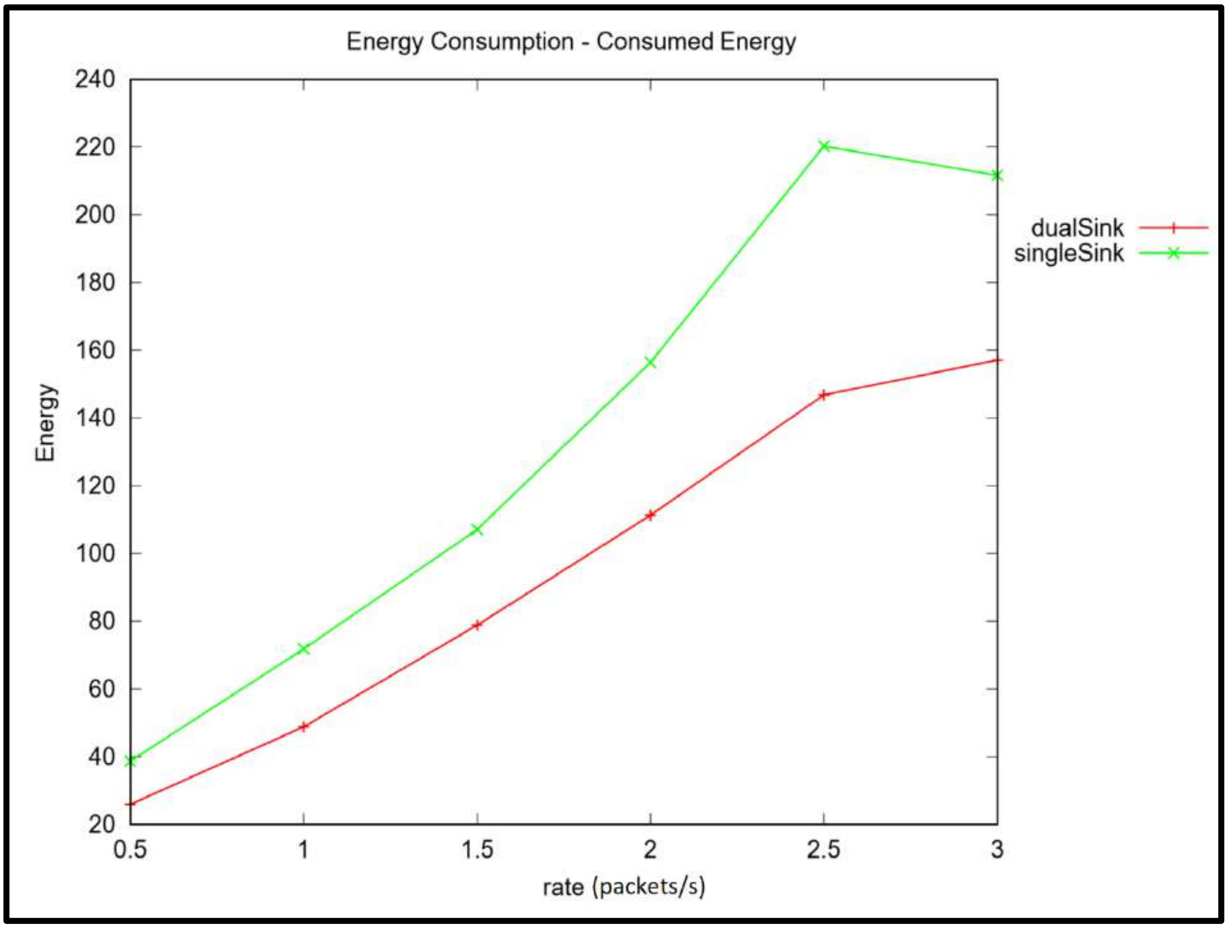


Fig. 28 Average Consumed Energy VS Packets Generation Rate (Random Deployment)

There is a noticeable difference in the energy consumed between Single and Dual Sink, where **Fig. 28** shows that using Dual Sink result in lower amount of energy consumed comparing to only Single Sink.

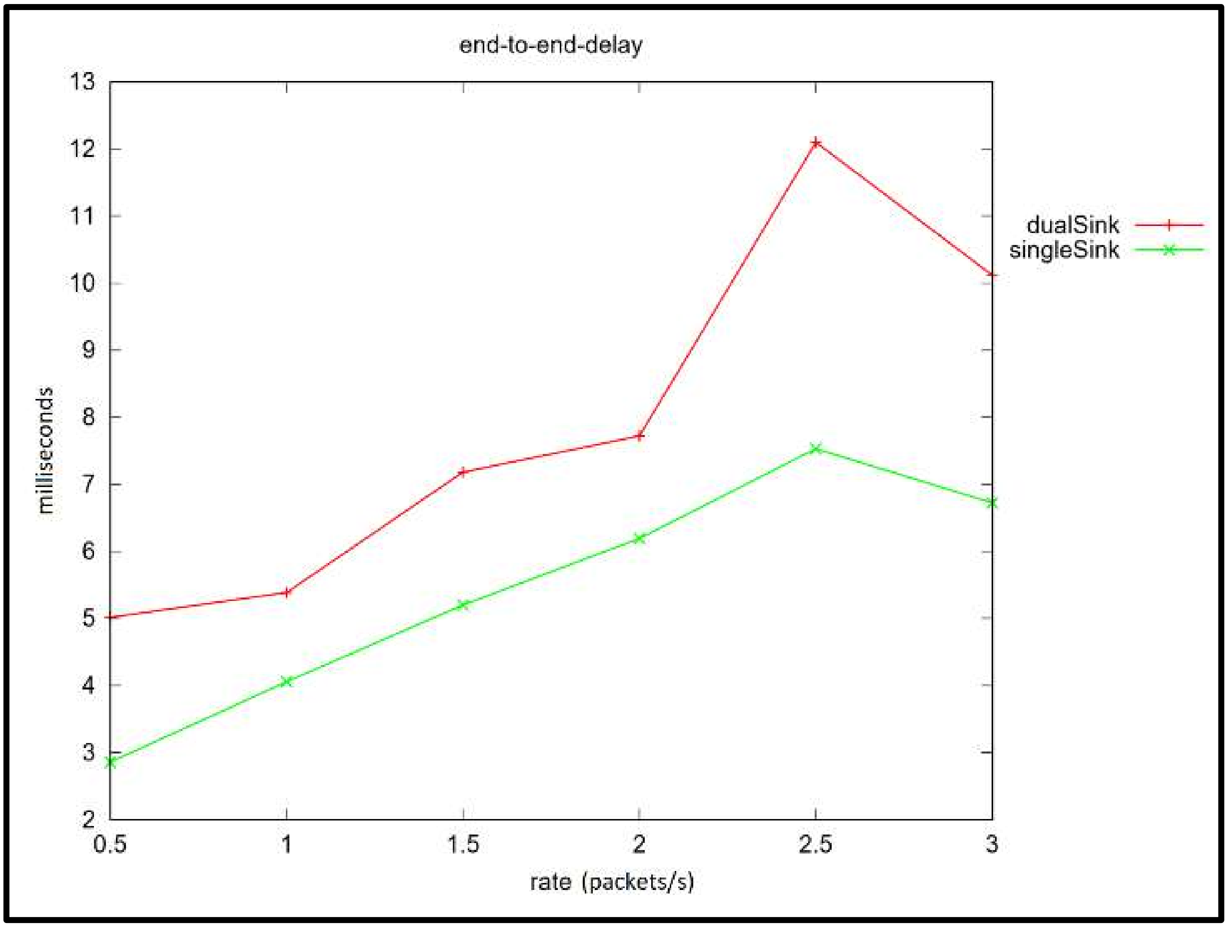


Fig. 29 Average End-to-End Delay VS Packets Generation Rate (Random Deployment)

The end-to-end delay results that are displayed in **Fig. 29** shows that when we use Dual Sink we still having higher delay than using Single Sink. As stated before, the higher total number of packets received by Sink affect the delay resulting in longer delay, which is the case for Dual Sink here.

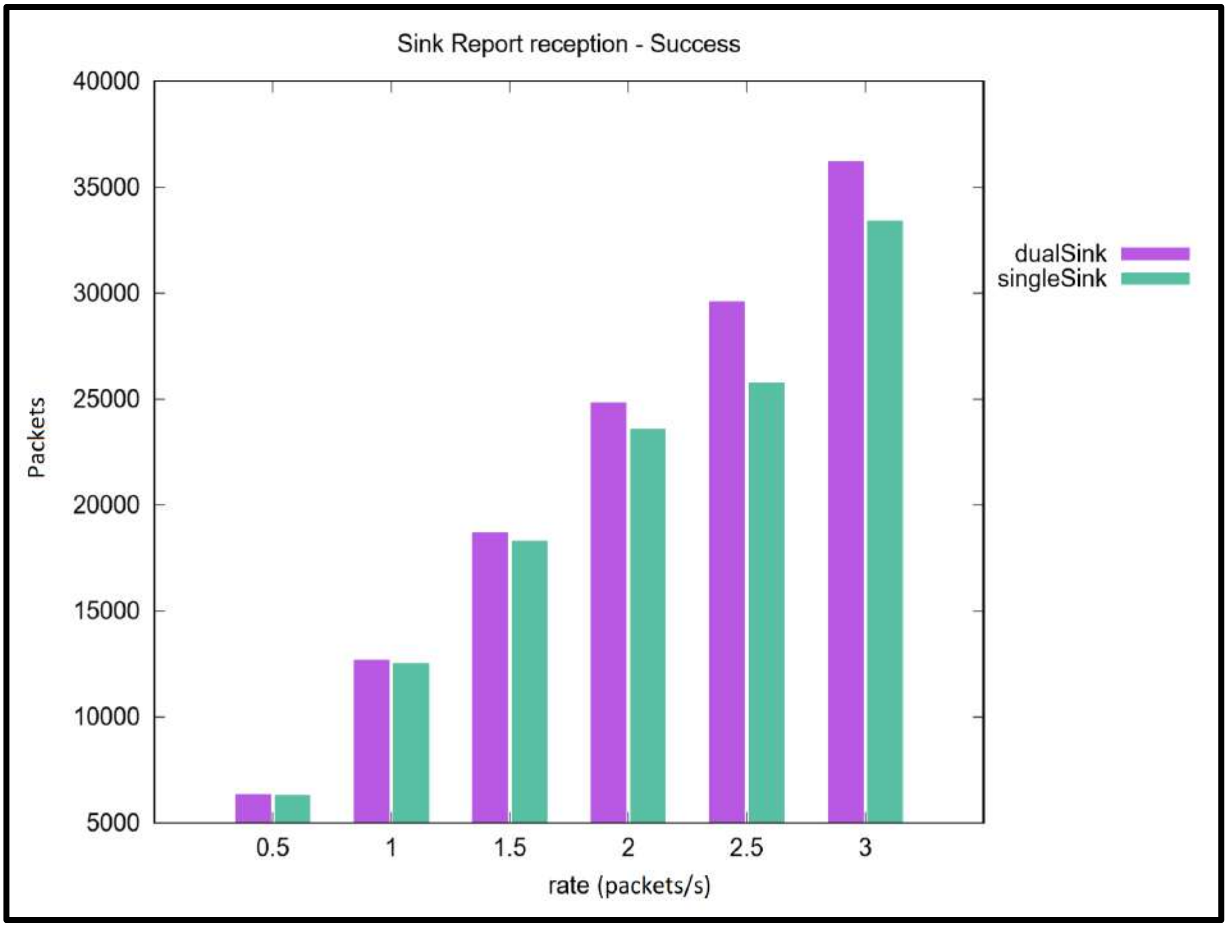


Fig. 30 Packets Received by Sink VS Packets Generation Rate (Random Deployment)

PDR results shown in **Fig. 30** indicate that in higher packets generation rate, Dual Sink gives a slightly better performance than using Single Sink, as for lower rate of packets generating we can see the results almost similar for both cases.

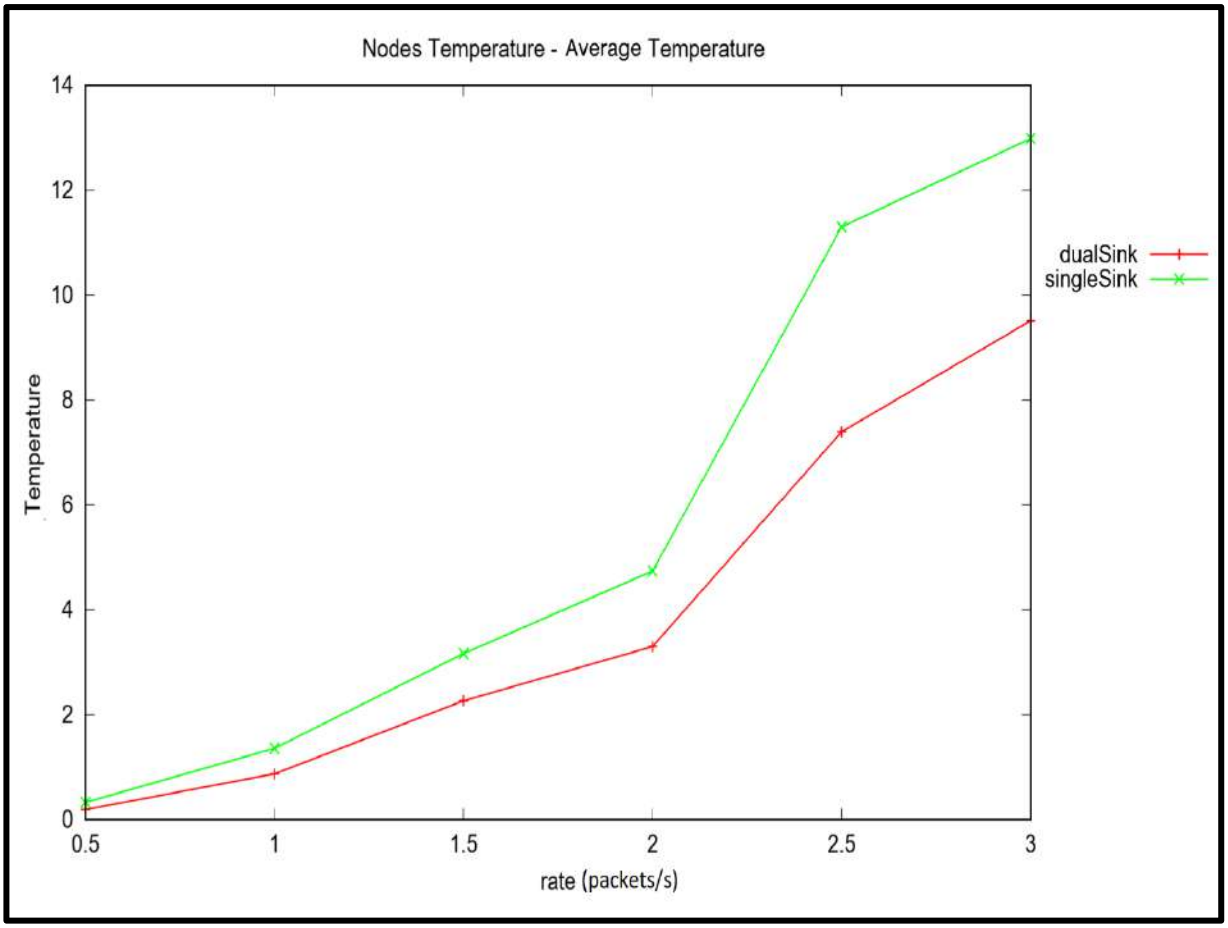


Fig. 31 Average Temperature Rise VS Packets Generation Rate (Random Deployment)

High packets generation rate affects directly the amount of heat produced in the network, and **Fig. 31** demonstrate this situation where the temperature values recorded in the case of Dual Sink are lower than using Single Sink that shows greater values in higher packets generation rates.

Varying the Temperature threshold in a Field of Random Positioned Nodes:
These representations below are the outcomes of the simulations running.

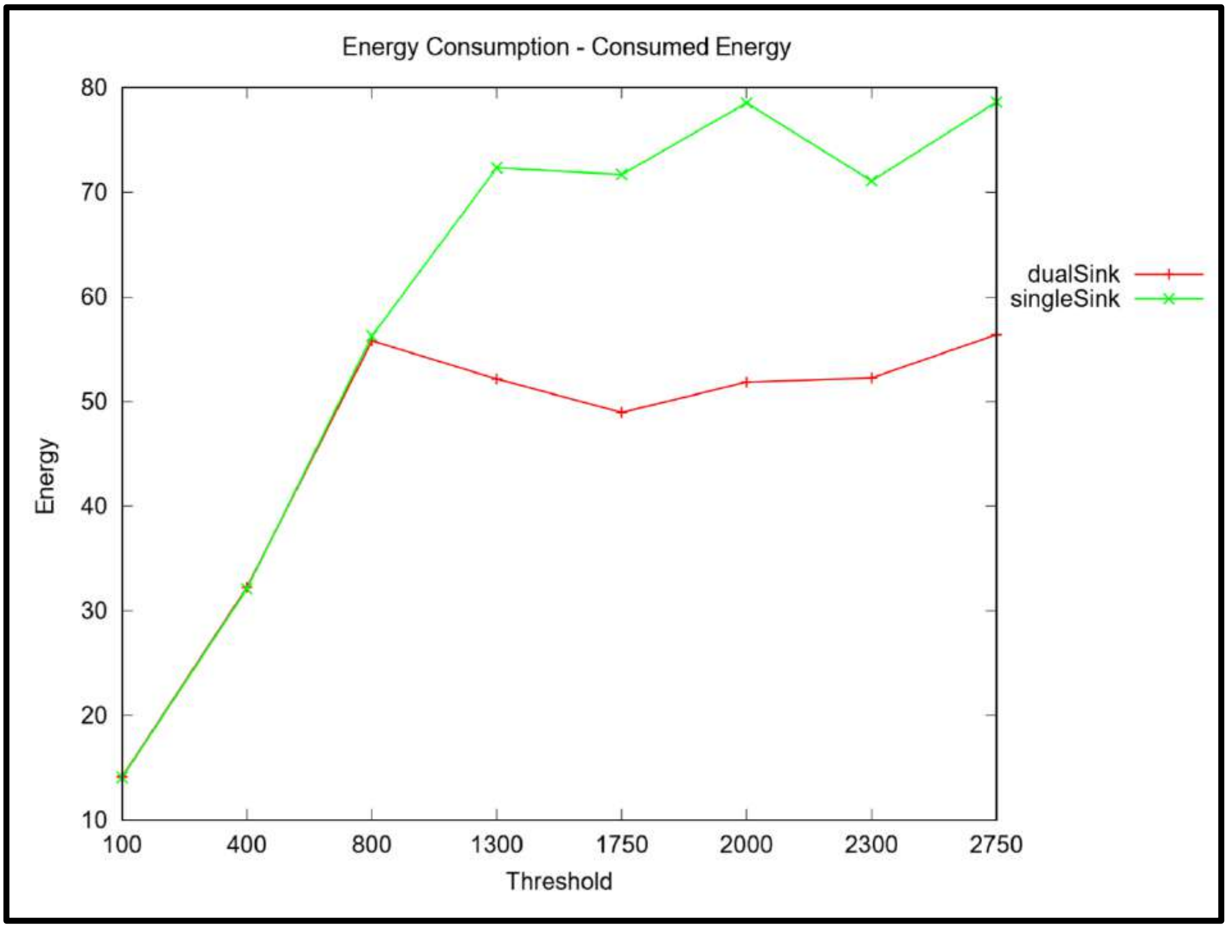


Fig. 32 Average Consumed Energy VS Threshold (Random Deployment)

Starting from threshold value of 800, as shown in **Fig. 32**, we can see that energy consumption for both Dual and Single Sink is almost stable, where using Dual Sink gives a less amount of energy consumption, on the contrary of Single Sink.

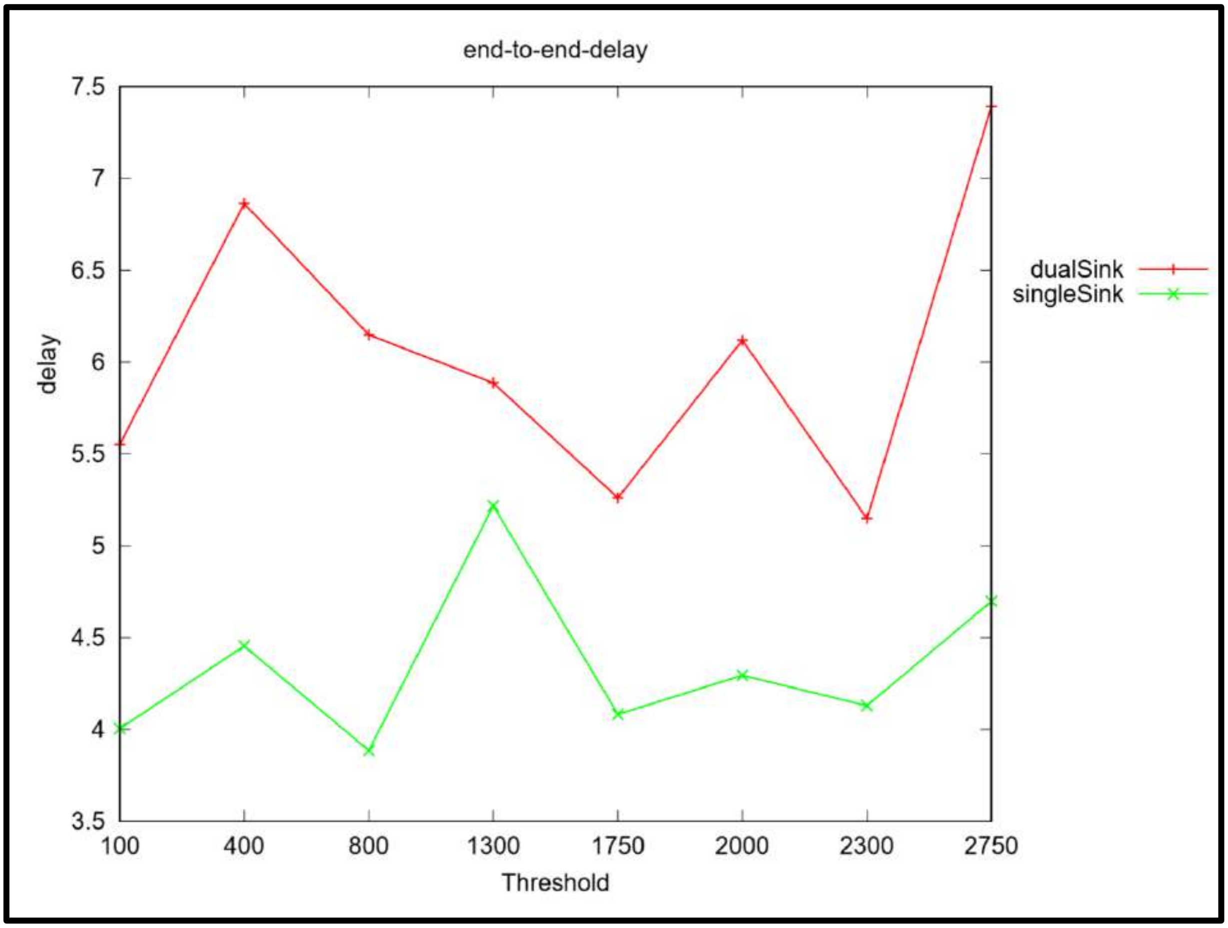


Fig. 33 Average End-to-End Delay VS Threshold (Random Deployment)

As much as the results represented in **Fig. 33** seem to be random, for the same reasons stated before about 11 distinct random number streams used in Castalia simulator [39], though we can easily deduce that results of Single Sink delay are noticeably much better than Dual Sink ones.

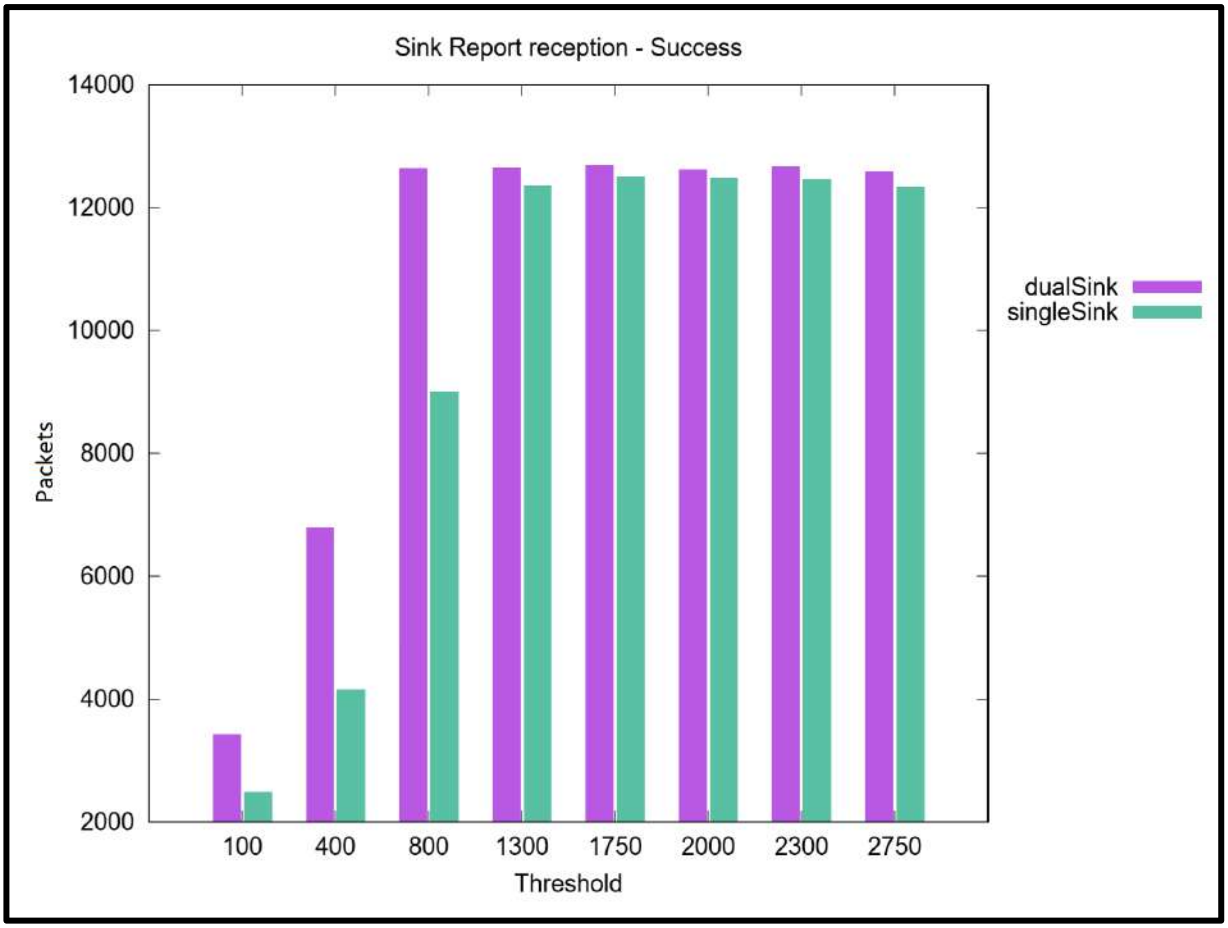


Fig. 34 Packets Received by Sink VS Threshold (Random Deployment)

For the higher threshold values, starting from 1300 in the **Fig. 34** results derived from the simulation shows that both Single and Dual Sink cases gives almost similar results. In the other hand, and for the lower threshold values, Dual Sink is showing way better results than Single Sink ones

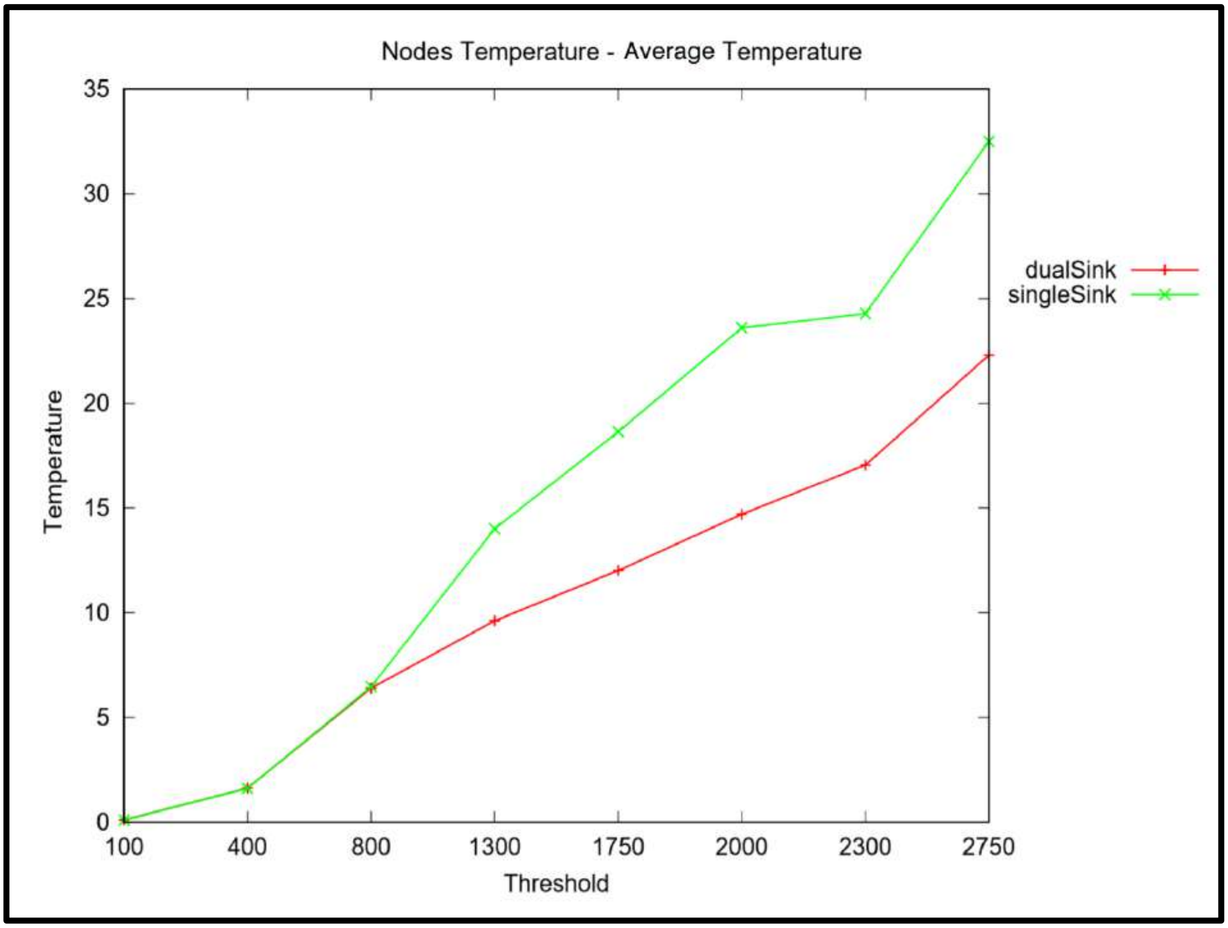


Fig. 35 Average Temperature Rise VS Threshold (Random Deployment)

Temperature results that are represented in **Fig. 35** gives an idea about the difference between using Single or Dual Sink, especially in high threshold values where Dual Sink shows better performance results than Single Sink case.

3.8 Conclusion:

Temperature rise as result of antenna transmission and reception in WBAN, is considered an issue that need to be solved and reduced in order to keep the surrounding tissue safe from damages and unexpected side effect as in vivo environments are very sensitive in case of temperature changes.

For this chapter, we have discussed Least Temperature Routing (LTR) that goes under thermal-aware protocols used to monitor the generated heat by data transmission and it has simple algorithm, with mechanism of discarding packets, and reducing the unnecessary hops and loops. We have also proposed a new approach of using Dual Sink as a solution that may enhance the LTR performance.

In addition, we used Castalia project within OMNeT++ IDE to implement LTR protocol using two different approaches, Single and Dual Sink then we tested the performance of both of them.

The obtained results, after simulating many different scenarios and choosing different parameters, showed that using Dual Sink is much more efficient than only Single Sink in application where we have high packet generation rates, in term of energy consumption and the total heat produced and it allow WBANs to balance the load of data flowing in the network, which help to distribute the temperature all over the network equally. For the PDR, and in higher packets generating rate and low threshold value, Dual Sink dominates with much better results as obtained from the simulations. Lastly, for the end-to-end delay, we have seen that using Single Sink gives always better results than Dual Sink scenarios.

General Conclusion

WBANs are meant to be the solution customized for healthcare and other body-involved applications. Typically, WBANs are a constrained version of WSNs, where we have to consider the in vivo environment proprieties and specifications. Therefore, routing protocols plays in important role to end up with best performance results of using the WBAN. Many researchers proposed different routing protocols, each focus on specific issue to handle while deploying WBAN systems.

In this thesis we have selected LTR as our study case, which is a protocol concerned on reducing the temperature in WBAN and distribute the heat over all the sensing field to avoid damages in the environment, such as tissue burns.

LTR was founded to work with Single Sink, so we intended to modify the functionality of this protocol to support Dual Sink and evaluate the performance changes along with this alteration. To do so, we needed specialized tools dedicated for testing and rate their efficiency, and for that we used Castalia project under OMNeT++ simulator to estimate the behavior of Dual Sink solution comparing to Single Sink.

The tests were done under different settings, first we used two different sensing fields, 8x4 Mesh topology and deployment of 98 nodes randomly then we varied the temperature threshold defined for all the nodes in the network excluding the Sinks, and the rate of data generated by nodes in specific time interval. We used 4 metrics for our evaluation: End-to-End delay, average temperature rise, energy consumption and number of received packets. Overall, using Dual Sink resulted in better performance regarding the temperature rise, packets reception and energy consumption except for the end-to-end delay where the results of Single Sink were slightly preferable, yet acceptable for Dual Sink as well, so in the case of the application where the delay is very important key, it safer to say that using Dual Sink may result in higher delay more than Single Sink case.

For the future perspectives, the LTR protocol can be tested using Dual Sink approach in several other studying cases and simulation scenarios with many different parameters, such as the mobility, where we can have different mobility cases like the regular or random ones. Also, the result of these tests may include the network life time as metric of evaluation, which is very important and highly considered in WBAN application and use cases, specially the medical ones.

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