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Routage avec Économie d'Énergie dans les Réseaux de Capteurs Sans Fils

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To my loving parents

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Abstract

Limited battery power is one of the major stringent factors in deploying Wireless Sensor Networks (WSNs), in spite of their numerous applications both on small scale as in Wireless Body Area Networks (WBANs) and on large scale as in agricultural and habitat monitoring. Especially, stationary sink based data gathering protocols for large scale WSNs have limited network lifetime, because relay nodes around the sink quickly deplete their battery power due to high traffic loads, making the rest of the network unreachable to the sink. On the other hand, sink mobility improves network lifetime by distributing relay nodes' energy consumption. However, mobile sink now has to periodically update the network about its changing position. This control traffic is non-negligible for low power, limited capacity sensors as it induces energy consumption problem. In this thesis, we are considering energy efficient routing protocols in the context of WBANs and large scale WSNs. Moreover, we also address multi-channel assignment algorithm with the aim of minimizing power consumption and increasing network throughput.

In the first part of this thesis, a deep analysis of the energy consumption of one hop vs multi-hop communications in WBANs is performed. In fact, recent advances in technology has led to the development of small, intelligent, wearable sensors which are capable of remotely performing critical health monitoring tasks, and then transmitting patient's data back to health care centers over wireless medium. But to the day, energy also remains to be a big constraint in enhancing WBAN lifetime [Net12]. Some recent literature on WBANs proposes deliberate use of multi-hops to transfer data from a sensor to the gateway via relay health sensors as more energy efficient than single hop communication. There are studies which argue contrarily. In this context, we have analyzed the single vs multi-hop energy consumption effect for real very short range sensor devices.

In the second part of this thesis, two distributed energy-efficient sink location update algorithms are proposed for large scale mobile sink WSNs. First algorithm, named SN-MPR, uses a combination of multi-point relay broadcast and a local path repair mechanism by means of which sink's location update packets are forwarded only to nodes which are affected by sink mobility; the rest of the network does not receive these update messages. Next, a duty-cycle aware multi-point relay based algorithm which is a modified version of the SN-MPR algorithm is proposed. It allows non-relay nodes to switch-off their radios when communication is not desired. Simulation results show that the two aforementioned algorithms minimize network's power consumption without compromising data delivery efficiency.

The final part of this thesis deals with traffic-aware channel assignment problem in IEEE 802.15.4 standard-based heterogeneous WSNs which have rather high traffic rate requirements than low-rate scalar WSN applications. In fact, traditional single channel communication suffers from interferences caused by concurrent transmissions in the same neighborhood. These parallel transmissions waste battery power as multiple retransmissions are required before a packet can be successfully delivered at the destination due to frequent collisions. Moreover, already limited network throughput of the single channel communication protocols is further degraded at higher traffic rates due to increased collisions and congestion. On the other hand, concurrent transmissions over multiple channels not only reduce power consumption as packet collisions are minimized or eliminated depending upon the efficiency of the concerned channel assignment algorithm, but also offer better network throughput and data delivery delays. Modern WSN platforms like crossbow's MicaZ nodes [Mot12] are equipped with single, half-duplex IEEE 802.15.4 standard-based radio which can operate over sixteen multiple channels. In order to make effective use of multiple channels, a number of channel assignment algorithms have been proposed recently for WSNs. However, they are suitable for rather low-rate homogeneous WSNs, and they consider fixed physical channel widths. These multi-channel assignments increase network throughput, but they may not be able to ensure QoS requirements of high bandwidth demanding multimedia traffic, as in the case of heterogeneous WSNs. In order to address the energy issue and at the same time increase network capacity, we propose a distributive Traffic-Aware Bandwidth-Adaptive (TABA) channel selection algorithm which enables the nodes to not only choose interference free channels in the neighborhood, but also to adapt channel-width to increase/decrease throughput according to varying traffic conditions.

Keywords: sensor networks, data dissemination protocols, sink mobility, multi-channel assignment, duty-cycle algorithms

Résumé

La limitation de la capacité de la batterie est un facteur clé dans le déploiement des réseaux de capteurs sans fil (WSNs), malgré leurs nombreuses applications en petite échelle comme pour les réseaux de capteurs embarqués sur des personnes appelés communément réseaux WBANs (Wireless Body Area Networks) et également en grande échelle comme dans le domaine de l'agriculture et de la surveillance de l'habitat. En grande échelle, les protocoles de routage à base d'un puits statique ont une durée de vie limitée. Cela est dû au fait que les noeuds relais proches du puits épuisent leur batterie rapidement à cause de la charge du trafic, et par conséquent avoir un réseau avec une destination non joignable. En revanche, la mobilité du puits prolonge la durée de vie du réseau par la distribution de la consommation d'énergie entre les noeuds relais. Cependant, le puits mobile doit diffuser périodiquement sa position dans le réseau. Ce trafic de contrôle est non-négligeable dans le cas des capteurs sans fil car ils ont une capicité très limité, ce qui engendre le problème de consommation d'énergie des noeuds.

Dans cette thèse, nous nous sommes focalisés sur la conception de protocoles de routage pour les réseaux de capteurs sans fils avec optimisation de la consommation d'énergie. Dans ce contexte, nous nous sommes intéréssés à deux applications des réseaux de capteurs sans fil; les réseaux WBANs, et les réseaux de capteurs à grande échelle. Dans un premier temps, une analyse approfondie de deux techniques de dissémination d'informations et de leur consommation d'énergie dans les réseaux WBANs est effectuée. Nous avons comparé la consommation d'énergie liée à la dissémination d'informations dans un réseau WBAN à un saut et dans un réseau WBAN multi-sauts.

Dans un second temps, on a étudié le problème de dissémination des données dans les réseaux de capteurs sans fil à large échelle et dans lesquels le collecteur de données, appelé communènement *sink*, est mobile. Dans ce contexte, on a proposé deux algorithmes de routage distribués. Le premier algorithme, appelé SN-MPR, permet de limiter la propagation des messages de contrôle sur la localisation du sink aux seules zones affectées par la mobilité de ce dernier. Le deuxième algorithme, appelè duty-cycle SN-MPR, permet d'économiser l'énergie des capteurs en permettant à ceux qui ne sont pas MPR d'éteindre leurs radios respectives quand ils n'ont pas de données à transmettre vers le sink.

Dans la dernière partie de cette thèse, nous avons traité la dissémination d'informations dans les réseaux de capteurs sans fils hétérogènes utilisant la technologie IEEE 802.15.4, et dans le contexte d'applications nécessitant un plus haut débit. En se basant sur l'utilisation parallèle de plusieurs canaux pour l'échange de données, on a proposé un algorithme distribué, appelé TABA, pour la sélection de canaux en fonction du trafic dans le réseau. Cet algorithme permet, d'une part, d'économiser la consommation d'énergie en minimisant les collisions et retransmissions de paquets, et d'autre part, d'offrir un meilleur débit pour l'envoi de données multimédias.

Keywords: sensor networks, data dissemination protocols, sink mobility, multi-channel assignment, duty-cycle algorithms

Table of contents

Chapter 1

Introduction

Contents

1.1 Wireless Sensor Networks

Advancement in technology has had a great influence in changing human lives during past few decades. This made us rely more and more on autonomous systems in almost all disciplines of our life, and this dependency is still increasing. Especially, the integration of tiny micro-processors, storage, sensing and communication equipments into small, low cost sensor platforms has opened doors to numerous applications. These devices are capable of performing sensing tasks, can organize themselves into networks, and, transfer sensed data to the control center without requiring any human intervention for long periods of times. These autonomous systems have facilitated many existing applications, and have also given rise to numerous new ones. A few among these numerous applications include surveillance, health care, habitat monitoring, disaster management etc. As these examples show, the scale of such networks ranges from only few medical sensors attached to a human body to hundreds and thousands deployed in large harsh terrains.

In large scale applications, the battery replacement might not be possible due to terrain or security conditions as in surveillance applications. Due to this, energy consumption is a very important research aspect in designing such networks. Moreover, huge variance in the scale, monitoring tasks, sensitivity of monitored information and QoS requirements of various applications present new research challenges [eaI02] [AMC07]. For instance, a habitat monitoring application can have relaxed delay and delivery constraints, but requires longer network lifetimes due to inaccessible terrains. A health monitoring application requires timely data delivery, especially in case of emergency; loss of connectivity with the data control center due to poor link quality or battery power is not tolerable at all. On the other hand, large scale multimedia WSN application like intrusion detection might have both; stringent data delivery and network lifetime requirements. These big differences in constraints of different applications usually require protocols tailored specially to meet their needs and constraints.

This thesis focuses on the energy efficient data dissemination in WSNs and deals one hand, with real time applications which have rather stringent data delivery delay requirements, and on the other hand, with data dissemination problem for delay tolerant applications. Before going into the details of the motivations behind this thesis and its contributions, we briefly discuss the architecture of typical wireless sensor platforms and their characteristics. Moreover, we discuss few real life applications of wireless sensor networks in order to highlight the important role they can play in both civil and military domains.

1.2 Sensor Node

A sensor network consists of a set of small battery powered devices equipped with one or more sensing units, a low power wireless radio, limited memory and a micro controller unit. Collaboratively, these devices establish a network to monitor activities in their sensing range and then the captured information is transmitted to a data collection center (sink) via multihop communication. Typically, a sensor node is composed of the following components;

- **Sensing Unit:** This component measures a physical activity of the parameter(s) of interest from the surrounding environment and transforms it into a digital signal before transmitting it to the processing unit. A sensing unit can measure rather simpler scalar physical phenomena like temperature, pressure, seismic waves, humidity, variation in luminosity, motion detection etc or rather sophisticated multimedia sensors are also capable of monitoring complex audio-visual physical activities.

- **Transceiver:** Mostly, sensing platforms are equipped with low-power limited-rate short-range half-duplex radios which usually operate on unlicensed 2.4 GHz Industrial, Scientific and Medical (ISM) band as in case of Chipcon's CC2420 transceiver

[Ins12b]. Moreover, transceivers which operate over un-licensed 433 MHz and 868-915 MHz bands are equally commonly used. One such example is Chipcon's CC1000 chip [Ins12a] which is attached with TelosB sensor platforms [Coo12b]. The above mentioned antennas can support data rates of 250kbps and 76.8kbps respectively. In addition, the half-duplex CC2420 chip can operate over multiple frequencies. Efficient use of multiple channel routing can mitigate interference and thus increase network throughput. In some applications like multimedia WSNs, relatively high rate wireless technologies like 802.11 might also be used to relay audio-visual traffic.

- **Controller:** A sensor node is equipped with a low power, low processing and smaller storage Micro Controller Unit (MCU) which processes sensed data and also controls other components of a sensor node. Sensor captures a physical event from the environment, transforms it into a digital signal and passes it to MCU which then processes captured signal before transmitting it over the transceiver.

- **Power Source:** A wireless sensing device is generally equipped with irreplaceable, limited power source like 3V AA batteries, although rather expensive lithium-ion might also be used. Therefore, energy conservation is of utmost importance in WSN applications as compared to QoS insurance in traditional networks. A sensing device consumes power in communication, sensing and processing. Among these, majority of power is consumed by the transceiver in communication. Therefore, radio utilization should be especially minimized when designing protocols on all layers of protocol stack.

1.2.1 Commercially Available Sensor Platforms

A number of sensor platforms with different sensing, memory and communication capabilities are available commercially due to vast range of civil and military applications of WSNs. Below, we provide a brief description of few widely used wireless sensor platforms;

- **MicaZ:** Chipcon's micaZ node [Mot12] embeds Atmel ATmega 128L MCU [Coo12a] with a IEEE 802.15.4 compliant Chipcon's CC2420 half-duplex transceiver [Ins12b] which operates over 2.4 GHz ISM band in one of the sixteen available channels and provides upto 100 m transmission range. MicaZ is powered by AA batteries, has 128 Kbytes flash memory and supports data rates of up to 250kbps. Thus, it is suitable for scalar sensing applications which do not have high processing and routing requirements.

- **Mica2:** The Mica2 platform [Cooa] is equipped with a multi-channel half-duplex CC1000 [Ins12a] transceiver which operates over 868/916 MHz, 433 or 315 MHz bands and can provide up to 38.4 Kbaud data rates. Mic2 and MicaZ both have the same MCU and AA battery. Thus, this platform is also suitable for scalar sensor applications.

- **Telosb:** It is feasible for very low processing and low rate scalar sensing applications like temperature, pressure, humidity etc because it has a very low frequency MCU which operates at 8 MHz and is equipped with 10 kB RAM. Although, it has the same IEEE 802.15.4 compliant Chipcon CC2420 transceiver [Ins12b].
- **Imote 2.0:** Due to its better 13-416 MHz processor, 32 MB flash memory and IEEE 802.15.4 compliant CC2420 transceiver which can support up to 250 Kbps data rate [Ins12b], the Imote 2.0 [Cooc] node is suitable for processer hungry applications like multimedia WSNs which have high data processing and bandwidth requirements.
- **Stargate:** A 400 MHz processor, 64 MB SDRAM, 32 MB flash memory, built-in Bluetooth and an attachable 802.11 card make this node suitable for data and processing intensive multimedia sensing applications [Coob].
- **Shimmer:** This is a wearable sensor device aimed to serve remote patient monitoring, rehabilitation, and sports applications. Shimmer sensors [Cood] are equipped with a 16 bit, 8 MHz MSP430 MCU, a CC2420 radio and a 2 GB microSD card slot. Moreover, it is equipped with 450 mAh rechargeable Li-ion battery for longer lifetime.

1.3 Applications of Wireless Sensor Networks

Wireless sensor networks have numerous applications ranging from very large scale deployments consisting of hundreds of thousands of nodes as in the case of habitat monitoring application to small range wearable body area networks consisting of one or few wearable sensors used for monitoring health. In this section, we discuss some of the real world WSNs projects to highlight their importance in the modern era.

Agricultural Monitoring: The Low Frequency Array (LOFAR) project [GTL05] aimed at using wireless sensor network consisting of tens of thousands of nodes for fine grained monitoring of potato crop fields in order to combat the Phytophthora, a fungal disease of potatoes. In LOFAR, one hundred sensors were deployed as a prototype to monitor the air pressure, temperature, humidity and illumination inside the potato fields as the development of Phytophthora disease depends strongly on the micro-climate changes inside the potato fields.

Health Monitoring: Wearable health monitoring systems integrated into a telemedicine system are novel information technology that will be able to support early detection of abnormal health conditions and prevention of its serious consequences. Many patients can benefit from continuous ambulatory monitoring as a part of a diagnostic procedure, optimal maintenance of a chronic condition or during supervised recovery from an acute event or surgical procedure. One such small wireless sensors have been developed by Shimmer Corporation [Cood] which can take ECG, EMG, GSR, accelerometer readings. Though Wireless Body Area Networks (WBANs) seem rather simpler and are smaller in size, yet they pose new applicability challenges on MAC and network layers different from classical large scale WSNs. WBANs have stringent quality of service, reliability and security requirements but continuous patient movement causes connectivity problems and also increases interference due to absorption of signals by the body and surroundings. A number of works have been done on the MAC layer [Lam05] [OEB07] [LT07] [TS04] and on the network layer [TTGS05] [BB06] [TXH+08] to address these issues and the research is still going on.

Wildlife Tracking: Wireless sensor networks are also being used to monitor the behavior of wildlife in many projects [JOW+02] [HBC+09] [GSGSL+10] [Bar10] [MCP+02]. For instance, sensors are deployed on zebras in Zebranet project [JOW+02] to study their behavior. A peer-to-peer data distribution technique, as described in the section-2.1.4.2 is utilized in which the data monitored by a sensor installed on a zebra is transmitted to the sensors installed on other zebras when pass by each other. This method enables the data collecting sink to gather data of majority of zebras by coming in contact with only few of them.

Every year, large number of animals die in natural reserves due to road accidents including some endangered species. Sanchez et. al. propose a mechanism to monitor the wildlife movement near the roads and railway structures in order to protect the precious life losses by averting locomotives about the wildlife movement [GSGSL+10].

Environmental Monitoring: Sensor networks can be deployed in remote terrains to monitor environmental changes and their affect on the climate [WALW+06] [RCOM05] [TPS+05] [MHO04] [HHSH06]. For instance, Oliver et. al. [RCOM05] deployed a WSN to monitor the impact of soil salinity and its effect on the performance of vegetation. In another project, Allen et. al. [WALW+06] deployed a WSN for monitoring seismic and infrasonic signals of dangerous volcanoes in Ecuador. Such projects can help in better comprehension of natural calamities and save thousands of lives.

Research community has addressed many issues related to WSNs on all communication layers such as application protocols, transport protocols [PVSA04], routing protocols [SA07a] [IGE+03] [LPP+06] [eaN08], MAC protocols [KSC08] [IEE03] [CHH+06], QoS [FLE06] and physical layer protocols [IEE03].

The aforementioned real life examples show the vast range of applications of WSNs. The versatile nature and requirements of each class of these applications pose research challenges quite unique from each other some of which will be discussed later in the chapter-2. In the remaining part of this chapter, the motivations and objectives of this thesis are described followed by a brief introduction to the contributions.

1.4 Motivations

In this thesis, we focus on data dissemination in wireless sensor networks. The main objective is to enable sensor nodes to transmit the monitored information to the data control center in an energy efficient manner by effectively using the transceiver. This is of utmost importance since transceiver is the biggest power consuming component in a wireless sensor platform. This problem needs equal attention in both small and large scale WSNs as battery replacement might not be possible in many applications. For instance, immediate replacement of a health sensor installed on a patient needed continuous monitoring, though valid, might be a problem if the patient is not in the proximity of his physician. Similarly, a large scale WSN deployed in harsh environments might be humanly inaccessible; hence, battery replacement is not an option. Thus, energy efficient data dissemination protocols to deliver monitored reports to the sink need to be designed for both types of the above described applications.

Existing WSN platforms like mica2 [Cooa] and micaZ [Mot12] are usually equipped with a half-duplex low-power low-rate transceivers which can support up to 256Kbps. However, some application may require higher data transfer rates and may also have stringent data delivery requirements, as could be the case in a heterogeneous multimedia WSN deployed for enemy surveillance in a battlefield. At higher data rates, traditional single channel communication protocols suffer from increased interferences due to frequent packet collisions. This interference wastes battery power as colliding packets have to be retransmitted a number of times before a successful delivery is ensured. Moreover, single channel protocols also offer a limited network throughput. In order to solve this problem, we address multi-channel communication in high data rate WSN applications, as concurrent communications on multiple channels not only minimize power losses due to interferences but also offers higher network throughput.

This thesis focuses on energy efficient data dissemination to the sink and deals with it in different parts;

- Firstly, we address energy minimization issue for WSNs where sensors need to deliver their monitored information to a single sink. On one hand, we analyze the energy consumption of wireless body area networks and show that deliberate use of multi-hops in such low range networks by lowering transmission power is not efficient. On the other hand, we address energy efficient data dissemination in classical large scale

WSNs in which the data collecting sink is mobile. We propose two data dissemination algorithms that aim to minimize mobile sink's location update control overhead and at the same time offer balanced power consumption in the network. The first algorithm is designed for applications which have rather stringent data delivery requirements, whereas the second algorithm is proposed for rather delay tolerant applications.

- Finally, we address multi-channel assignment problem in the last part with the aim to minimizing energy consumption of the network while also enhancing the network throughput at the same time.

1.4.1 Thesis Contributions

The contributions of this thesis consist of analysis of energy efficient routing choices in wireless body area networks, two data dissemination mechanisms for large mobile sink-based WSNs and a multi-channel assignment scheme with the goal of minimizing energy consumption of the network. Moreover, in the last contribution, the channel assignment algorithm also aims at increasing network throughput along with minimizing the energy consumption of the network. Here, we list the proposals made during this thesis along with their motivations;

1.4.1.1 Energy Based Data Dissemination in Wireless Body Area Networks

A Wireless Body Area Network (WBAN) is composed of small wireless health monitoring sensors capable of monitoring health factors like blood pressure, temperature, pulse rate etc. These sensors are attached to a human corps and they send the monitored information to the remotely installed health monitoring server by passing through a relay like a smart phone or a PDA to which the wearable sensor transfers data via wireless technologies like Bluetooth [Tec12] and ZigBee [All12] etc. Due to very short distances between wireless sensors and the relay unit like PDA, multi-hop communication is usually not needed. Recently some researchers proposed to deliberately use multi-hop communication between the on-body sensors by deliberately minimizing the transmission power and termed it as energy efficient as compared to direct higher power communication over a single hop which does not seem to be plausible.

Contribution: in order to test the above mentioned two arguments, we did the power consumption analysis for wireless body area networks to find out which option consumes lesser network power; a single hop high power transmission to the PDA or a very low power multi-hop transfer.

- Y. Faheem, S. Boudjit: ”Wireless Body Area Networks: Information Dissemination Analysis”, *in Proceedings of 3^{rd} IEEE HealthINF Conference*, 20-23 Jaunuary, 2010, Valencia, Spain

1.4.1.2 SN-MPR Algorithm for Mobile Sink WSNs

Majority of the algorithms found in the literature propose static sink-based data dissemination. However, the static sink can be seen as a bottleneck in enhancing network's lifetime, since nodes close to sink die quickly due to excessive relaying. On the other hand, sink mobility solves this problem by distributing the energy consumption in the network. However, the sink now needs to periodically update the network about its changing position to ensure sensors-to-sink connectivity, and this additional control traffic overhead increases the network's energy consumption. Some works try to minimize this control traffic by supposing that sensors know the mobility pattern of the sink and can calculate its current position. However, such algorithms require fine tuned geographical positioning devices or localization algorithms; higher economical cost of GPS devices and/or increased energy consumption of the localization algorithms would make the use of these algorithms impractical in real sensor platforms. Taking these limitations into account, this contribution proposes a distributed local path repair mechanism which limits the broadcast of sink location update messages to only those subset of network nodes whose route towards sink is affected by the change in sink position. No assumptions have been made about the availability of geographic positioning or sink mobility patterns.

Contributions: to achieve the above mentioned goal, we propose a distributive local repair based algorithm for WSNs named SN-MPR which limits the transmission of sink location update messages to only the nodes which have been affected by its mobility. Simulation results show that local-repair technique combined with efficiency of Multi-Point Relay broadcast [QVL02] reduces network energy consumption, thereby increasing network lifetime.

- Y. Faheem, S. Boudjit and K. Chen: Dynamic Sink Location Update Scope Control Mechanism for Mobile Sink Wireless Sensor Networks, *in Proceedings of 9th Wireless On-Demand Networks Conference (WONS)*, Italy, 2011

- Y. Faheem, S. Boudjit: SN-MPR: A Multi-Point Relay Based Routing Protocol for Wireless Sensor Networks, Proceedings of 3rd IEEE/ACM Int'l Conference on Green Computing and Communications & Int'l Conference on Cyber, Physical and Social Computing (CPSCom/WISARN), Hangzhou, China, 2010

1.4.1.3 A Duty-Cycle Aware SN-MPR Algorithm

A wireless radio consumes power in transmission, reception, idle listening and sleep states. Among these states, transmission consumes maximum power followed by approximately equal consumption in reception and idle states, while power consumption is almost negligible when radio is put to sleep state. Among these states, idle listening is the major power consuming factor in scalar WSN platforms because of the relatively low traffic rates; transceiver is in idle listening state most of the time and has high power consumption cost almost equivalent to the cost incurred in reception state. Thus, this power resource wastage in idle listening needs to be avoided by using radio only when communication is desired. In the literature, this issue is usually addressed at two layers: a) at MAC layer by controlling the radio's duty cycle and b) at routing layer by organizing topology into virtual structures like clusters and virtual grids where only a limited number of nodes stay awake to ensure sensors to sink connectivity, whereas remaining nodes switch-off their respective radios.

Contributions: in the second contribution, we propose a duty-cycle aware version of the SN-MPR algorithm for applications in which the sink need not always be mobile. This algorithm allows the nodes which are not involved in data relaying to minimize power consumption by switching off their respective radios when communication is not desired. Simulation results demonstrate that this duty-cycle aware algorithm is more energy efficient than SN-MPR, balances energy consumption in the network and thus increases network lifetime.

- Y. Faheem, S. Boudjit: Duty-Cycle SN-MPR Algorithm for Mobile Sink Wireless Sensor Networks, Elsevier Journal of Network and Computer Applications *(submitted)*

1.4.1.4 A Traffic-Aware Channel Selection Algorithm for 802.15.4 based WSNs

Traditional single channel communications have poor network performance due to frequent interferences caused by concurrent transmissions in the same geographical area. Moreover, network quality further degrades with increase in density and the scale of WSNs. This only wastes the scarce battery resource due to excessive collisions and channel access delays. Contrarily, multiple channels enable concurrent transmissions in the shared medium over orthogonal physical spectrum, and optimal channel distribution schemes can significantly increase the network throughput. Multi-channel assignment problem has been throughly addressed for multi-radio wireless mesh networks, however, it has not been exploited for WSNs where majority of the routing protocols work only on single channel [LYC$^+$05] [E. 08] [IGE$^+$03] [eaS08] [WC07] [CKN08] [LPY$^+$08]. Although, existing wireless networks platforms like micaz [Mot12] and telosb [Coo12b] are equipped with single, half-duplex transceivers which are capable of communicating over multiple channels. Only recently, few works have addressed proposed multi-channel communication algorithms for WSNs [CHH$^+$06] [LHA08] [WWF$^+$09] [YCF$^+$10] [WSHL08]. The exploitation of non-overlapping channels in these algorithms does increase the network throughput, however, most of these algorithms do not ensure QoS to applications while assigning channels, because they do not consider variable data rates into account. For instance, in the case of multimedia WSNs as they are equipped with audio-visual sensors in addition to simple scalar ones.

Contributions: in order to address the aforementioned limitations of the existing schemes and minimize power wastage due to increased interference in single channel communication protocols, this work proposes a traffic-aware, channel-width adaptation algorithm for 802.15.4-based heterogeneous WSNs. The proposed algorithm named Traffic-Aware Bandwidth-Adaptive (TABA) makes topology aware and traffic aware channel assignments by not only using sixteen standard 2MHz wide channels as specified in the IEEE 802.15.4 standard [IEE03], but inspired from work by Chandra et. al. [CMM$^+$08], TABA algorithm also variates channel widths to increase or decrease maximum channel capacity according to varying traffic rates.

- Y. Faheem, S. Boudjit: TABA: A Traffic-Aware Channel Selection Protocol for 802.15.4 Based Wireless Sensor Networks, *in Proceedings of the 12th ACM international symposium on Mobile ad hoc networking and computing (Mobihoc)*, Paris, 2011

1.5 Thesis Organization

The remainder of this thesis is divided into seven chapters. In chapter 2, we give an overview of the research on data dissemination mechanisms in WSNs and then we classify existing strategies into different classes. In chapter 3, we provide analysis of the energy consumption in wireless body area networks to show that deliberately using multi-hops in such networks might not be energy efficient as argued by some existing works. In chapter 4, we present our SN-MPR data dissemination algorithm along with its performance evaluation. Next, we discuss a duty-cycle aware version of SN-MPR algorithm in chapter 5, and present its performance evaluation. In chapter 6, we concentrate on network capacity enhancement strategies in the heterogeneous WSNs, and provide a brief state of the art of channel assignment strategies in the said domain, followed by the proposal of our TABA channel assignment algorithm. Finally, we conclude this thesis and also discuss possible future research directions in chapter 7

Chapter 2

Overview of Data Dissemination Strategies in Wireless Sensor Networks

Contents

The data dissemination protocols proposed initially for wireless sensors networks considered sink as a static entity [IGE$^+$03] [WTC03] [MA01] [SL02] [YG02]. However, as shown in the figure 2.1, the static sink based WSN suffers from the energy hot spot problem as sensors close to the sink have considerable traffic as they forward data reports of other nodes to the sink. Due to heavy relaying, nodes close to the sink consume their battery power more rapidly and quickly die off. The death of sink's neighbors causes a disconnection between sink and the rest of the network which is still functional. On the

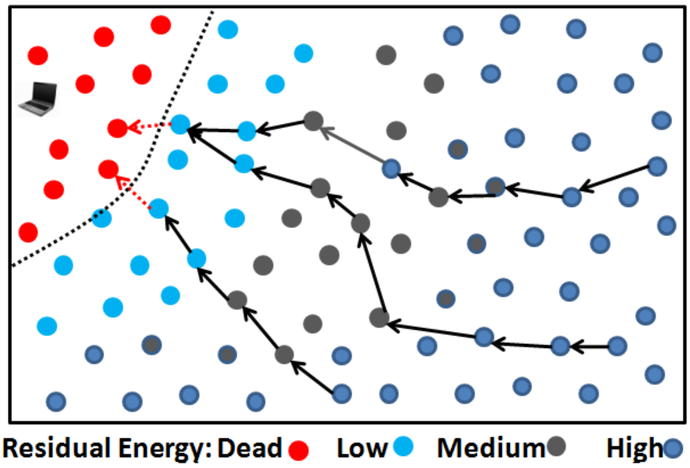

Figure 2.1: Energy Hot Spot Problem with Static Sink WSNs

other hand, sink mobility mitigates energy hot spot problem as change in the position of the sink distributes the role of heavy relaying among different nodes of the network, which ultimately helps in increasing the network lifetime. Due to this advantage, Mobile Sink based Wireless Sensor Network (MSWSN) has received a lot of attention from the research community during past few years. Its appealing characteristics of providing longer network lifetimes, delay optimizations and the flexibility to adapt dissemination strategies according to the requirements of applications have proved to be more efficient. Numerous mobile sink based data dissemination strategies have been proposed. This chapter presents state of the art literature review on MSWSN data dissemination strategies. Issues and flexibilities that did not exist with static sink WSN have been discussed. A classification of the available data dissemination strategies and their pros and cons has been discussed.

Al-Karaki et al. in [AKK04] presented a very detailed state of the art review about the routing techniques in WSN. They presented complete classification of routing categories and architectures. Moreover, I. F. Akyildiz et al. [eaI02] also present a state of the art review on OSI protocol layers in WSN. Their work presents a complete classification of different techniques and methodologies in WSNs. When [eaI02] and [AKK04] were written most of the research in those days was on routing issues with static sinks. It was only later that mobile sink data dissemination approach got real attention. Its multi-fold advantages like hot spot problem removal, longer network lifetimes, energy optimizations were realized and studied.

This lead to the proposal of numerous mobile sink data dissemination strategies. Sink mobility introduced new issues that did not exist in data disseminations techniques with the static sink. This chapter presents a state of the art review on MSWSN data dissemination techniques, the available options and its related issues. The rest of this chapter is organized as follows. Section-2.1 presents architectures and classification of major strategies in MSWSNs. Section-2.2 gives a detail overview on available MSWSN and their classification according to discussion of section-2.1. At the end in section2.3, we conclude the chapter and also discuss the reasons which lead us to choosing particular characteristics for the algorithms proposed in this thesis.

2.1 Data Dissemination and Collection Classification in MSWSN

MSWSN data dissemination algorithms can be classified on the basis of network organization structures, sink cardinality, mobility patterns, route creating entities and application types. A MSWSN data dissemination algorithm is generally a combination of these aforesaid characteristics. Below, we will provide a detailed classification of the existing WSWSN data dissemination algorithms;

2.1.1 From Multi-hop to Passive Data Collection

In static sink WSNs, sink anchors itself at some particular position in the network, broadcasts its location to the whole network and starts collecting data. This mechanism has low network organization costs but offers limited network lifetime as continuous data gathering from the same position creates energy hot spot problem around the sink; Nodes deployed closer to the sink consume more power than the distant ones due to excessive relaying and die quickly. This results in network disconnection since sink is inaccessible to the sensors and vice versa, although, major portion of the network is still functioning. Sink mobility not only solves the hot spot problem, but as described below, it also offers new data collection choices ranging from single hop passive communication to multi-hop data source to sink data dissemination mechanisms.

2.1.1.1 Multi-hop Relaying

This is a classical case, where *source-to-sink* communication is over multi-hops [WWJ+09] [iHsE06] [iHIsE06], and at least $\frac{distance_{source,sink}}{transmission\_range}$ hops are required to deliver data to the sink. Unlike static scenario, mobile sink needs to regularly transmit its changing location to the network. Location update cost is high at the expensive of low data delivery delays for time sensitive applications. This compensates for the hot spot problem as sink's neighbors don't loose battery power before the rest of the network which was resulting in disconnected network in case of static sink WSNs.

2.1.1.2 Limited *h* Multi-hop Communication

In some applications, sink might be interested in gathering data from particular network regions. In this case, it broadcasts queries within a limited $TTL=h$ hops area, and then gathers data from only that region. One such proposal is given by Chatzigiannakis et. al. [CKN08]. In this approach, sink divides network into equal square regions, and then it randomly visits each region passing through the cell centers which enables the sink to collect information from a certain area at a time. This mechanism reduces power consumption because of lesser data relaying, but this gain comes at the expense of data delivery delays as nodes have to wait for sink's queries. Thus, this technique is feasible for applications which have non-stringent delay requirements.

Methodology	**Power Consumption**	**Data Delay**
Multi-hop Relaying	medium	Medium-low
Limited Multi-hops	low	medium-high
Direct Source to Sink	high	lowest
Passive Collection	lowest	highest

Table 2.1: Efficiency of Data Collection Approaches in Wireless Sensor Networks

2.1.1.3 Direct Source-Sink Transmission

In another approach, sensors could directly transmit data reports to a sink over a single hop. Obviously, this approach seems impractical keeping in view the power constraints and intrinsic limitations of the wireless medium; Especially, in case of homogeneous WSNs where all deployed sensors have similar limited resources. However, this approach might be feasible for heterogeneous WSNs where some powerful nodes are deployed along with normal sensors. These powerful nodes gather data reports from near by neighbors, then, transmit them directly to the sink via high power transmissions. One such algorithm is proposed by Khan et. al. [eaN08], where powerful cluster heads gather reports from resource constrained h hop neighbors, and transmit them directly to the sink.

2.1.1.4 Passive Data Collection

In this approach, no multi-hop transmissions are required as sink visits all sensors one by one to collect data from them [CKNR07] [CKN08] [SRJB03]. One such mechanism is proposed in [CKN08] in which the mobile sink periodically broadcasts short range beacons, and its current neighbors respond by transmitting their buffered monitored reports to the sink. In another work, Shah et. al. [SRJB03] also present a passive data gathering technique in which the mobile sink referred to as MULE in which mobile sinks gather data from one hop neighbors and then drop of the data at the access points in order to be delivered to the control center.

Naturally, passive data collection offers longest network lifetimes, but this advantage comes at the expense of very long data delivery delays. Thus, passive data collection is feasible for extremely delay tolerant applications like habitat monitoring. Sometimes, a small part of the network might be unreachable due to harsh terrain. Under such circumstances, the proposed algorithm should be flexible enough to perform limited hops communication so that maximum data be gathered.

2.1.2 Mobility Patterns

Sinks can adapt mobility schemes according to the nature of WSN application and its requirements. A sink may move continuously updating the routing paths as it moves, or it may follow anchor position based solutions where it sojourns at some position for certain duration, configures routing paths, sends queries and then data forwarding takes place. Once the sink sojourn time expires, it moves to a new sojourn position and restarts the whole process. Based on the moving pattern, sink mobility schemes can be classified into the following categories [eaS08]:

2.1.2.1 Random Mobility

This is the most widely adopted scheme for MSWSN [WWJ+09] [PLKK09] [LYC+05] [AD06] [WWJ+07a] [iHsE06] [KAK03] [JOW+02]. No network information is required as sink's decision of deciding next sojourn position is random. This is easily applicable solution as sink's movement pattern does not depend upon network conditions. This may not give optimal network lifetimes. It might be possible for source nodes to route data towards various places of the network. Random mobility requires continuous sink position updates and route reconstruction.

2.1.2.2 Predictable Mobility

In certain applications, user (sink) moves according to a certain strategic plan. Sink could inject its trajectory information into the network. Sensor nodes then use this information to determine sink's future location. Lee et. al. in [LPY+08] propose a Predictable Mobility-based Data Dissemination protocol (PMDD) for battlefield application which uses the same working principal. Authors are of the view that the movement pattern of battlefield soldiers and firefighters are determinable in advance as they follow a planned strategy. Thus in PMDD, the sink sends a data query which contains its trajectory and speed. This information enables the source nodes to predict sink's current position after time duration *t*. Once source node calculates sink's current position, it transmits its data report towards its expected current location.

Predictable sink mobility strategy does not require frequent sink location updates which makes it more efficient than non-predictable mobile sink routing strategies as they require continuous global network-wide updates [XL04], or in some protocols local updates [iHIsE06] [WWJ$^+$09] [PLKK09] [CSA03] to reconfigure the routing paths. However, predictable mobility is acquired at the expensive of costly on-board GPS chips or localization techniques which incur traffic overhead due to additional message exchanges, and thus also consume more battery power.

Another category of predictable mobility includes periodic movement over fixed paths like on a straight line or in a circle. This enables the source nodes to estimate the arrival time of the sink. Thus, nodes can optimize their sensing tasks and transceiver power consumption which is the major source of energy drain in WSN.

2.1.2.3 Controlled Mobility

In this case, sink mobility is not predictable but could be controlled by certain network parameters such as residual energy, event location etc. For instance, sink can take mobility decisions in order to increase the network's lifetime. One such example is HUMS protocol [YC07] which proposes a sink mobility strategy for continuous data-gathering applications. In HUMS, every propagated data packet contains the position and identifier of the nodes having the maximum and minimum residual energies encountered on the path. Once the sink obtains information about the current energy distribution of the network, it moves towards the node which has maximum residual energy, and during its trajectory, the sink avoids the regions which have minimum residual energy nodes.

Basagni et. al. in [eaS08] propose a similar but heuristic approach for controlled sink mobility called Greedy Maximum Residual Energy (GMRE) mechanism. In GMRE, sink collects residual energy information from surrounding areas. An area with better residual energy than sink's current position greedily directs the sink towards it. Unlike HUMS [YC07], sink also takes into account current data routes release cost, new route establishment cost, sink mobility rates and constraints on sink mobility to increase global energy efficiency.

In event-based WSN applications, upon the detection of events, a considerable amount of traffic might be generated to deliver reports to the sink which might be currently too far from the event detecting nodes. On the other hand, there is very little traffic in the network when no event is detected. In order to minimize energy consumption in event-based applications, Vincze et. al. [VVV$^+$06] proposed a sink mobility technique which enables the sink to adapt its mobility according to the evolution of current events; sink tries to position itself at a place which minimizes the overall energy consumption of multi-hop transmissions.

2.1.3 Information Dissemination Categories

As also stated by [HC08], the data communicated in WSN belongs to one of the following categories;

2.1.3.1 Data Dissemination

This is the dissemination of the monitored information i.e. the tasks that sensors are supposed to perform and report to the sink. The amount of data traffic ratio depends upon the application type (event based, continuous delivery, query based) and the data dissemination strategy in use (section 2.1.4).

2.1.3.2 Meta-data dissemination

This includes the dissemination of information about the sensed data. For example, in TTDD protocol [LYC+05], the source node upon detecting an event constructs a virtual grid and sends data announcement packet to one node in every cell of the grid. These packets contain the information about the detected event and the source. Upon the reception of this meta-data packet by one of its current neighbors in the virtual grid, the sink queries the source node to direct the sensed information towards its current position.

2.1.3.3 Sink-location Dissemination

It is the information the sink needs to transmit to the network to declare its locality. Unlike static sink WSN routing, this information needs to be disseminated at a much higher frequency in MSWSN. The frequency, scope and the cost of this location dissemination depends on the speed, mobility pattern, the data collection strategy (section 2.1.1) and the data dissemination approach in use (section2.1.4).

2.1.4 Data Dissemination Approaches

The biggest advantage of using a mobile sink is the flexibility of deciding who keeps the information, how it is kept and where it is kept. This is not the case with static sink WSNs where the only data gathering choice is *many-to-one* i.e. nodes direct their reports to the sink over multiple hops. Below, we present the flexibilities provided by the mobile sink in choosing data dissemination approaches;

2.1.4.1 N to 1 dissemination

All the nodes send their sensed data to a single node present inside the network. This enables the sink to collect the network-wide data by visiting a single representative node. The representative data collecting node can either be selected by the nodes themselves by Geographic hashing, by the sink or through some other mechanism. The problem with this dissemination approach is that it has zero fault tolerance as the failure of the representative data collecting node would cause the loss of all the collected information. Moreover, this approach would also create energy hot spot problems as nodes near the data collector affecting the life time of the network.

2.1.4.2 N to M dissemination

In N-to-M strategy, a small subset M among N nodes takes the responsibility of storing the network wide data. This enables the sink to collect most of the monitored data by visiting only a subset data collector nodes as in the case of [JOW$^+$02].

2.1.4.3 1 to N dissemination

With this strategy, every node keeps data reports of the rest of the N-1 nodes i.e. the entire network. Thus, the sink can visit any single node to capture network wide data. This technique is not practical due to its extreme energy consumption requirements. However, this technique might be useful in battlefields where enemy presence may not permit any user (sink) mobility. Sensors destruction due to enemy attack might also have disconnected the network. The authors could not find such proposal in the current literature as current technology suffers the problem of energy scarcity. Advancements in energy storing technology could make it possible in the coming future.

2.1.4.4 1 to M dissemination

In 1-to-M strategy, every node sends its monitored information to a subset of nodes. Thus multiple instances of monitored data are distributed in different locations in the network. In [VZF09] data report generated by a node is randomly forwarded to maximum $\frac{n}{2}$ nodes. All forwarding nodes also keep copy of data report before forwarding them. The goal is to enable the sink to collect network wide n information by visiting only a small subset of nodes. This approach may be used in applications where the WSN is deployed in very harsh extremely inaccessible terrains. Under such cases, a flying device like unmanned aerial vehicle could pass over some part of the network once and collect all the data in a single go.

2.1.4.5 1-1 Dissemination

In this strategy, every sensor stores the monitored data in its local buffer. The mobile sink visits all the nodes one by one, and passively collects the monitored information from them. Once such multiple sink passive data collection algorithm is proposed by I. Chatzigiannakis et al. in [CKN08] in which mobile sinks individually visit deployed sensors, transmit beacons periodically during mobility in order to collect data from nodes which can receive their beacons; sensors upon receiving sink‚Äôs beacon send their monitored information to the sink. The 1-1 passive data dissemination strategy is feasible for delay-tolerant applications. Under certain conditions, as in harsh terrains, the sink might not be able to visit some part of the network. Therefore, the deployed MSWSN data dissemination/gathering strategy should be flexible enough to detect and cope with such problems.

2.1.5 Data Dissemination Structure Creating Entity

The network entity which creates the data dissemination structure has a subtle influence on the overall performance of the WSN. In WSNs, data dissemination structure can be created by either the sink itself or it can be created by a sensor or a set of sensors collaboratively depending upon the design of the protocol in use. Here we, discuss the available routing structure creating entities, their effects on the network performance and the pros and cons of every approach;

2.1.5.1 Source-oriented Approaches

In such an approach, an event detecting source node creates a data dissemination structure, either a tree or a virtual grid, to transmit a packet containing the meta-data of the event and source’s identity in order to inform the sink about the event. Once the mobile sink receives the information about the occurrence of the event through a meta-data packet, it utilizes source created tree or virtual grid structure for forwarding query and then collecting event report from the source. One advantage of this approach is that the data dissemination structure is not affected by the changing positions of the sink due to mobility. TTDD [LYC$^+$05] and SEAD [KAK03] are two well known source-oriented protocols. Building one routing structure per source node can be energy consuming especially when the number of sources in a network is large and/or if too many sources detect events at the same time as in the case of mobile events as in surveillance application. Detection of a moving target in such an application would trigger all the sources which detect the moving object to create an independent routing structure per source node. Due to this reason, protocols like TTDD [LYC$^+$05] and SEAD [KAK03] are not energy efficient when the number of sources is large and these protocols may also not be suitable to be used with low rate WSN standards like IEEE 802.15.4 due to high control traffic overhead rates.

2.1.5.2 Sink-oriented Approaches

In sink oriented approach, the sink periodically disseminates its location information to the network and creates a routing structure e.g. a tree rooted at itself; this enables the sensors to direct their data reports towards the sink using this sink created structure. Sink-oriented approaches require the sink to broadcast periodic location updates to keep nodes aware about the sink's location, and thus continuous control traffic is generated in the network, as opposed to only in the case of event detection in source-oriented approaches described above. However, it has its own advantages; only one routing structure is created in the network as sensors don't have to create meta-data structures of their own. Moreover, the control overhead generated due to periodic broadcast of network wide sink location update packets can be minimized if efficient broadcast algorithms are used, just like two algorithms proposed in this thesis. These algorithms will be discussed in the chapter-4 and chapter-5 of this dissertation.

2.1.6 Sink Cardinality

The limited-hop or passive data collection strategies described in section-2.1.1 reduce the energy consumption of the network, but they increase the data delivery latency. In order to reduce this data delivery latency, multiple sinks can be deployed in the WSN to reduce the waiting time of the nodes between consecutive visits of the sink. Once deployed, multiple mobile sinks can coordinate by distributing the data gathering regions and tasks among themselves. A number of multiple sink based data gathering approaches have been proposed in the recent few years [CKNR07] [iHIsE06] [WC07] [WXC$^+$08] [K. 09] [SA07b] [CKK08] [SA07a] [CMP07]. For instance, Chatzigiannakis et al. propose three multiple-sink based passive data collection algorithms in [CKNR07];

i- A centralized algorithm that balances the data collection region among sinks. Every sink knows its own data gathering region.

ii- A distributed random walk based mutual path avoidance algorithm whereby a sink passing by an area leaves behind the trace of its trajectory in the sensor nodes visited by it. This enables the other sinks to avoid regions that have already been visited by their counterparts.

iii- Thirdly, a distributed cluster-based approach is proposed in which the nodes organize themselves into clusters, and a Cluster Head (CH) is selected in each of the clusters. These cluster heads then aggregate data from the members of their group. Moreover, virtual service groups of cluster heads are formed to distribute the work load among multiple sinks. Once this is done, one sink per group is responsible for collecting data from the region chosen by it.

In another work [WC07], X. Wu et al. propose a combination of static and mobile sinks for a WSN application in which the data is continuously disseminated by the sensors. In this algorithm, a static sink is deployed at the center of the network, whereas the mobile sinks collect data from neighbors which are limited within *h-hop* distance from them. When a node has a packet to transmit to the sink, it forwards the packet to the mobile sink if its hop distance to the mobile sink is less than the distance to the static sink or vice versa.

2.2 MSWSN Data Dissemination Strategies

A WSN may consist of hundreds of thousands of nodes deployed over large regions. Under such conditions, disseminating monitored information to the sink(s) with efficient utilization of power, memory and processing resources requires sophisticated routing structures. This requires that the deployed physical topology be organized into virtual infrastructures such as virtual grids, clusters, dominating sets, trees etc as these virtual infrastructures offer many advantages: They decrease the communication overhead as sink's queries, location update messages, and data reports generated by the nodes pass through these overlay structures, unlike flat approaches in which all nodes take part in routing the traffic, all the time. Once, a virtual infrastructures like cluster or grids are created, then the data dissemination algorithms can be used on top of these virtual infrastructures. This sections presents a brief classification of the data dissemination strategies used in MSWSN. Table-2.2 presents categorization of some of the under described mechanisms. These mechanisms utilize combination of the techniques described in the section-2.1.

2.2.1 Virtual Grid Based Data Dissemination

TTDD: In the Two-tier Data Dissemination protocol (TTDD) [LYC$^+$05], an event-detecting source node creates a virtual grid in the network as shown in the figure-2.2, and nodes closest to the grid's crossing points are selected as meta-data dissemination nodes. These dissemination nodes contain the information about the detected event and its source. When the sink requires information, it broadcasts a query in its local area; the dissemination node in the neighborhood of the sink forwards this query towards the source node via dissemination nodes on the virtual grid. Then, the source forwards data to the sink on the reverse path of the sink's query packets. TTDD protocol is not very energy efficient as it requires the

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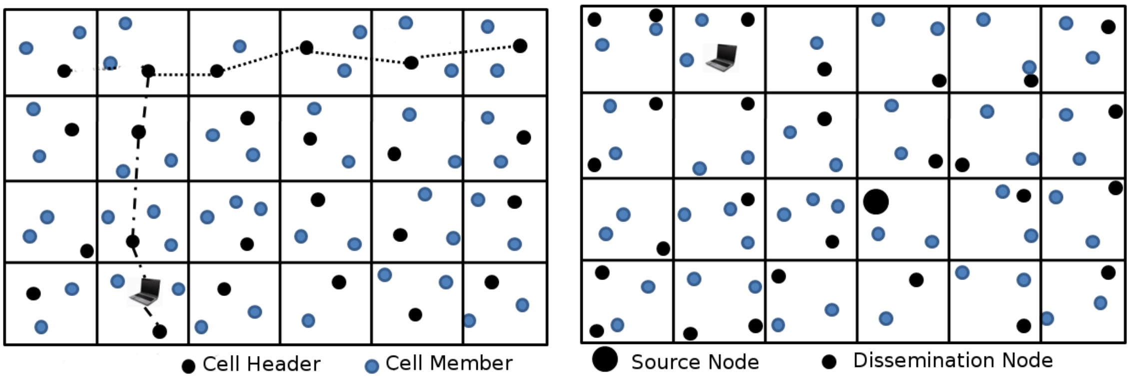
[1] Application Type {Event (E), Query (Q), Continuous (C)

Protocol	Location	Energy	Sink Oriented Approach	Application Type	Multiple Sinks	Mobility Model	Structure [1]	Aggregation	Local Update
TTDD [LYC^{+}05]	✓		source	E	✓	Random	VG		
SMS [PLKK09]			✓			Random	Tree		✓
PMDD [LPY^{+}08]	✓		✓	E+Q	✓	Predictable	Nil		
LURP [WWJ^{+}07a]	✓		✓	E+C		Random	Greedy		✓
ALURP [WWJ^{+}09]	✓		✓	E+C		Random	Greedy		✓
ART [iHsE06]	✓		✓			Random			
HUMS [YC07]	✓	✓	✓	C		Controlled			
QCCA [KAK^{+}08]	✓			E+Q		Any		✓	
MS-SWR [SA07a]									
DST [iHIsE06]	✓		✓		✓	Random	Tree	✓	
EEDD [ZXW06]	✓			Q	✓	Random	VG		✓
GBEER [K. 09]	✓			E	✓	Random	VG		
CODE [XL04]	✓	✓	✓	Q	✓		VG	✓	
SEAD [KAK03]	✓				✓	Random	Tree		
MILP [eaS08]		✓	source			Controlled			
26 [XL04]	✓		✓	E		Random	VG	✓	✓
19 [WWJ^{+}07a]		✓		C		Controlled			✓
10 [M. 08]				C					
DSM [PLL^{+}07]			✓	Q		Random	Tree		

Table 2.2: Classification of Data Dissemination Strategies



(a) Example Virtual Grid (b) Source based VG like TTDD

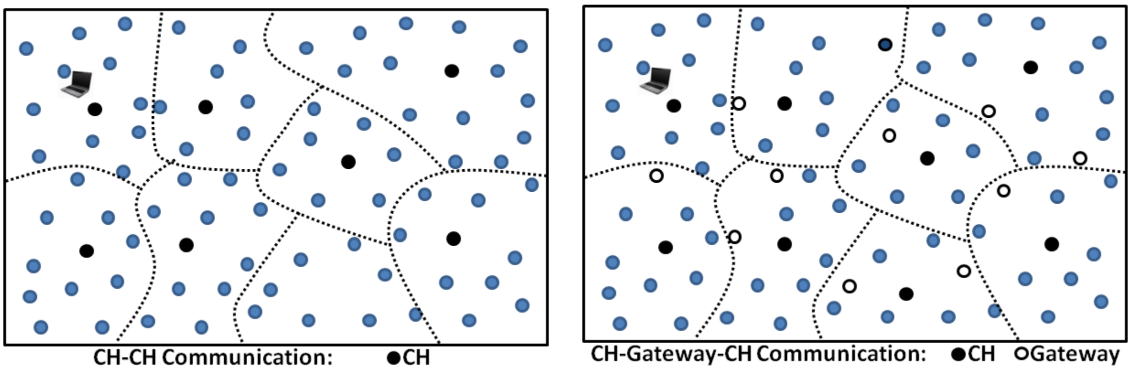
Figure 2.2: Virtual Grid Based Data Dissemination

creation of a separate routing structure per event detecting source; increase in the number of event detecting nodes will increase the control overhead.

LBDD: In Linear-Based Data Dissemination protocol (LBDD) [E. 08], a permanent virtual data gathering *rectangular area* is created in the middle of a square grid. Upon the detection of a stimulus, the source node sends data packets to the already created *rectangular area* nodes called *in-line* nodes. The source's data packet is stored by the first in-line node encountered on its trajectory. When the sink wants to collect that data report, it sends queries to the virtual area and once the query packet reaches inside virtual area, it travels linearly until the node which has buffered the data report is encountered; data is then transmitted towards the sink via geographic routing.

GBEER: Kweon et. al. [K. 09] propose a multiple sources to multiple mobile sinks data transfer algorithm in which the location aware nodes built a single permanent grid structure by dividing network into cells. Every cell has a randomly selected header node which is responsible for aggregating the locally collected data. The header node disseminates an announcement packet containing meta-data of the event in linear cells (called quorums). Thus, information of the detected event is distributed linearly in cell headers. The mobile sink queries the nearest cell about any event detected in the network; the meta-data packet is then sent to the sink. The GBEER protocol is an improvement over TTDD [LYC^{+}05], because as compared to one virtual grid per source, only one virtual grid is built in the network.

CODE [XL04]: This protocols also divides the network into a virtual grid in which one node among many members is selected as grid head; only the transceiver of the grid head remains active whereas other cell members switch-off their radios to sleep mode to economize power consumption. Then, the members of each cell take turns to become group head in order prolong network time by distributing their relaying loads. In the CODE protocol, when the sink wants to gather data, it assigns a grid head which is closest to it as its agent which is responsible disseminating sink's queries and gathering data on behalf of the sink. Once the agent collects data reports from the source node, it transmits them to the sink. Sink mobility out of the current agent's vicinity causes the selection of new agent node which creates a new path towards the source node. Also, old agent forwards cache-removal message to the source to delete the old path.



(a) CH-CH Communication (b) CH-Gateway-CH Communication

Figure 2.3: Cluster Based Data Dissemination Structures

2.2.2 Cluster-Based Approach

Organizing the physical topology into virtual hierarchical structures via clustering also offers better energy efficiency and scalability in WSNs [WHB00] [eaN08] [LCC06] [WHFW08] [ACN06] [NKN10]. In cluster-based algorithms, few nodes called cluster heads are selected either distributively by nodes themselves or by a central entity. These Cluster Heads (CHs) are then responsible for collecting and aggregating data reports from their respective members, and for forwarding queries to them. Moreover, CHs communicate with other CHs in order to relay messages to/from the sink via multiple hops. Here, we discuss few cluster-based algorithms;

LEACH Protocol: Low Energy Adaptive Clustering Hierarchy (LEACH) protocol was proposed by Heinzelman et. al. in [WHB00]. In LEACH, few nodes are randomly selected as cluster-heads in every round without any mutual coordination. This allows the nodes to rotate the role of the cluster-head which helps in balancing distributing power consumption in the network. In LEACH, nodes periodically transmit data reports to their respective cluster-heads, which then compress the received reports and transmit an aggregated report to the sink.

LEACH increases the network lifetime, however it has some limitations due to the assumption made by authors. Firstly, LEACH supposes that nodes have sufficient power to directly communicate with the sink over a single hop which might not be possible in large scale networks. Secondly, in every round, a subset of nodes become cluster-heads randomly with a certain probability without any mutual coordination. Thus, it is possible that in a particular round, most of the cluster-heads are aggregated in the same region while some other network regions have no cluster-heads in their vicinity. This limitation may make it impossible for certain nodes to communicate with the sink.

QCCA: Quasi Centralized Clustering Approach (QCCA) [eaN08] is a data dissemination protocol designed for heterogeneous sensor networks in which a limited number of powerful nodes are deployed along with the standard sensor nodes. These powerful location-aware nodes act as cluster heads. They collect and aggregate data of their respective neighboring regions over multi-hops, and then deliver reports directly to a mobile sink or to a satellite over a single hop. The power cluster-heads utilized in QCCA algorithm will minimize energy consumption of normal sensors but this solution might not be economically feasible for some applications.

HCDD: Unlike QCCA, the Hierarchical Cluster-based Data Dissemination (HCDD) protocol [LCC06] does not require powerful position-aware nodes. In HCDD, nodes organize themselves into clusters and inter-cluster communication is done through the gateway nodes; in QCCA, CHs communicate directly with the sink. In HCDD, mobile sink selects a nearby cluster-head to disseminate queries to the network, gather data from it and then eventually transfer reports to the sink.

Cluster-based techniques are better for large scale WSNs. This advantage comes with additional overhead of hierarchical structure maintenance. Local leaders in cluster-based techniques quickly drain off their energy as they also perform additional relaying and data aggregation tasks. Therefore, nodes should periodically exchange CH role to balance this load among all nodes, and this role exchange process should incur minimum control overhead in order to increase the lifetime o the network.

2.2.3 Non-Hierarchical Approaches

Flat data dissemination mechanisms propose homogeneous role assignment to all nodes [IGE$^+$03] [LPP$^+$06] [WWJ$^+$09] [YC07]. In flat protocols, no virtual infrastructures are created and all nodes equally participate in relaying and query forwarding tasks. Since, sink mobility necessitates periodic location updates to reconfigure source to sink routes, flat data dissemination mechanisms may have limited scalability and some might not be an ideal choice for large MSWSN applications. In order to minimize the control overhead, some data dissemination strategies also propose to dynamically repair the nearby paths by means of which the mobile sink updates its location to a limited neighborhood. Depending upon the efficiency of the limited zone repair technique the traffic overhead due to location update messages can be reduced by to a great deal. Here, we discuss some flat routing algorithms belonging to this category;

ART Protocol: Hwang et al. proposed an Adaptive Reversal Tree (ART) based algorithm in [iHsE06] which creates a tree directed towards a sink-assigned temporary root node. The temporary root node initially floods a control packet to all the nodes; source nodes then use this tree to direct data reports towards root node which then delivers data to the sink. When the sink moves out of the range of this temporary root node, it assigns one of its current neighbors as a new root which then performs local repair to reconfigure only the affected paths to direct the reversal tree at itself. This reversal tree dynamically changes with changing sink position through the assignment of new temporary root node. ART protocol efficient path repair mechanism reduces sink's communication overhead but may result in sub-optimal source to sink paths.

ALURP and LURP G. Wang et. al. in [WWJ+07a] propose a geographic data dissemination approach called LURP. In LURP, sink initially floods its location information plus a Virtual Circular area (VC) centered around its current position. Afterwards, the sink performs only local broadcasts as long as its mobility is confined in the VC; Sink's exit from the VC requires global flooding. In LURP, nodes outside the VC use geographic routing to route data towards the sink. Once a packet arrives inside the VC, shortest path routing is used on paths which are update by sink through local broadcasts. G. Wang in ALURP [WWJ+09] propose an amelioration over LURP. In ALURP, radius of the VC is adapted according to the mobility of the sink which reduces local broadcast cost. In addition, number of global flooding requirements are also reduced as VC size can be dynamically increased. This protocol is efficient in terms of control overhead but due to geographic routing the nodes need to be equipped with expensive GPS components which are neither cost nor energy effective.

DST: The Dynamic Shared Tree (DST) [iHIsE06] protocol uses a multiple-sink, sink-oriented tree-based technique that utilizes local update technique to repair the broken links. Only one sink called Master sink registers itself to a temporary root node which then creates tree rooted at itself. Other sinks, known as slave sinks utilize the tree created by the master sink. The data transfer to the slave sinks is via a longer and inefficient *source→master_sink→slave_sink* path. DST protocol can be applicable for firefighter application in which all firefighters may need information from one centralized source for better coordination; only one firefighter maintains the master routing structure whereas other firefighters (sinks) utilize the master sink for data collection.

Sink Mobility Support (SMS): Sink repairs changing paths by acquiring neighbor tables of neighbor nodes. This enables sink to repair changing paths due to mobility. Unlike LURP [WWJ+07a], ALURP [WWJ+09] and DST [iHIsE06] SMS does not require position aware nodes. However, the protocol seems to repair paths only through 2-hop exchanges which could result in extremely inefficient longer paths. Nothing is mentioned about when and if global updates are used or not to minimize this limitation.

All of the above described algorithms try to reduce the flooding costs with more and less efficiency, each one offering its own advantages at the expense of some limitations. Thus, the decision of choosing a particular algorithm for a WSN application should be made in the light of the requirements and characteristics of the application under consideration.

2.3 Conclusion

In this chapter, a state of the art review of MSWSN data dissemination strategies has been presented. These strategies have been classified according to the mobility models, data collection architectures, route initiating entities, application types and sink cardinality. Moreover, the effect of these strategies on the network lifetime and the application requirements has been discussed, and pros and cons of each of these classified approaches have been highlighted. It is shown that the aforementioned criteria play a vital role in the performance of WSNs. Thus, based on the classifications presented in this chapter, the strategies selected by the contributions made by this thesis are briefly summarized below;

Sink mobility model: As discussed earlier in this chapter, sink mobility pattern could be random, predictable or continuous, and the choice of a particular mobility model depends largely upon the nature of the WSN application under consideration. In the first contribution proposed in the next chapter, we will see that the propagation of the sink's position update broadcasts is distributively controlled by the nodes deployed in the network rather than the sink itself. Therefore, the algorithm works irrespective of whatever mobility pattern the sink follows. Due to this reason, random mobility pattern has been used for the performance evaluation. Whereas, a different mobility pattern is chosen for proposition in chapter-5 due to different working principal of the proposed algorithm.

Data dissemination approach: In order to eventually disseminate data reports to the mobile sink, one among the N-to-1, N-to-M, 1-to-N, 1-to-M or 1-to-1 approach may be used depending upon the application for which the network is deployed, as discussed in the section-2.1.4.2. Except the N-to-1 approach in which the monitored information is transferred to the sink by nodes, other methodologies require the sink to personally visit all or a subset of nodes to gather reports from entire network. Thus, such data dissemination techniques are suitable for delay tolerant applications. Since, we propose a data dissemination approach for rather real time application in the next chapter, therefore a N-to-1 data dissemination approach has been adopted.

Data Dissemination Structure Creating Entity: Source-oriented routing structures induce more control traffic overhead as every event detecting node in the network creates its own routing tree (SEAD [KAK03]) or a virtual grid (TTDD [LYC$^+$05]), requiring routing structures equal to number of sources in a single network. In contrast, sink-oriented approaches have lower control traffic overhead as they require the creation and maintenance of only one routing structure per mobile sink. Due to these reasons, a sink-oriented approach is selected in this thesis, and a routing tree rooted at sink is preferred over virtual grid structure because: a) virtual grid creation requires GPS enable sensors and b) the intrinsic nature of the proposed algorithm is suitable with sink-rooted tree structure.

Chapter 3

Energy Based Data Dissemination Analysis in Wireless Body Area Networks

Contents

Wearable health monitoring systems integrated into a telemedicine system are novel information technology that will be able to support the early detection of abnormal conditions and will allow prevention of their serious consequences. Many patients can benefit from continuous ambulatory monitoring as a part of a diagnostic procedure, optimal maintenance of a chronic condition or during a supervised recovery from an acute event or surgical procedure.

Recent advances in technology has led to the development of small, intelligent, wearable sensors capable of remotely performing critical health monitoring tasks and then transmitting patient's data back to health care centers over wireless medium. But to the day, energy remains to be a big constraint in enhancing Wireless Body Area Networks (WBAN) [Net12] lifetime. Some recent literature on WBANs proposes multi-hop sensor to gateway data relay as more energy efficient than single hop communication. There are studies which argue contrarily. This study analyzes the single vs multi-hop energy consumption effect for real short range sensor devices.

3.1 Architecture of a Wireless Health Monitoring Platform

A general multi-tier system architecture of a WBAN is shown in the figure 3.1. It consists of the following main components;

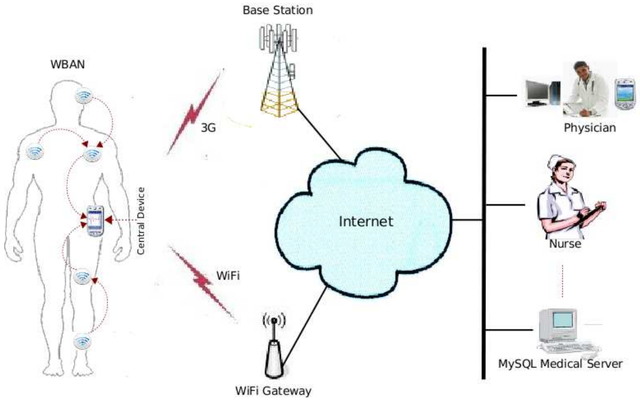


Figure 3.1: Wireless Health Monitoring Platform

- A Wireless Body Area Network (WBAN) is composed of various wireless health monitoring sensors attached to a human corps which are ultimately connected to a central data relaying device via wireless technologies like Bluetooth [Tec12] and ZigBee [All12] etc.
- A relaying central device, which could be a cell phone or a PDA. This component will implement the functions of active patient monitoring, especially in the case of connection loss with the remote server. It will serve as the bridge between the WBAN and the global Internet network.
- A remote server that collects all data from various patients and stores them in a central database. It will generate statistics, information for doctors, and alarms in case of emergency which will then be transmitted to a personal care unit.
- The doctor or, generally speaking, the medical staff will be the privileged consumer of the platform provided information. Due to this, users can have multiple interactive interfaces:
  - Mobile Interface: this interface will be designed for personal digital assistants (PDAs) or smartphones.

However, the establishment of such an architecture requires solving certain scientific problems at all the platform levels. In this chapter, we concentrate our analysis on the patient side and focus on the power consumption of routing between sensors and the central device.

3.2 Energy Analysis in Wireless Body Area Networks

Several studies have shown that multi-hop routing in WBAN result in a non-negligible lifetime increase of sensors as compared to direct communication between sensors and the central device. In this case, information dissemination between sensors and the central device requires an ad hoc routing protocol. Contrarily, some other studies argue that direct communication between sensors and the central device considerably increase the lifetime of a wireless body area network. They show that executing a multi-hop ad hoc routing protocol on embedded sensors consumes too much energy.

In this chapter, we are exploring both of the aforementioned information dissemination techniques in a WBAN. The objective here is to make a trade off analysis between the number of hops in the network and the energy consumption. In this study, both analytical models and simulations are used.

3.3 Problem analysis

Power consumption for transceivers is different in different communication states i.e. transmission/reception/idle/sleep. Transmission energy depends upon the power with which signal is propagated to attain longer ranges while consumption in other states is less variable. Unlike other technologies, reception/idle state consumption for low power, limited range WSN is not negligible as compared to transmission state power consumption. Thus global energy minimization requires optimum selection of transmission range. Latré et. al. in [Dem04] showed that utilizing multi-hop communication by reducing transmission power in WBAN reduces overall energy consumption. This is true but authors in [Dem04] ignore increased energy consumption due to multiple receptions. Wang et. al. in [QWY06] propose a realistic power consumption model for WSN. [QWY06] shows that multi-hop communication is more energy efficient when destination is out of reach. That is when destination cannot be reached in single hop. They show that multi-hop communication by controlling transmission power does not necessarily result in energy gain. This is due to non-negligible energy consumptions in reception and Idle modes.

In sensor motes energy consumption in reception and idle mode is relatively high. It can be equal to or greater than transmission energy consumption for low power transmissions.

Scenario	Hops	Distance	Nodes
1	1	60	$n_s \rightarrow d$
2	2	30	$n_s \rightarrow n_4 \rightarrow d$
3	3	20	$n_s \rightarrow n_3 \rightarrow n_5 \rightarrow d$
4	6	10	$n_s \rightarrow n_2 \rightarrow n_3 \rightarrow n_4 \rightarrow n_5 \rightarrow n_6 \rightarrow d$

Table 3.1: Simulated scenarios

Transmission power (dBm)	Power consumed (mW)	Reception power/Listening power (mW)	Idle	Transmission range (meter)
05	76.2	30		60
-07	32.4	30		30
-14	27.9	30		20
-20	25.8	30		10

Table 3.2: Mica2 Mote Power Consumption and Range Values

For low transmission ranges as in WBAN, utilizing single hop data delivery to gateway node while other sensors are put in idle/sleep state might be more energy efficient. Real experiments conducted in [AFP+04] show that reception and idle listening consume a considerable amount of energy. Especially for sensor nodes, very low power transmissions for ranges as short as in WBAN consume lesser power than reception. For micaZ motes [Ins12b], reception energy is higher than transmission energy even with maximum power transmission. Above stated variations in literature, motivated us to better understand this energy consumption scenario and choose a better communication strategy for our future test bed implementation for WBAN.

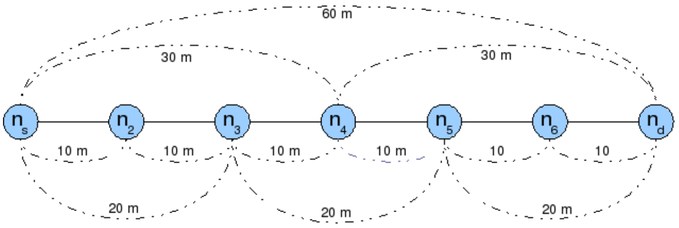


Figure 3.2: Simulation scenarios

3.3.1 Channel model and Energy Consumption

Let P_t and P_r be the transmission and reception signal power respectively, where P_r is equal to receive sensitivity of mica2 node (-98 dBm). Let d be the communicating nodes' inter-node distance and, L the system loss, then our WSN model can be represented by the well known *TwoRayGround* radio model:

$$P_r = ReceiveSensitivity = \frac{P_t G_t G_r h_t h_r}{d^4 L} \tag{3.1}$$

Where G_t=G_r=1.2 are antenna transmission and reception gains respectively. h_t=h_r=16cm are transmission and receptor's antenna heights. Transmission power P_t is varied according to desired range. Equation (3.1) can be rearranged to determine *d* for given values of P_t as follows:

$$d = [\frac{P_t G_t G_r h_t h_r}{P_r L}]^{\frac{1}{4}} \tag{3.2}$$

We need minimum P_t that ensures successful reception of packet at destination with P_r>*ReceiveSensitivity*. For given values of P_t, approximate range values are obtained from radio model given in (3.2). The actual power consumed by mica2 while transmitting with permissible power P_t is obtained from CC1000 data sheet [Ins12a]. The range results for given P_t (Table 3.2) conform to the mica2 data sheet and experimentally obtained range values.

Energy consumption of sensor nodes in various states can be obtained by the following equations:

$$E_{tx} = P_{tr} \times T_{tx}$$

$$E_{rx} = P_{rec} \times T_{rx}$$

$$E_{idle} = P_{idle} \times T_{idle}$$

where P_{tr}, P_{rec}, P_{idle} are the powers consumed by the Mica2 mote's CC1000 transceiver in transmission, reception and idle mode respectively, and T_{tx}, T_{rx}, T_{idle} are times spent in each mode. Time for transmitting a packet of size *b* bits is equal to $[\frac{b}{R}]$ where *R* is the data rate. Total energy consumed by the network is given by;

$$E_{total} = E_{tr} + E_{Rec} + E_{idle}$$

3.3.2 Simulations

Network Simulator 2 (NS-2) is used for performing simulations. We performed simulations utilizing the actual power consumption values of sensor motes in various states. In order to have an insight view of the energy consumption in various working modes, the power consumption values of Mica2 [Cooa] sensor motes have been used. Mica2 has an on-board CC1000 transceiver for communication. Thus power consumption values for communication have been taken from CC1000 data sheet [Ins12a].

Deployed topology consists of a set of seven equidistant nodes $\{n_s, n_2, n_3, n_4, n_5, n_6, n_d\}$ deployed linearly with adjacent inter-node distance of 10 meters. This accounts to maximal source-destination ($n_s \rightarrow n_d$) distance of 60 meters. Source n_s generates packets at regular intervals and transmits them towards sink n_d. Simulations are performed with four different relaying scenarios. Details are given in figure 3.2 and in table 3.1. $n_s \rightarrow n_d$ transmission is varied from single hop to a maximum of six hops. In all the scenarios source node n_s sends 50 bytes packets towards destination node n_d. MAC layer issues like collisions, retransmissions and scheduling are not taken into account. This is realistic assumption as the goal here is to analyze only the energy consumption effect with varying hop distances.

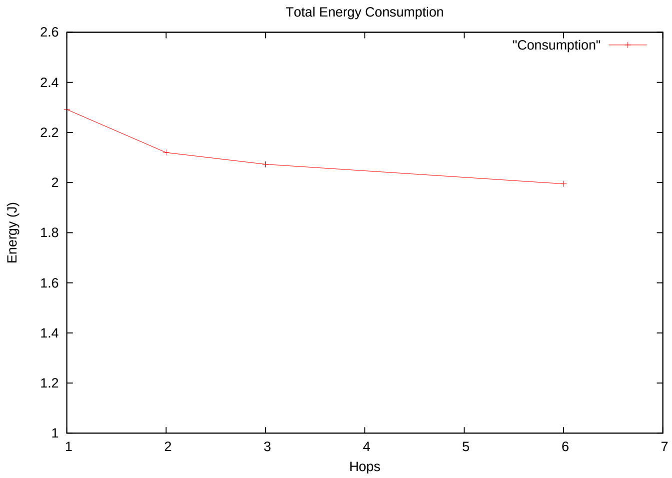


Figure 3.3: Total Energy Consumption when Radio always ON/IDLE

Figure 3.3 shows total network energy consumption when radio is always active i.e. either in Tx/Rx state or in idle state. In this case energy consumption reduces a bit with increasing number of hops. Note that for this case P_{rec}=P_{idle}=30mW. This is because current draw through mica2 is same when it is either receiving a packet or performing idle listening. Power transmission values P_{tr} for each case are obtained from table 3.2. Energy consumption for direct $n_s \rightarrow n_d$ communication is 2.29J. For two hops $n_s \rightarrow n_4 \rightarrow n_d$

and three hops $n_s \rightarrow n_3 \rightarrow n_5 \rightarrow n_d$ scenarios total energy consumption slightly reduces to 2.12J and 2.07J respectively. Results are not very appealing. With least transmission power of -20dBm, that draws 25.8mW from mica2, minimum total consumption of 1.99J is acheived. This accounts to maximum energy saving of 13% as compared to direct $n_s \rightarrow n_d$ communication. At -20dBm, power consumed $P_{tr} < P_{rec}$ (25.8 <30mW). As compared to this, multiple WBAN sensors are very close to each other (tens of centimeters) and to the gateway node e.g. PDA. In such a scenario, further reduction in transmission power will increase multiple receptions/Listening dominancy over transmission energy. Thus multi-hop option is not practical in small WBAN. Heinzelman et. al. in [WHB00] propose a WSN based energy model. They also conclude that multi-hopping is energy efficient when destination cannot be reached in a single hop. A contrary argument to this point could be that transmission range reduction is necessary to avoid collisions and large number of over hearings. This is true, but in small scale WBANs, source to sink synchronized single hop communications while keeping other nodes' transceivers off would be more optimal.

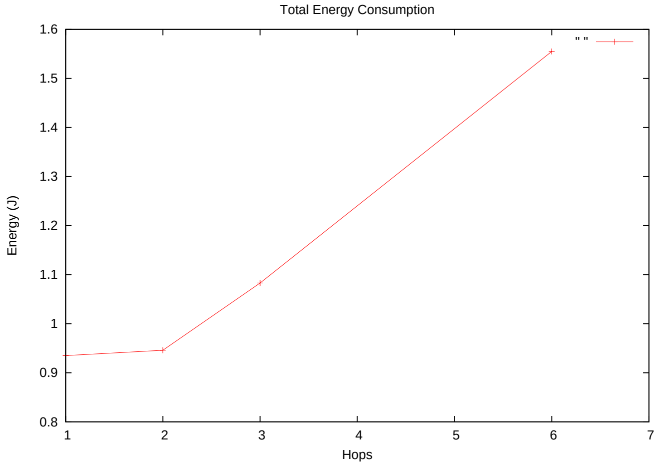


Figure 3.4: Total Energy Consumption when Radio "ON" only for transmission

Figure 3.4 shows network energy consumption when nodes switch on their radio only when they need to transmit their information. Energy consumption for direct $n_s \rightarrow n_d$ communication is 0.93J. For two hops $n_s \rightarrow n_4 \rightarrow n_d$ and three hops $n_s \rightarrow n_3 \rightarrow n_5 \rightarrow n_d$ scenarios total energy consumption increases to 0.946J and 1.083J respectively. With least transmission power of -20dBm, that draws 25.8mW from mica2, minimum total consumption of 1.55J is acheived.This accounts to 40% increase in network's total energy consumption as compared to direct $n_s \rightarrow n_d$. Clearly, reducing transmission range to perform data relaying does not seem to be good option in WBAN. Energy efficiency gain in WSN is maximum when sensor nodes periodically go to deep sleep mode. We are not considering this case

Algorithm 1 : Beacon processing at node$_i$

```
Recv(Beacon$_{new}$,node$_j$)
    // New Beacon received
    if (sequence_no($Beacon_{new}$) >
        sequence_no($Beacon_{last}$))
            next_hop$_{coordinator}$=node$_j$
            rebroadcast(Beacon$_{new}$)
    //multiple copies or old beacon received
    else if (sequence_no($Beacon_{new}$) <=
        sequence_no($Beacon_{last}$))
            discard($Beacon_{new}$)
```

here as turning off health sensing equipment may prove fatal to patient's life. Patient's health needs to be regularly monitored and transmitted to the concerned data center. Although the periodicity of monitoring depends upon the nature of observation and patients condition. It may not be necessary to transfer health update to data center. This could be utilized only under emergency condition to trigger the call for medical assistance.

From the aforementioned discussion, it is concluded that unless really required, unnecessary multi-hop relaying in case of WBANs should be avoided. However, some real experiments show high path attenuation values in WBAN with α as high as 5.8. This may happen, for instance, if a patient is sitting on a chair, and has one sensor installed on his back and the PDA device is in his front pocket. In this case, the PDA may not be able to receive a packet transmitted by the sensor as the signal gets absorbed by the human body and the chair on his back. If such a condition arrives, the data dissemination mechanism in use should be able to transmit data to the personal coordinator via another health sensor installed on the body; the sensor on the back could transmit data to the PDA via another sensor installed on for example patient's shoulder as this would allow nodes to communicate with PDA over two hops, when required. The assumption of using maximum two hops seems logically correct as this option will be used in only special scenarios described above. Normally, PDA to sensors' connection will be over a single hop due to the very small scale of the network.

To solve the aforementioned issue, a simple beacon based protocol is used by the personal coordinator to configure the WBAN network. The personal coordinator (PDA) can simply broadcast a beacon with a Time-To-live value of 2 to its neighbors, which then rebroadcast it only once. This enables the health sensors to also configure a two hop path to the PDA by using the health sensor from which the beacon is received with the highest rssi value. Afterwards, a sensor can send its packets to the coordinator via an intermediate health sensor if it cannot be directly reached in a single hop due to reasons explained in the aforementioned example. The pseudocode of such a beacon mechanism is presented in the Algorithm-1.

Our assumption of considering two hops has also been enforced by the IEEE 802.15.6 Wireless Personal Area Networking group which recently recommended to use two hops in case of WBANs.

3.4 Conclusion

An energy consumption comparison for various communication scenarios has been made. It has been shown that at very low ranges, transceivers consume almost equal or more power on receiving packets than on transmitting them. Thus, deliberate reduction of transmission range to induce multi-hop scenario is not energy efficient. Though this is device dependent but general characteristics of very low power transceivers seem to show the same results.

In the following chapter, we deal with the energy efficient data dissemination in large scale wireless sensor networks in which the sink is mobile. We will present our first contribution, named SN-MPR algorithm , which is a distributive local path repair data dissemination mechanism for MSWSNs.

Chapter 4

SN-MPR: A Multi-Point Relay Based Data Dissemination Algorithm for Mobile Sink based Wireless Sensor Networks

Contents

Several recent works propose mobile sink based data gathering approaches to distribute energy consumption in Wireless Sensor Networks. However, mobility based algorithms require the sink to periodically update its location to the network to ensure multi-hop connectivity. This additional information increases the control traffic overhead, and thus energy consumption also increases. In this chapter, we propose a distributive energy efficient sink location update mechanism for mobile sink WSNs, along with a *preemptive buffering* data collection technique. This sink location update mechanism combines MPR based broadcast [QVL02] algorithm with a distributed local repair mechanism, whereby, sensor nodes dynamically control the scope of sink location update messages. In *preemptive buffering* mechanism, sink's neighbor nodes act as temporary data collection points, referred as roots, to prevent data loss when sink moves out of their vicinity. We show by simulations that our proposal effectively reduces the energy consumption and data losses of the network.

4.1 Introduction

Advancement in micro-electronics technology has led to the development of small inexpensive wireless sensor devices capable of performing wide range of tasks. A wireless sensor consists of a micro-controller, wireless transceiver, memory, battery and sensor(s) for the task it is supposed to perform like temperature, pressure, motion detection, etc. These small devices are capable of performing fine grained sensing tasks and then communicating them over wireless media. Sensor networks applications are very vast ranging from large scale habitat monitoring, battle fields, intrusion detection applications to small critical health monitoring body area networks. Due to their wide applications, WSNs have seen a lot of interest from the research community. In fact, numerous issues related to data dissemination, energy consumption, auto-configuration, etc. have been addressed.

Communication is the most power consuming task in WSNs and since sensors are accompanied by low power batteries and battery replacement is not possible in many applications, any proposed solution for WSNs should consider the energy consumption constraint. Indeed, sensors may be randomly spread by an airplane, for example, over a large harsh terrains or an enemy area, and hence are not human accessible once deployed. Limited energy resource limits communication range and Sensors-Sink communication could be over multi-hops. Therefore, a routing protocol to compute the paths between the sink and all the sensors is needed. In addition, once deployed sensors should organize themselves to create a functioning network. Self-organization and data dissemination techniques that ensure longer network lifetimes while respecting application requirements and minimum control overhead are an utmost necessity.

We consider a mobile sink based WSN where sensors are not aware about sink location, and therefore, periodic broadcast is needed to update the network about the changing paths in order to ensure sensors-sink data dissemination. However, flooding based solutions, like Directed Diffusion (DD) [IGE+03] protocol are not suitable for resource limited WSNs, as they consume a lot of energy and increased control overhead also affects network throughput.

In this chapter, we propose a Multi Point Relay (MPR) based efficient sink location update mechanism for mobile sink WSNs called SN-MPR. We combine MPR based broadcast algorithm [CJ03] with a distributed local repair technique. This mechanism limits the scope of sink location update messages to the area affected by the mobility of the sink. This will significantly limit the control messages overhead and save network energy.

4.2 Related Work

Routing algorithms designed for static sink WSNs offer shorter network life span, as sink's neighbors die off quickly due to continuous data relaying. This makes the sink inaccessible to the remaining network, though, majority of the nodes are still functioning. On the other hand, mobile sink based data gathering algorithms promise longer network lifetimes, as sink mobility ensures energy distribution. However, mobile sink increases traffic control overhead, as it has to update network about its changing position to ensure connectivity to the network. Hence, routing algorithms that ensure energy efficient sink accessibility should be devised for MSWSNs. In this section, we give a quick reminder of some the existing algorithms, also discussed in chapter-2, that try to minimize periodic sink location update costs and compare them with the proposed approach. As stated earlier, WSN data dissemination structures can be broadly classified into two main categories;

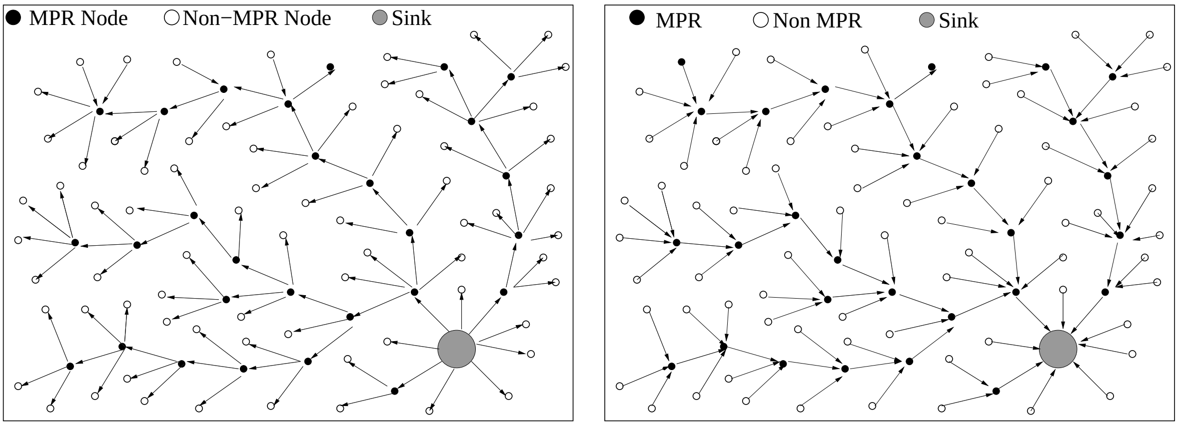
Backbone-based structures: In such structures, nodes organize themselves into either clusters or virtual grids to create virtual a topology on top of the physical topology. In cluster-based approach, nodes organize themselves into clusters where mostly only one Cluster Head (CH) per cluster is responsible for data aggregation and query forwarding LEACH [WHB00] [eaN08] [LCC06] [WHFW08] [ACN06] [NKN10]. Cluster-based mechanisms are scalable, however, they require periodic communication among nodes to switch the CH role in order to distribute power consumption in the network which increases power consumption. An alternate approach is to organize the network into virtual grids on the basis of their geographic location in which one node per cell may perform data aggregation and communication with the network as is proposed in [K. 09] CODE [XL04] [LYC+05]. Both, cluster-based and virtual grid based mechanisms scale well for large networks, but they require periodic exchange of control messages to maintain virtual structures. Moreover, virtual grid construction also requires on-board GPS units or localization techniques which is not cost effective from both energy and economic point of view.

Tree-based dissemination structure: may be either source-based or sink-based. In *source-*

based structures, event detecting node broadcasts event's information to the network and creates a tree-rooted at itself, and then, the sink uses this tree to retrieve data from the source. Contrarily in *sink-based* structures, sink broadcasts its location to the network which creates a tree rooted at the sink or sink assigned root node. Then, nodes use the reverse tree path to deliver data to the sink. Both, source-based or sink-based mechanisms have their pros and cons. Source-based tree makes routing structure independent of the sink mobility as sink may use any tree branch to demand data from the source. However, source-based structure requires one tree formation per source-node making this mechanism infeasible for applications which have large number of sources. In contrast, sink-rooted mechanisms have relatively lower routing structure creation overhead as they require only one tree for per sink, irrespective of the number of sources. However, sink mobility necessitates periodic location updates to the network. These periodic location updates increase the control traffic overhead and network's energy consumption. Several solutions have been proposed to reduce these periodic sink location updates [WWJ$^+$09] [PLKK09]. This work also addresses a tree-based sink-rooted data dissemination scenario, and the objective is to minimize the control overhead of the mobile sink's location update traffic without damaging the data delivery application related traffic. Our proposed MPR broadcast based algorithm maintains a dynamic data dissemination tree with minimum control overhead.

G. Wang et. al. [WWJ$^+$07b] proposed a location aware solution called LURP. In LURP, sink initially floods its geographic location and a virtual circular area (VC) centered at its current position to the whole network. Afterwards, the mobile sink performs periodic local flooding inside VC area and sink's exit from VC requires global flooding. Sensor nodes use geographic routing to direct sensed information towards the VC. Once a packet arrives at a node within VC, shortest path routing is performed on sink updated paths. LURP's VC based limited area flooding reduces sink location update overhead, but this mechanism still uses pure flooding when sink moves out of VC and also requires access to GPS for geographic routing.

J. Yang et. al. [JYS] (as cited in [XLS10]) proposed a local path repair scheme in which, similar to SN-MPR algorithm, sink location update messages are transmitted only to affected paths. In [JYS], the mobile sink periodically exchanges hellos with its neighbors and it marks a neighbor as *lost* when it looses a two hop connection with it and *semi-lost* when it excludes a direct neighbor from its one hop neighborhood but that *semi-lost* neighbor is still accessible via another one hop neighbor termed as *recovery neighbor*. Local repair mechanism in [JYS] differs from SN-MPR in two aspects. Unlike [JYS], SN-MPR does not require the sink and sensors to obtain geographic location information through GPS/localization techniques as nodes in SN-MPR use reverse path routing on the tree constructed by MPR-based forwarding of sink's location update messages. Secondly,



(a) Sink location Dissemination (b) Sensors→Sink tree with sink as root

Figure 4.1: SN-MPR location dissemination and path configuration mechanism

location update message in SN-MPR contains only sink's address and it is forwarded by only those MPRs whose next hop towards sink changes, where as location update message in [JYS] contains list of *recovery neighbors'* addresses which is *a)* selectively forwarded by receiver nodes if their address is included in *recovery neighbors* list and/or *b)* retransmitted by those receivers for which next hop node towards the sink changes due to sink's position update. Nodes, which satisfy the above stated second condition in [JYS] broadcast location update messages through flooding, which stops at a node whose next hop towards sink does not change which could result in greater overhead than selective MPR broadcast.

In Sink Mobility Support (SMS) [PLKK09], the sink repairs changing paths by acquiring neighbor tables of neighbor nodes. Global broadcast is avoided at the cost of periodic exchange of neighbor tables between sink and its neighbor nodes. Continuous local repair may result in sub-optimal paths. [PLKK09] does not address this sub-optimal path effect. Also, it does not address when/if global location update will be performed. Unlike [WWJ$^+$09], [PLKK09] does not require node location awareness. All of the mentioned solutions [WWJ$^+$07b], [WWJ$^+$09], [JYS], [PLKK09] reduce flooding costs but still use flooding when network wide update is needed. Our proposed algorithm not only performs local path repair to limit the scope of location update messages to only the routes affected by sink mobility, but also utilizes efficient MPR-based broadcast to minimize the location update overhead.

4.3 Multi-Point Relay Broadcast

This section provides a brief introduction of the MPR broadcast mechanism. This mechanism was proposed by Qayyum et. al. [QVL02] for mobile ad hoc networks. It has been used in the well known Optimized Link State Routing (OLSR) protocol [CJ03]. The MPR broadcast mechanism reduces flooding costs by minimizing the number message forwarding nodes. In [QVL02], nodes exchange *hello* messages periodically, and a *hello* generated by a node n_i contains; source's address, its *willingness* to be chosen as MPR, already discovered neighbors list and their link statuses (unspecified, asymmetric, symmetric, lost). Exchange of *hellos* enables every node to obtain information about its one hop and two hop neighbor, referred to as n_{i_1} and n_{i_2} respectively. One should note that apart from hello messages, neighboring nodes will only communicate if they have established a symmetric link between them.

Once, n_i has discovered its one-hop and two-hop neighbors, it chooses a minimum subset among its n_{i_1} neighbors, such that node n_i can access all its two hop neighbors i.e. n_{i_2} via this subset. These minimum number of one hop neighbors are referred to as MPRs of node n_i. A topology update message generated by n_i will only be forwarded by its MPRs, whereas its remaining non-MPR n_{i_1} neighbors do not forward them. Thus, the MPR broadcast algorithm minimizes network update costs by reducing the number of retransmissions of broadcast packets. One should note that a node can avoid itself from being selected as a MPR by its neighbors by lowering its *willingness* field value. It can also refuse to act as MPR by setting its *willingness* to 0. This field can be used by the nodes which have less battery power to avoid being selected as a MPR.

4.4 Motivations and Assumptions

4.4.1 Motivations

- In ad hoc networks, nodes periodically diffuse topology control messages to handle mobility. However, such continuous periodic updates are not necessary in many WSN applications as deployed nodes remain static throughout their lifetime. Therefore, n_{i1_hop} and n_{i2_hop} sets of n_i do not change after network initialization phase, except due to energy drain out. For the moment, link loss due to congestion is not being considered.

- In comparison to the *many-to-many* communication paradigm in ad hoc networks, WSNs with *many-to-one* paradigm require only path towards the sink. Only the sink requires to inform the network about its location and disseminate queries into the network. Other MPR nodes never generate location update messages. They only forward the sink generated messages. Their function is to provide a virtual topology to reduce flooding cost. This lead us to consider a sink rooted tree based routing protocol.

- SN-MPR requires only two hop neighborhood information. Nodes do not need to have network wide unique addresses and information.

4.4.2 Assumptions

Following assumptions are made in the proposed network model:

- Once deployed nodes remain static as is the case in most WSN applications.
- Nodes are not aware of their geographical position.
- Network topology is relatively dense.
- Nodes transmit with same transmission power.
- Nodes transmit monitored data to a single mobile sink.

4.5 SN-MPR

This section presents the proposed SN-MPR algorithm. All changes made in MPR algorithm [QVL02] to adapt it for resource constrained sensor networks have been explained.

4.5.1 Neighbor Discovery

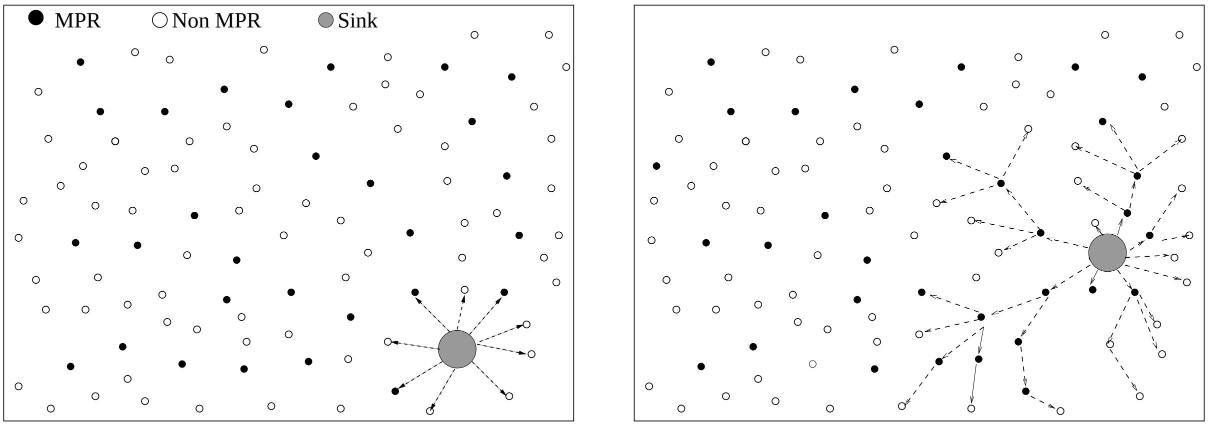
Neighbor discovery mechanism of SN-MPR is the same as described in 4.3, however *hellos* are not exchanged periodically through out the network lifetime. *Hellos* in SN-MPR are exchanged only the during network initialization phase and afterwards between the mobile sink and its current neighbor nodes. SN-MPR's neighborhood discovery process can be divided into two categories. Static sensor-to-sensor neighbor discovery and mobile sink-sensor neighbor discovery.

4.5.1.1 Sensors Neighborhood Discovery

This is executed at the network initialization phase as sensors remain static after deployment. Once configured, there is no need to send periodic control packets. Newly deployed nodes start exchanging hello packets with 2 seconds interval. With every new *hello* message reception, new neighbors and/or their link information is updated. *Hello* message exchange is stopped, once no more changes are detected in already discovered neighbors and their links after certain number of *hello* exchanges. At the end of the neighbor discovery process, an efficient MPR based virtual relay topology is in place. Afterwards, nodes will transmit hellos only under certain conditions.

4.5.1.2 Sink Neighborhood Discovery

The mobile sink enters the network once the sensors' neighbor discovery process has converged. The sink transmits hello messages every 2 seconds. A node upon receiving a *hello* message verifies the ID of the sender. If sink is the source of the *hello* message, it replies to the sink with a hello packet. This updates the links between sink and its current neighbors. Note that nodes transmit hello packets only in response to sink's hello message. Periodic hello transmission does not occur as sensors' neighborhood discovery has already converged. This enables the sink to discover new neighborhood as it changes its positions. Sink and its neighbors delete their respective entries when they can no longer hear each other after SINK_NEIGB_HOLD_TIMEOUT of 2×hello_interval.



(a) Update message Dissemination Scope with Stationary Sink

(b) Update message Dissemination Scope with Mobile Sink

Figure 4.2: SN-MPR location dissemination and path configuration mechanism

4.5.2 Sink Location Updates

The sink broadcasts location update messages periodically to reconfigure changing paths and to transmit queries. Here, we refer to these as Sink Location Update messages (SLU). A SLU message contains the ID of the sink, and if required, the sink may also append its queries in this message. When sink broadcasts a SLU packet, it is only retransmitted by only its MPRs, and then onwards by the MPRs of its neighbors and so on till the message update is transmitted to the whole network. Thus, MPR broadcast consume much lesser energy than the protocols like Directed Diffusion (DD) [IGE+03] which uses pure flooding for broadcasting location updates. Figure-4.1a describes, how sink's generated SLU message is propagated in the network. One can observe that only a limited number of MPR nodes (dotted black) rebroadcast the message where as majority of non-MPR nodes (dotted white) receive the SLU message but do not forward it.

When the sink enters the network for the first time, it generates a SLU message and diffuses it to the whole network as shown in Figure-4.1a. However, when the sink is moving in the network, its mobility may affect the routes of only a limited network area between two consecutive periodic SLU messages generated by it; the routes of the nodes placed far away from the sink may not change towards it. The range of the network area affected due to change in the position of the sink depends upon its mobility characteristics such as its speed, direction and SLU message interval. Thus, it might not be feasible to update the whole network about its location frequently when in reality the paths of only a limited number of nodes change due to sink mobility. In order to tackle this, we introduce a distributed local path repair mechanism in order to reduce sink's location update costs in the section-4.5.5.

4.5.3 Reverse Tree Route Configuration

We propose a reverse tree based data dissemination mechanism in order to enable the network to communicate with the sink. Suppose the sink broadcasts a SLU message at an instant t, which is then received by its neighbors. Every neighbor of the sink chooses SLU message's reverse propagation path to configure its next hop route towards the sink. Every node n_i chooses as its next-hop relay node towards the sink, referred to here as $next\_hop_{sink}$, the neighbor from which SLU message is received with minimum hop count. Sink's all one hop neighbors will select their respective next hop relay as sink i.e. $next\_hop_{sink}$ = *sink address*, since the SLU is received directly from the sink. Then, only MPR neighbors of the sink retransmit SLU message in order to disseminate it in the whole network.

Naturally, in contrast to sink's one hope neighbors, its two hop neighbors ($sink_{2\_hop}$) and nodes beyond may receive multiple copies of SLU message from different neighbors due to transmission and queuing delays. However, in order to construct the reverse shortest-path sink-rooted tree, SLU receiving node should select as its next hop towards the sink the neighbor from which the SLU is received with minimum hop count, else the reverse tree will not be a shortest path tree and the resulting topology may have routing loops. Suppose, till instant $t+x$, n_i has received SLU message from several neighbors. Now, n_i will choose as $next\_hop_{sink}$, the neighbor which has shortest path towards the sink. This can be determined from Time To Live (TTL) value contained in SLU's packet header. The processing of a sink generated SLU message, reverse tree creation and local repair mechanism (section-4.5.5), when a node n_i receives SLU via an intermediate node n_j is explained in the pseudocode presented in the algorithm-2; all nodes configure their routes using this algorithm. Thus, the reverse MPR broadcast path creates a reverse routing tree which is rooted at sink. An example of such a reverse routing tree is presented in the figure-4.1b.

4.5.4 MPR Role Exchange

MPRs consume more energy than non-MPRs, because they also act as relays in addition to forwarding their own data. To distribute this role among nodes, we use the *willingness* field described in [CJ03]. In SN-MPR, once the battery level of a node n_i falls below a certain threshold, it lowers its *willingness* value and transmits it in a *hello* message. Neighbors upon receiving this *hello* observe the lowered *willingness* of n_i, and locally exchange few *hellos*. This helps in balancing the power consumption in the network as nodes reselect MPRs with higher residual energies. One should note that MPRs are not reselected periodically as hellos are exchanged only at the beginning of the network initialization phase; no more hellos are transmitted once the neighbor discovery process among sensors has converged. However, MPRs will only be reselected when later on a node decides to lower its willingness value to avoid acting as MPR as it has consumed too much energy in relaying. At this point, such a node will exchange only few hellos with its neighbors and this exchange will stop again.

Moreover, when the sink changes its position, its routing tree changes and thus the set of forwarding nodes among the MPRs also changes. This is because, a node n_i receiving a SLU from a neighbor n_j will forward it, if and only if, *node* n_i is MPR for n_j. Thus, nodes which forward sink location updates and relay data packets are different for different sink positions. Thus, as described in the upcoming sections, the non-leaf nodes in the routing tree automatically change with sink mobility which distributes data forwarding tasks among different sensors; Due to this relaying role switching, SN-MPR algorithm offers a better power consumption distribution in the network due to the nature of MPR algorithm [CJ03].

4.5.5 Local Repair

For a limited time interval, sink mobility affects only a limited network area. Thus, it may not be necessary to forward sink's SLU message to the whole network. We introduce a distributed local repair mechanism, whereby, MPR nodes dynamically decide whether to rebroadcast incoming SLU packets or not. A node upon receiving a SLU verifies if the previous next_hop node to the sink (next_hop_{sink}) and the node from which the new SLU has been received are same or not. In case, new SLU message is received from the same old neighbor, it is not forwarded as the routing structure of the node is not affected by the change in the sink position. However, if a new SLU message is received from a different neighbor than the previous one, then the receiving node decides to rebroadcast the SLU if it is MPR of the neighbor which just retransmitted the SLU. Furthermore, the receiving node redirects its traffic towards the sink via the sender of the SLU message.

Let us explain the functioning and the advantages of the local repair mechanism with two example topologies: one in which the sink remains stationary and the other in which the sink is mobile.

4.5.5.1 Local Repair Functioning with a Stationary Sink

First, consider a scenario where the sink remains stationary between two consecutive SLU messages. Here, we refer to these respective messages as; SLU_{old} and SLU_{new}. Let's suppose that the figure-4.1a and the figure-4.1b present the broadcast of the SLU$_{old}$ message and the reverse tree formation process respectively, and the figure-4.2a presents the situation when a SLU$_{new}$ is broadcast by the sink. Upon receiving the SLU_{new}*'s* message, sink's the MPRs among the sink's neighbors verify the sender of the SLU$_{new}$ message, and compare it with the sender of the previous SLU$_{old}$ message. If the sender of SLU$_{old}$ and SLU$_{new}$ is same, SLU$_{new}$ is not retransmitted as topology view of nodes beyond this zone will not change. Thus, if the sink remains stationary, its SLU packets will never be retransmitted by its MPR nodes, unless if for some reason the sink decides to explicitly order the nodes to retransmit the SLU message to the whole network without using local repair mechanism.

4.5.5.2 Local Repair Functioning with a Mobile Sink

Now let us consider a mobility scenario where change in the position of the sink increases the broadcast scope of SLU messages. The scope of the SLU$_{new}$ message depends upon sink's speed and direction. Suppose a *node* n_i had established $next\_hop_{sink} = n_j$ on the basis of the previous SLU_{old} message, and now n_i receives SLU_{new}. If the SLU_{new} is received from the same node n_j with minimum TTL value, then its transmission stops at n_i, and thus, it is not forwarded.

Contrarily, if a *node* n_i receives a SLU_{new} from a neighbor $n_k \neq n_j$, it will rebroadcast SLU_{new}, if and only if, n_i is MPR for n_k. Moreover, node n_i will also choose n_k as its next_hop relay towards sink. This is shown in the figure-4.2b where SLU_{new} is relayed only on dotted links. It is not relayed beyond that point because sink mobility has not affected the routes of nodes beyond that range.

In short, the scope of SLU messages is dynamically controlled by nodes in a distributed manner. The slower the sink mobility, the lesser is the range of SLU broadcast zone and vice versa. Clearly, this local update mechanism in combination with efficient MPR broadcast mechanism will reduce the network energy consumption.

Algorithm 2 : SLU message processing and Tree formation algorithm at node n_i

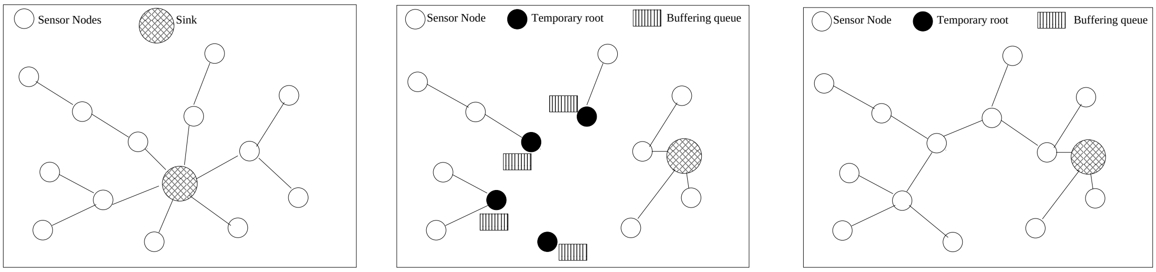
```
Recv($SLU_{new}$, $n_j$)                                             // $SLU_{new}$ broadcast by $n_j$
Initialize forward$_{SLU}$ ← false

if !Symmetric_link($n_i$, $n_j$)  // if $n_i$ & $n_j$ are not symmetric neighbors, drop the received SLU message
        drop($SLU_{new}$)
else
            // If the received SLU is seen for the first time, process it and update reverse tree route
        if (sequence_no($SLU_{new}$) > sequence_no($SLU_{last}$))
                if (is_MPR($n_i$, $n_j$))                                   //if $n_i$ is MPR of $n_j$
                        save($SLU_{new}$)                   // save $SLU_{new}$ message in a temporary buffer.
                        delay_relay($SLU_{new}$, delay_time)       // delay retransmission of SLU as another
same
                                                        // SLU message from a shorter path may arrive

                if ($n_i$→next_hop$_{sink}$==$n_j$)       // if reverse routing tree is unaffected by sink mobility
                        distance$_{node\_i,sink}$ = ttl($SLU_{new}$) // simply update hop count as distance to sink
                                                        // via same sink might have increased/decreased
                        forward$_{SLU}$ ← false;           // Even if $n_i$ is MPR of $n_j$, don't forward SLU as
                                      // routing tree to sink remains unaffected (Local repair mechanism).

                if ($n_i$→next_hop$_{sink}$ != $n_j$)       // if previous next hop relay node is different than $n_j$
                        $n_i$→next_hop$_{sink}$ = $n_j$                          //update reverse routing tree
                        distance$_{node\_i,sink}$ ← ttl($SLU_{new}$)          // distance to sink via new relay $n_j$
                        forward$_{SLU}$ ← true                  // retransmit $SLU_{new}$ if $n_i$ is MPR of $n_j$
        //if multiple copies of same $SLU_{new}$ are received
        else if (sequence_no($SLU_{new}$)==sequence_no($SLU_{last}$))
                if (ttl($SLU_{new}$)<=dist$_{i,sink}$))  // if this copy is received from relay closer to sink than
                                                                                   //previous one.
                        next_hop$_{node\_i,sink}$ ← $n_j$                      // update the next hop to the sink
                        distance$_{node\_i,sink}$ ← ttl($SLU_{new}$)          //update the distance to sink via $n_j$
                esle if (TTL($SLU_{new}$) == dist$_{i,sink}$))
                        if (next_hop$_{i,sink}$ == $n_j$) // Finally, if $SLU_new$ is received from the neighbor
                                                              which was next hop relay previously then
                                                        routing tree towards sink remains unaffected.
                            forward$_{SLU}$ ← false // Due to the local repair algorithm, $n_i$ will not
                                                        retransmit $SLU_{new}$ even if it is MPR of $n_j$.
        //Discard the packet if an older SLU processed before $SLU_{new}$ is somehow received
        else
                discard($SLU_{new}$)

            // Once the approximated timer of receiving multiple SLU copies from different neighbors expires,
    retransmit the $SLU_{new}$ stored in temporary buffer if $n_i$ is MPR or $n_j$
Delay_relay($SLU_{new}$, t)
        if (forward$_{SLU}$ == true)                      // if $n_i$ is MPR of $n_j$ and local repair zone is
                                      affected by sink mobility, retransmit the $SLU_{new}$ message.
                decrement_ttl($SLU_{new}$)
                broadcast($SLU_{new}$)
```



(a) Configured reverse routing tree (b) Preemptive buffering at temporary root nodes (c) Reconfigured reverse tree after transmitting buffered packets

Figure 4.3: Preemptive buffering mechanism

4.5.6 Preemptive Buffering

This section presents a preemptive buffering mechanism to minimize the data loss between the mobile sink and its immediate neighbors, which act as relays to forward network traffic to the sink. In static-sensor mobile-sink WSNs, the routes which change more frequently are between sink and its neighbors. For explanation, lets divide a data packet's *source*→*sink* route in two partitions; a) static sensor→sensor multi-hop route between data source and last relay node (sink's neighbor), where packets are relayed over stable links, and b) a direct link between a last relay node (sink's neighbor) and the sink itself, where sink mobility causes change in its neighboring topology as links continuously break and re-establish between the sink and its changing neighbors.

Data reports suffer less transmission losses when transmitted from source till last relay node i.e. sink's 1-hop neighbor, as static sensors have stable links among themselves. Though, these links may suffer packet losses due to collisions and congestion. However, due to changing links, transmission losses are higher between moving sink and its neighbors. When data arrives at neighbor nodes of the sink they may suffer losses due to link breakages as sink may move away from relay nodes vicinity. In SN-MPR, sink transmits hello messages and SLU messages every two and five seconds respectively. Suppose at an instant t, a node n_i receives a *hello* message from the sink and a symmetric link is established between them. Afterwards, n_i will change this link to asymmetric if it does not receive any *hello* from the sink for 2 consecutive hello intervals i.e *hello_interval*×*2 = 4 seconds*, which could result in data loss. Suppose sink moves out of n_i's range at instant $t+\epsilon$. As n_i keeps on considering its link with the sink as symmetric for $t+4-\epsilon$ more seconds, all data transmitted to the sink during this duration is lost.

We propose a preemptive buffering mechanism to minimize this loss, whereby sink's one hop neighbors act as temporary roots, if they do not receive sink's *hello* after *t+hello_interval*.

As an act of precaution, sinks one hop neighbors consider that sink may no longer be in their vicinity, and thus, they stop sending data reports to the sink. At the same time, they start buffering all incoming data packets and data reports generated by itself. This precautionary measure prevents unnecessary data loss and energy wastage. These temporary data buffering roots will redirect the buffered packets to the sink when they receive updated sink location information either through a *hello* or *SLU* message. Figure-4.3b describes how sink's neighbors start acting as temporary root nodes, when they do not receive sink's *hellos*. Figure-4.3c shows temporary root nodes returned to the normal state, after they have reconfigured their route, and transmitted all buffered packets to the sink. These nodes now behave as normal relay nodes. Another possible approach to minimize data loss could be the increase in sink's hello transmission frequency, but it is infeasible as it increases energy consumption of neighboring sensors, and increased control traffic may also reduce network throughput.

One should note that preemptive buffering is performed by only sink's neighbors for at maximum few seconds; one *hello* period of 2 seconds if a node which has activated preemptive buffering receives a new *hello* message from the sink or one *SLU* period of 5 seconds when it receives a new *SLU* from the sink. Upon the reception of new *hello* or *SLU* message, the node performing preemptive buffering starts transmitting its buffered and newly arriving packets towards the sink. Thus, this limited duration buffering does not increase the delivery delay to the extent that monitored information expires. Also, there is no problem of local memory overflow as buffering is activated only for few seconds.

4.5.7 Performance Evaluation

In this section, the performance of the SN-MPR is evaluated through simulations. First, details of the simulator used, algorithm implementation details and network parameters is provided in the section-4.5.7.1. Then, detailed evaluation of the proposed algorithm is provided in the remaining subsections. The results show the scalability and efficiency of the SN-MPR under varying environments.

4.5.7.1 Implementation Details

SN-MPR algorithm is implemented in the discrete event Network Simulator (NS-2) [ns2]. We modified an existing implementation of the OLSR protocol called UM-OLSR [Fra09] to implement our proposal since OLSR protocol also uses MPR broadcasting for network wide updates. Transceiver's power consumption values have been taken from [Cooa] and remain the same during all simulations. We consider that radio consumes 0.081 J, 0.03 J and 0.03 J in transmission, reception, and idle states respectively. Moreover, we consider the TwoRayGround radio propagation [two12] as path loss model. Hence, energy of the

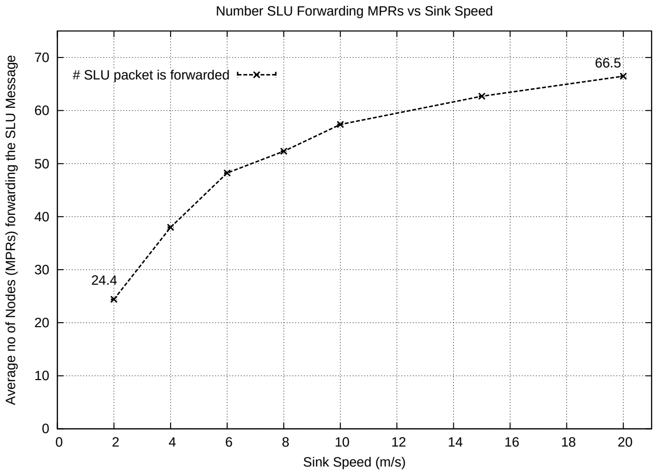


Figure 4.4: Number of SLU message Forwarders vs Sink Speed

received signal depends mainly upon the distance between the transmitter and the receiver. Moreover, all nodes and the sink have 80m transmission range and 170m interference range i.e. a bit more than double the communication range. Using variable transmission range and realistic propagation models will not affect the functionality of the proposed algorithm as communication in SN-MPR is allowed only on symmetric links. All simulations have been performed using 802.11 CSMA/CA as MAC protocol. In all simulations, sink follows a random mobility model unless stated otherwise, as in the section-4.5.7.5 in which the behavior of the algorithm is observed under different sink mobility patterns.

4.5.7.2 Control Overhead

First of all, the control overhead of the local repair SN-MPR algorithm is evaluated to observe the efficiency of the local repair technique in combination with MPR broadcast. Since, the data collecting entity could be a human walking through the network while carrying a laptop or a vehicle passing through it, therefore, sink speed is varied from very low pedestrian speeds of 2 m/s up to vehicular speeds of 20 m/s but remains constant for a particular scenario with a pause time of 10 seconds. We generate a set of 10 random topologies with 400 nodes deployed randomly in a 1000mx1000m grid, which gives an average node degree around 11. Moreover, every simulation run lasts 1000 seconds. In these set of experiments, the performance of SN-MPR is compared with: a) network wide flooding and b) MPR based network wide broadcast by only sink without any local repair mechanism.

Mean SLU Retransmissions vs Sink Speed: Figure-4.4 shows the average number of MPRs which forward the SLU packet whenever it is generated (every 5 seconds) against

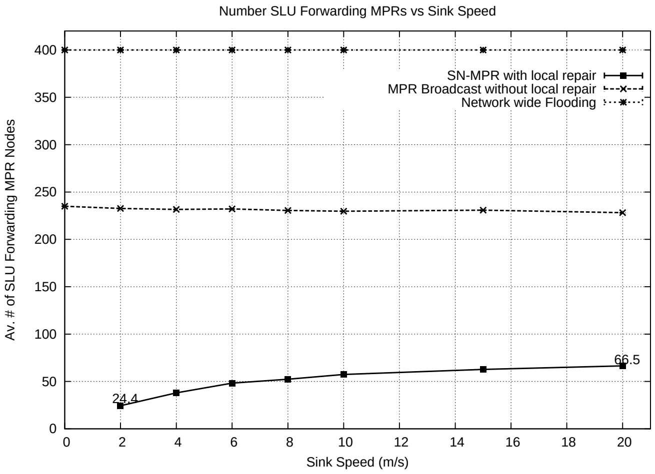


Figure 4.5: Number of SLU message Forwarders vs Sink Speed: A Comparison

varying sink speeds. The results are generated with a 95% confidence interval. On the average, only 24.4 MPRs among 400 nodes forward the SLU packet when sink moves at 2 m/s. This accounts to only 6% of total deployed nodes. The number of SLU forwarding MPR nodes increase gradually with the increasing sink speeds. As can be seen, the mean number of MPRs which forward the SLU increases to 66.5 when the sink moves at maximum 20 m/s speed which accounts to only 16.62% of the total deployed nodes. For the sink speeds varying from slowest 2 m/s to fastest 20 m/s, the mere 6% and 16% data forwarding nodes among the total 400 deployed nodes clearly shows the low control overhead of the SN-MPR algorithm and proves its efficiency for large scale WSNs.

In figure-4.5, we compare the efficiency of SN-MPR algorithm with a) network wide flooding and b) network wide MPR-based broadcast without any local repair technique. Results show that our proposal outperforms network wide MPR-based broadcast by a considerable margin. It is to be noted that the control overhead of network wide MPR broadcast is insensitive to the sink speed, although the curves shows little variation which is due to the the topology dependency and sink mobility pattern. As can be observed, around 230 MPRs out of 400 nodes forward the SLU packet every time it is transmitted by the sink when network wide MPR broadcast is utilized. As compared to constant control overhead of 400 retransmissions in case of pure flooding, this efficiency is achieved by the efficiency of the MPR broadcast mechanism [CJ03].

In resume, even at the highest sink speeds, network wide MPR broadcast algorithm and pure flooding algorithms have approximately 350% and 600% higher control overhead cost than the proposed SN-MPR local repair algorithm. These results clearly depict the better efficiency of our proposal.

Topology Variance Effect on the Control Traffic: The efficiency of the local repair algorithm will variate when the sink moves in different network topologies. The average SLU packet forwarding zone may be larger in some topologies and lower in the others. In order to evaluate the efficiency of the algorithm under different networks, 10 random topologies consisting of 100 nodes each were deployed in a network area of dimensions 400mx400m. In these set of simulations, sink used the same mobility pattern on all of these 10 topologies in order to eliminate the effect of its different mobility patterns. Moreover, the sink moves at the same speed of 10 m/s in all the simulations.

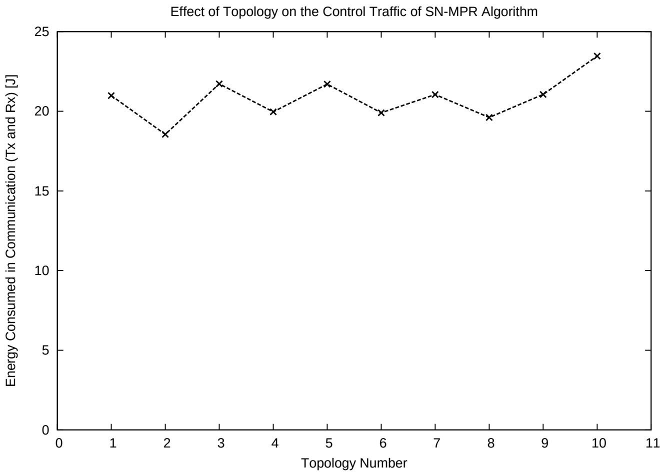


Figure 4.6: Energy Consumed by SLU and hello messages in Different Topologies

We observe the energy consumed by only the control traffic i.e. SLU and hello messages by the network. Moreover, we consider the energy consumed by the radio in only transmitting and receiving these packets as it gives the exact picture of the amount of traffic exchanged in the network. The result presented in the figure-4.6 shows that more or less comparable amount of SLU packets are exchanged in all the topologies. On the average, minimum traffic is generated in the second topology in which the whole network consumes 18.55J in exchanging *hello* and *SLU* packets, where as maximum power is consumed in the tenth topology in which 23.4J energy is consumed. Thus, the local repair technique seems to be equally efficient in all the topologies.

4.5.7.3 Data Delivery Ratio

In these sets of experiments, 100 nodes are randomly deployed in a 400mx400m area. To test the End-To-End (E2E) data delivery performance of our proposed solution, we use a non-acknowledgment based UDP protocol. Every node transmits a 64 bytes CBR packet with an interval of 10 seconds and transmits it to its next hop neighbor towards the sink.

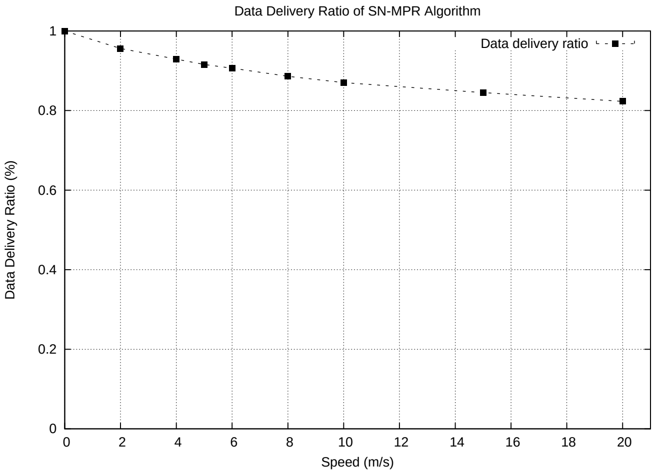


Figure 4.7: Data Delivery Ratio

Figure-4.7 shows that all packets are successfully delivered to the sink when it is stationary. This data delivery ratio decreases linearly with increasing sink speeds and reduces to about 82% when the sink moves at maximum speed at 20 m/s. Note, that we also performed experiments without the preemptive buffering mechanism explained before in section-4.5.6, and we observed that preemptive buffering mechanism increases the network delivery ratio from 1% to 3% under various conditions.

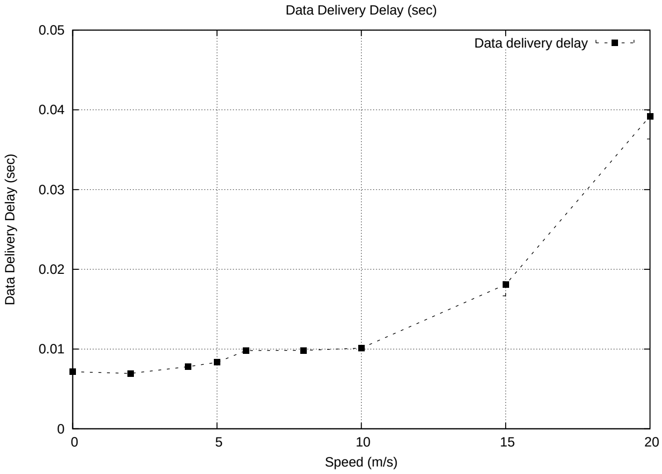


Figure 4.8: Data Delivery Delay

4.5.7.4 End-to-End Data Delivery Delay

Figure-4.8 shows the mean data delivery delay of all the sources over the entire simulation period. As can be seen, delay is lowest when the sink is stationary and increases with increasing sink speeds. This increase in delay is due to the preemptive buffering mechanism which helps in improving data delivery ratio by avoiding packet loss due to sink mobility, but it increases the data transfer delays. Two sets of simulations were performed; a) End-to-End delay without buffering mechanism and b) End-to-End delay with buffering mechanism. End-to-End delay without buffering mechanism is of the order of milliseconds but this delay increases when buffering mechanism is used. Once packets are buffered at temporary root node n_i, the maximum delay it will suffer is equal to SLU message update interval as packets are redirected to sink's new position as soon as new SLU message is received at node n_i. Upon careful analysis we found that sink's neighbor nodes go into root-based buffering mode only a limited number of times. In most of the cases sink's hello messages are successfully received by its neighbors. Even if sink moves out of n_i range into its two hop neighborhood, its new position update is quickly received by n_i due to hello message exchange between the sink and its current neighbors. As soon as n_i's one hop neighbor node n_j announces sink as its symmetric neighbor, n_i redirects its buffered packets towards n_j which then relays them directly to sink.

One can argue that sensor platforms like Crossbow's micaZ [Mot12] and [Cooa] have limited memory space, which could limit the MPR's buffer size of our root-based mechanism. This is true, but sink's neighbor MPRs act as temporary root nodes for only few seconds. Buffered packets are transmitted to the sink as soon as route to the sink is updated via the reception of a new *hello* or *SLU* message. Thus, the proposed algorithm does not impact the temporary root node's buffer size as most WSN applications have low traffic intensities.

4.5.7.5 Energy Distribution Efficiency

A balanced distribution of the power consumption among nodes plays an important role in the lifetime of the network. For instance, stationary sink based data dissemination algorithms usually have shorter lifetimes as network suffers from energy hot spot problem; Nodes closer to the sink consume more energy due to continuous relaying and quickly die making the rest of the network inaccessible to the sink. On the other hand, sink mobility minimizes this hot spot problem but the routing protocol may or may not distribute energy efficiently. In order to see the energy distribution efficiency of SN-MPR algorithm, a power distribution graph is presented in this section. Simulations were executed for a longer time duration of 10,000 seconds on a topology of 100 nodes deployed randomly in a network

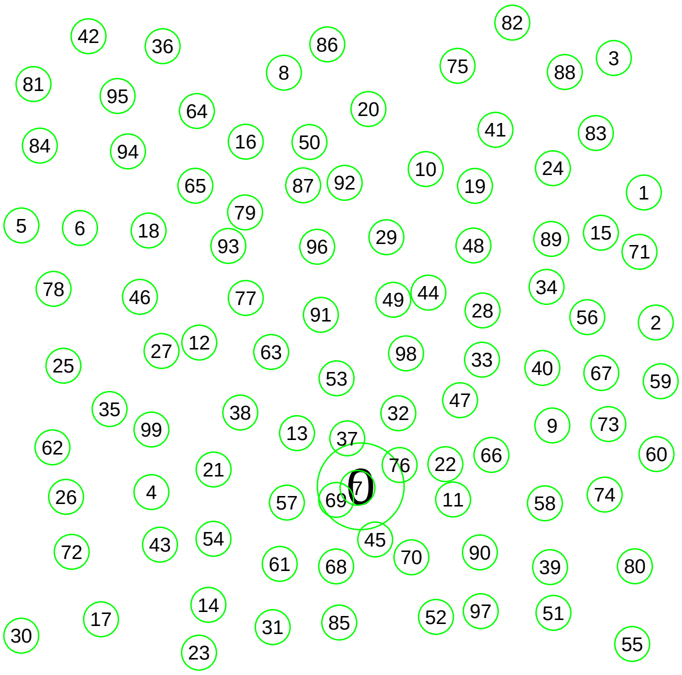


Figure 4.9: Power Consumption Distribution of SN-MPR Algorithm with Random Sink Mobility

grid of area 400mx400m, as shown in figure-4.9. Power distribution is observed from two aspects in this section;

- First, distribution of total power consumed by nodes' transceiver in transmission, reception, and idle listening states is observed.
- Secondly, a three dimensional view of the power consumed by nodes' transceivers in only communication is presented, i.e. only in transmission and in reception excluding idle listening, in order to observe only the behavior of MPR role balancing among nodes. This is necessary because in low rate WSN applications energy consumed in idle listening state dominates the power consumed in actually transmitting or receiving the data; transceiver remains idle most of the time during node's life and generally transceiver's power consumption in idle listening is almost equal to that in receiving state.

Distribution of Total Power Consumption with Random Sink Mobility:

The total energy consumption distribution i.e. power consumed in transmission, reception and idle listening of the whole network is presented in the figure-4.10. As can observed, SN-MPR algorithm balances the power consumption of the nodes in a very efficient way as the nodes end up consuming almost equivalent power of 30J each. This is due to the following reasons:

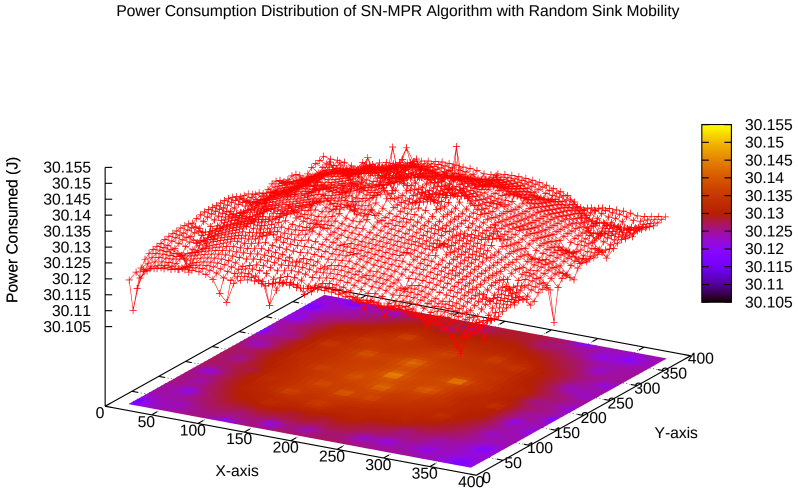


Figure 4.10: Power Consumption Distribution of SN-MPR Algorithm with Random Sink Mobility

1. When the sink changes its position, the reverse routing tree also changes which changes the set of nodes which are actually relaying the information i.e. are non-leaf nodes at a particular instant *t*. In fact, once selected at network initialization the set of MPRs do not change normally during network lifetime except if a node's energy falls below a certain threshold, but among those subset of MPRs only few nodes in the network are acting as relays (non-leaves) at a particular instant *t*.
2. Once a MPR looses energy beyond a certain threshold, it lowers its *willingness* field value, and announces its decision to its neighbors via a *hello* message. Once a MPR's neighbors receive this message, they exchange few *hellos* locally in order to select a new MPR according to the standard MPR selection algorithm explained in [CJ03]. This allows the nodes to balance energy consumption throughout the network lifetime.
3. As discussed before, as compared to static sink WSNs, naturally the sink mobility helps in balancing the energy consumption of the nodes as energy hot spot problem is minimized.

Together, all these factors allow the uniform power distribution in the network as depicted in figure-4.10. However, nodes on the network perimeter consume lesser energy as they perform lesser relaying tasks. This effect is not due to the proposed algorithm but due to the random mobility model of the sink which causes the sink to move more around the central regions than at the network perimeter, and as a result nodes situated towards center relay more date on the average than others.

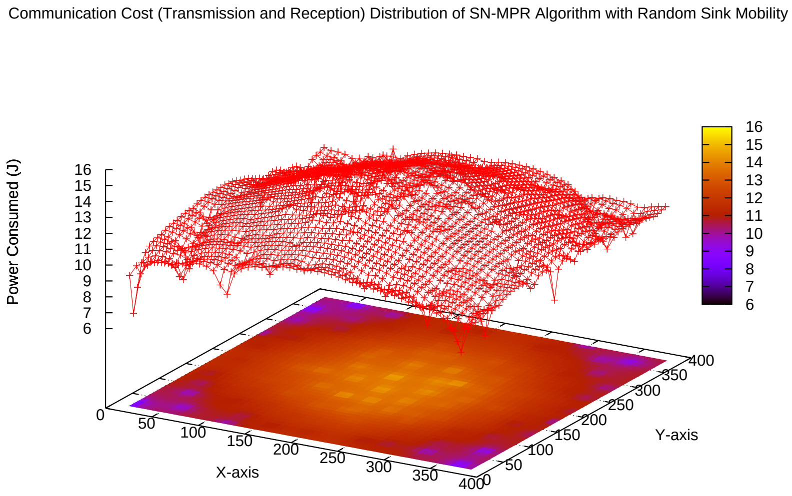


Figure 4.11: Communication Cost (Transmission and Reception) Distribution of SN-MPR Algorithm with Random Sink Mobility

Distribution of Power Consumed in Communication with Random Sink Mobility:

Next, due to the aforementioned reasons, the power distribution of energy consumed only in transmitting and receiving control and data traffic is analyzed in the figure-4.11. Power consumption is minimum at the four corners of the network which is normal as nodes placed at the extreme corners of the network seldom relay data on behalf of rest of the network; the nodes lying close to the network perimeter will have high relaying loads only when the sink passes more often through the corners.

Apart from the corners, the power consumption of most of the nodes is rather uniform with most of the nodes consuming power in the range 11J to 13J, and only few at the center consume higher 14J-16J due to the reason that sink moves more around central regions and thus nodes at center have to relay more information on the average than others.

Distribution of Total Power Consumption with Perimeter Sink Mobility:

Next, the power distribution of the algorithm is evaluated using the perimeter mobility model in which the sinks moves continuously at the network boundary. Such mobility is possible in some WSN deployments like in very harsh terrains where it may be physically impossible for someone to enter the WSN deployment region or due to security reason as in battlefield environment. Figure-4.12 shows the power distribution of the energy consumed by the network during simulation. The overall power consumption is uniform again throughout the network with most of the nodes consuming approximately 30 Joules energy in their lifetime.

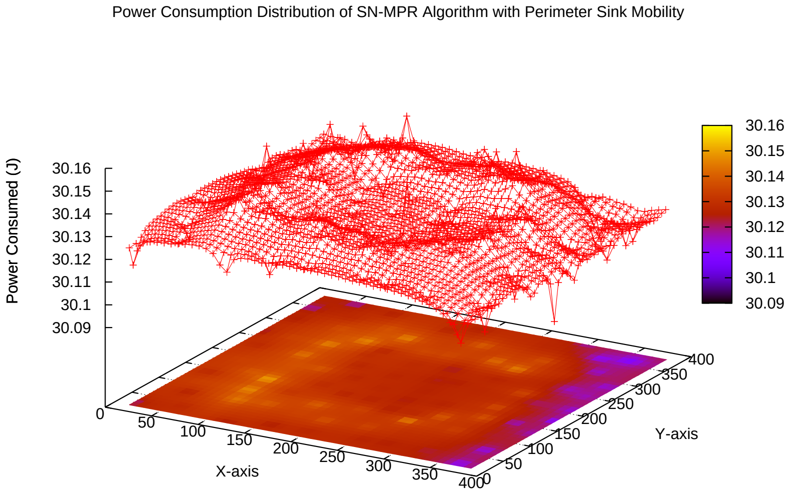


Figure 4.12: Power Consumption Distribution of SN-MPR Algorithm with Perimeter Sink Mobility

However, as compared to the power distribution of the random sink mobility model in figure-4.10, rather higher power consuming nodes are situated at the network boundaries in contrast to being at central region. This is due to the fact that when ever the sink is closer to a particular spot at the network perimeter, the MPRs around it have to relay the data traffic of all the network nodes behind it.

4.6 Conclusion

In this chapter, we presented a distributed MPR based sink location update algorithm for mobile sink WSNs, whereby nodes distributively control the scope of sink's broadcast messages. We also proposed a *preemptive buffering* algorithm to minimize the data delivery losses caused by sink mobility. Simulation results show that the temporary root-based buffering algorithm, along with distributed local path repair SN-MPR mechanism effectively reduces the energy consumption while minimizing data delivery losses.

In the next chapter, we propose a duty-cycle aware version of SN-MPR algorithm in order to further minimize energy consumption.

Chapter 5

A Duty-Cycle Aware SN-MPR Algorithm for Mobile Sink Wireless Networks

Contents

As stated in previous chapters, communication is the major energy consuming component of a wireless sensor device with nodes consuming power in transmission, reception, idle listening and sleep states. Among these four states, a wireless transceiver consumes maximum power to transmit data, whereas power consumption is of the same order in reception and idle listening states; comparatively, a very small fraction of the power is consumed in the sleep state. Among these four states, a transceiver wastes most of its energy in idle listening as WSN applications usually generate data at a low rate. Thus, a sensor nodes pass majority of their time in monitoring events, and only a fraction of time is spent in transmitting sporadic events to the sink. A node can minimize this power loss due to idle listening by switching its radio to sleep mode when it has no data to transmit/receive; It will activate its radio when it has data reports to transmit. This switching between active and sleep states is known as duty cycling, and it allows the nodes to regulate their power consumption according to their traffic rates. Duty-cycling is defined as the fraction of time a node's transceiver is in the active state during its lifetime.

Duty cycling can be achieved in a number of ways at different communications layers of the OSI stack. As explained below in the next section, duty cycling can be achieved either by exploiting topology control and/or power management schemes by controlling schedules at lower layers.

5.1 Topology Control

Wireless sensor networks may consist of large number of nodes many of which might be redundant as only a small subset of these nodes can suffice to form the connected backbone to deliver data reports to/from the sink. Under such cases, the aforementioned small subset of nodes can stay active to maintain the network connectivity, where as the remaining redundant sensor nodes can switch to sleep state whenever they have no more data to transmit or receive, because they are currently not acting as relays. This exploitation of node redundancy to find the minimum subset of active nodes which form the connected network backbone is referred to as Topology Control. Efficient use of topology control can enhance the network lifetime by not only maximizing duty cycling nodes, not part of the connected backbone (active nodes), but also an efficient topology control technique should enable the nodes to exchange data relaying responsibilities from time to time in order to distribute the network's power consumption.

In this chapter, we propose a topology control strategy at the network layer in order to minimize network's energy consumption. A duty-cycle aware version of the SN-MPR algorithm presented previously in chapter-4 is proposed which allows the leaf nodes (non-MPRs) in the data forwarding tree to switch-off their transceivers when they have no data to transmit, and then alternate between active and sleep states. In order to enable the nodes to exchange the data relaying responsibilities we exploit mobility of the sink as the change in sink position changes the reverse routing tree structure, which in fact means the data relaying nodes among the set of already selected MPRs change automatically for different sink positions.

5.2 Power Management

In the above described case, the active nodes need not maintain their transceivers on all the time. These data relaying active nodes can further minimize energy consumption by performing duty cycling i.e. such active nodes can switch off their respective transceivers when communication is not required and then switch between on and off states. However, such duty cycling requires coordination among communicating neighbors as transceivers of both nodes should be active at the same time to exchange information. This scheduling of on/off states is mostly implemented as part of the MAC layer protocols. Some TDMA based MAC protocols like HyMAC [SSK07], LMAC [vH04], ML-MAC [IvHJH11], TMMAC [ZZH$^+$07] and Y-MAC [KSC08] have already been proposed for wireless sensor networks. However, in this chapter we address the energy minimization issue via topology control technique and present a duty-cycle aware SN-MPR algorithm at the network layer.

5.3 Duty Cycle SN-MPR Algorithm

This section presents the details of the proposed duty-cycle aware SN-MPR algorithm. All the changes made to the previous algorithm to adapt it for resource constrained sensor networks have been explained.

5.3.1 Neighbor Discovery

Neighborhood discovery process can be divided into two categories. Static sensor-sensor neighbor discovery and mobile sink-sensor neighbor discovery.

5.3.1.1 Sensors Neighborhood Discovery

The proposed duty-cycle algorithm uses the similar sensors-to-sensors neighbor discovery mechanism used by the SN-MPR algorithm presented in the chapter-4. All sensors exchange *hello* messages periodically at the network initialization with an interval of 1 seconds. *hello* messages are sent only during initial configuration as nodes remain static after deployment. Once configured, there is no need to send control packets. With every new *hello* message reception, new neighbors and/or their link information is updated. Once no new changes are detected in the links after additional *hello_counts* their transmission is stopped. At the end of neighbor discovery, an efficient MPR based virtual relay topology is in place.

5.3.1.2 Sink Neighborhood Discovery

In the duty cycle SN-MPR algorithm, the sink follows a sojourn based mobility model, and thus does not move continuously in a random fashion as in the previously presented SN-

MPR algorithm. This model is suitable for many delay tolerant applications as in habitat and agricultural monitoring in which the sensors need not to urgently send data reports to the sink. Thus in duty-cycle SN-MPR algorithm, sink randomly choses a sojourn position and starts moving towards it. Once it arrives at the selected sojourn position, it starts transmitting *hello* messages periodically. Since the sensors' neighbor discovery process has terminated, the sink's current neighbors will transmit *hellos* only in reply to the sink's *hello* messages. Once the sink has gathered its two hop neighborhood information, it selects selects its MPRs among its one hop neighbors and informs them about its MPR selection decision. In addition, to the neighbor discovery information, the sink also appends the time duration the sink is going to sojourn at the current position. This time allows its neighbors to update their timers about when to delete the sink's entry from their one hop neighbor's table. Afterwards, the sink's neighbors will delete its entry once its sojourn duration at current position expires because after that the sink will move towards another randomly chosen sojourn position.

5.3.2 Sink Location Updates

Once the sink has selected its MPRs in its new sojourn position, it needs to broadcast its location to the network via Sink Location Update (SLU) messages. However, prior to that it has to calculate two parameters in order to inform the network about its sojourn schedule and its mobility plan to the next sojourn position in the next round.

5.3.2.1 Information Carried by SLU Message

The two parameters the sink calculates and then appends to the SLU message are its *sojourn duration* and *mobility time*, and in addition, it may also add queries in the SLU message. Below, we give a brief description of these parameters;

a) Sojourn duration (sojourn_t): It is the time span the sink will remain stationary at the current sojourn position. This information enables the leaf nodes in the currently constructed reverse routing tree to switch-off their transceivers for $sojourn_t$ seconds. During this period, a leaf node only switches on its radio for few milliseconds when it has a data packet to transmit to its parent node. It switches off its radio as soon as it receives an acknowledgement from the receiving parent node or after three unsuccessful tries, as per rules specified by the MAC protocol used in the simulations, in which case the data packet is dropped. The data packet is dropped by the sender, because a simple non-acknowledgement based UDP protocol is used at the transport layer in order to test the efficiency of the algorithm in the worst conditions.

b) Mobility duration (mobility$_t$): It is the time the sink will require to reach the next sojourn position once it starts moving towards it after its $sojourn_t$ at the current sojourn point expires. When the sink arrives at a sojourn position, it randomly selects its next sojourn position in advance, in order to calculate the time duration it will require to move from the current sojourn position to the next one. It is supposed that the sink knows its mobility speed. Hence, it can easily calculate its $mobility_t$ value using speed and distances between the current and the next sojourn point.

c) Queries: The data control center may want to change the application parameters such as the data rate at which the reports should be sent or the events the to be monitored. The sink may also append such application related queries in the SLU message when required.

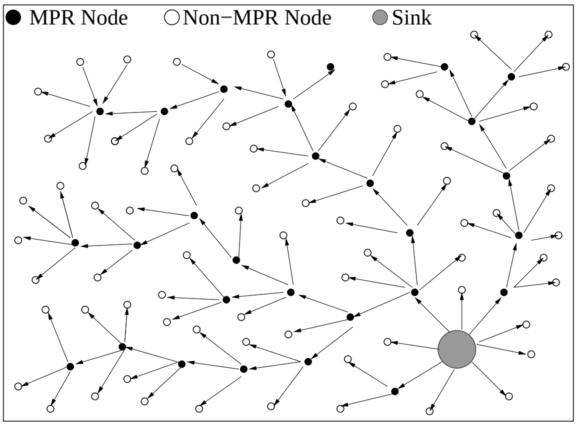


Figure 5.1: An Example Topology of the Duty Cycle Aware SN-MPR Algorithm

The sink appends all the above information in a SLU message and broadcasts it once for every sojourn position in the network. This SLU message will then be retransmitted by the MPRs in the network forming a forwarding SLU broadcast tree as shown in the figure-4.1a. All nodes receiving this message will then configure their reverse routing paths to disseminate data reports to the sink. The processing and forwarding of the SLU message is described in the next subsection.

5.3.2.2 Processing of SLU Message by Intermediate Nodes

A SLU generated by the sink, containing all the above information in addition to the details described in SN-MPR algorithm is forwarded by only MPRs to the whole network, and thus its broadcast consumes less energy than flooding based protocols. A node n$_i$ upon receiving a SLU from a neighbor n$_j$ processes it as follows;

- n_i stores the $sojourn_t$ and $mobility_t$ from the SLU packet.
- Now, if n_i is not a MPR for n_j, it puts its radio to sleep state for $sojourn_t$ + $mobility_t$ duration, because n_i will act as a leaf-node in the routing tree. Afterwards, if n_i has a data report to transmit in the first $sojourn_t$ seconds, it will switch-on its radio, transmit the data packet to its parent relay node, and then, it will switch-off its radio again once it receives an acknowledgement from the parent node or after three unsuccessful tries.

  Once the sink's $sojourn_t$ expires, it starts moving to its next sojourn position which it has already selected randomly, all nodes deployed in the network will switch-off their radios for $mobility_t$ seconds, as sink will not be reachable while it is moving. One should note that the sink does not transmit any *hello* messages while it is moving, and unlike the SN-MPR algorithm (chapter-4), no local repair is performed.

  Figure-5.1 presents the propagation of a sink generated SLU packet by only a limited number of MPRs (dotted black), whereas majority of the non-MPRs (dotted white) do not forward it, and economize power consumption by duty cycling.
- If n_i is MPR for n_j, it rebroadcasts the SLU packet and does not switch off its transceiver during first $sojourn_t$ seconds, because it will be acting as a relay to forward the data reports to the sink. However, n_i will switch off its radio once the sink's sojourn time $sojourn_t$ at the current position expires, and it will keep it off for $mobility_t$ *seconds*. Once the $mobility_t$ expires i.e. the sink arrives at its next sojourn position, all nodes will switch-on their radios to receive a new SLU packet from the sink so that they can reconfigure their routing paths according to its new sojourn position.

When a next SLU is received, nodes will process the packet according to the above described algorithm. Thus, the change in sink's position automatically changes the SLU forwarding nodes, as they switch relay or leaf state roles from time to time. This duty cycle mechanism minimizes the network's energy consumption by minimizing transceiver's idle listening, and the sink's mobility balances the power consumption of the network.

5.3.3 Reverse Tree Route configuration

The above described SLU broadcast creates a forwarding tree as shown in the figure-5.1. In our algorithm, nodes use the reverse path of the SLU forwarding tree to route data towards the sink. Every node n_i selects its neighbor n_j as next hop relay to the sink from which it has received the SLU packet on the shortest path. Thus the packet is transmitted to the sink by the nodes by using only next hop neighbor routing information towards the sink. Thus similar to SN-MPR algorithm presented in chapter-4, the reverse path of MPR

Algorithm 3 : SLU message processing and Tree formation algorithm at node_i

```
Recv(SLU$_{new}$, node$_j$)                                  // $SLU_{new}$ received from neighbor $n_j$
Initialize sleep ← false                 //Used for deciding for duty cycling decision making

if !Symmetric_link(node$_i$, node$_j$)                   //if $n_i$ & $n_j$ are not symmetric neighbors
    drop(SLU$_{new}$)                                                   //Drop the SLU packet
else
    // If this SLU is received for the first time process it
    if (sequence_no($SLU_{new}$) > sequence_no($SLU_{last}$))
        decrement_ttl($SLU_{new}$)
        if (is_MPR($n_i$, $n_j$))                                       //if $n_i$ is MPR of $n_j$
            sleep ← false                           $n_i$ can't switch-off radio as it is a relay
            Broadcast($SLU_{new}$)                        //MPR $n_i$ rebroadcasts the packet
        else
            sleep ← true                                          //$n_i$ will switch off radio
        distance$_{node\_i,sink}$ = ttl($SLU_{new}$)                  // Save hop count to the sink
        node$_i$→next_hop$_{sink}$ = node$_j$                    //parent node of $n_i$ in reverse tree
        sojourn$_{i,t}$ = SLU$_{new}$→sojourn$_t$          //Save sink sojourn duration at current position
        mobility$_{i,t}$ = SLU$_{new}$→mobility$_t$ //Mobility duration for reaching next sojourn position

        //Leaf node switches off its radio till sink will arrive at its next sojourn position. During
    the 1st sojourn$_{i,t}$ seconds, $n_i$ alters between active/sleep states for sending data reports. After that all
    nodes switch off their radios during sink mobility.
        Duty-cycle(sojourn$_{i,t}$ + mobility$_{i,t}$)

    //multiple copies received
    else if (sequence_no($SLU_{new}$)==sequence_no($SLU_{last}$))
        if (ttl($SLU_{new}$)<=dist$_{i,sink}$))
            next_hop$_{node\_i,sink}$ ← node$_j$
            distance$_{node\_i,sink}$ ← ttl($SLU_{new}$)

    //old SLU received
    else
        discard($SLU_{new}$)
        ----------------------------------------
Duty-cycle(sojourn$_t$, mobility$_t$)                 //This functions controls the duty cycling tasks
if (sleep is true) //Non-MPR node
    radio_sleep(now, sojourn$_t$+mobility$_t$) //Switch-off radio right now till sink arrives at next
                   //position. $n_i$ can activate its radio only during 1st sojourn$_t$ sec. for sending data
                        //pkt and then switches it off immediately after receiving acknowledgement.
else //if MPR node
    radio_sleep(now+sojourn$_t$, mobility$_t$) //MPR switches off its radio once sink starts moving for
    mobility$_t$ seconds.
```

broadcast creates a reverse routing tree which is rooted at the sink. The resulting reverse routing tree is presented in the figure-4.1b. The pseudocode of the processing of a SLU message when n_i receives it from a neighbor n_j is presented in Algorithm-3.

5.3.4 MPR role exchange

MPRs consume more power than the non-MPRs as they not only act as relays for other nodes but also as data generating sources. One can argue that nodes should switch MPR role to equally distribute the traffic load. For m→1 WSN scenario, change in the sink position automatically changes the forwarding nodes (non-leaves in the tree) among the set of MPR nodes. Nodes that forward sink location updates and relay data packets are different for different sink positions. Thus, this role automatically changes with sink mobility and distributes the data forwarding tasks among different sensors. One should keep in mind that MPRs are not reselected after the network initialization phase as neighborhood discovery process between sensor has stopped.

5.3.5 Data buffering

When the sink's sojourn time $sojourn_t$ expires, and it starts its journey towards its next sojourn position, all nodes switch-off their respective radios for $mobility_t$ seconds i.e. the time the sink will take to arrive at its destination. Since the transceivers are off during this period, all nodes buffer data reports generated by them and the packets to be relayed to the sink in their local memory. These buffered packets are delivered to the sink once it announces its new position via a SLU packet and the reverse routing tree rooted at the current sink sojourn position is re-configured.

Extreme care should be taken while fixing the range of sink's sojourn and mobility durations to avoid excessive delays and data loss. For instance, in all the simulations, sink's sojourn time is chosen randomly but is at least equal to the time the sink takes to arrive to the current sojourn position. This lower limit on sojourn$_t$ has been imposed to avoid packet drops due to congestion and also due overflow of the nodes' respective data buffers. As stated above, as soon as a new routing tree is constructed at the sink's new position, the nodes start transmitting their currently generated data reports and the ones they had stored in their data buffers when their radios were off during sink mobility. Thus, the data transmission rate sort of doubles if the sink sojourns for at least the duration it was mobile. Thus, the sink's sojourn and mobility duration should be carefully chosen as they strongly effect the delay of the application related packets and also the delivery reliability.

If the sink sojourns for only short durations and passes majority of its time in hopping from one spot to another, larger network delays will be observed as the data reports will be stuck in the local buffers of the nodes most of the time. Moreover, the traditional sensor platforms like micaz [Mot12] and mica2 [Cooa] have limited memory. Thus, buffer overflow may occur if nodes keep on adding data reports to local memory when the sink is in mobility. Due to the above explained two reasons the application data rate, local memory size and maximum tolerable delays must be take into account by the network designers while modeling the sojourn and mobility behavior of the sink.

5.4 Performance Analysis

This section presents an evaluation of the proposed algorithm. First two sub-sections present the implementation details and network parameters. The obtained results are presented and analyzed in the last section.

5.4.1 Implementation Details

The algorithm has been implemented in the Network Simulator 2. An implementation of the OLSR the protocol [CJ03] called UM-OLSR [Fra09] was modified to implement the duty cycle aware SN-MPR algorithm.

The proposed routing mechanism works at the network layer of the OSI model but a cross layer communication approach is necessary to implement all the functionalities of the algorithm due to the following two main reasons;

1. The proposed algorithm works at the network layer but needs to coordinate with the MAC layer for controlling the duty cycling of radio since the actual transmission of packets on the wireless media is controlled at the MAC layer. When the sink stops at its sojourn position, and via SLU message, announces the network about its sojourn_t duration at the current position and the mobility_t duration for moving to the next position after the sojourn_t expires, the leaf (non-MPR) nodes switch off their radios. At the same time, the routing agent also updates the MAC layer about the values of sojourn_t and mobility_t. Afterwards, during the sojourn duration, a leaf node in the routing tree activates its radio temporarily to transmit a data report towards the sink, and then, puts radio to sleep once it receives an acknowledgement from the receiver or after three unsuccessful tries. When a data packet arrives at the MAC layer of a leaf node, it wakens the radio if sojourn_t hasn't yet expired, and sends the packet using CSMA/CA protocol. When the acknowledgement is received at the MAC layer of a leaf node, it switches off the radio again if sink's sojourn_t hasn't yet expired. In the other case, the MAC layer switches off the radio after three unsuccessful tries.

2. The routing agent at the network layer controls sojourn_t and mobility_t timers but the actual commands to switch-on/switch-off the transceiver can only be passed at the physical layer of OSI model. Therefore, network layer has to coordinate with the physical layer whenever it has to switch off/on the radio.

All the aforementioned details along with the routing agent were implemented in the NS-2.

5.4.2 Simulation Environment

For the physical layer modeling, the two ray ground radio propagation model [two12] has been used. Hence, energy of the received signal depends mainly upon the distance between the transmitter and the receiver. All nodes and the sink have 80m transmission range and a bit more than double 170m interference range. All nodes transmit 64 bytes data packets each every 10 seconds during the simulation. Moreover, a non-acknowledgement based UDP protocol has been used at the transport layer to test the efficiency of the algorithm under worst conditions. We consider that radio consumes 0.081 J, 0.03, 0.03 J and 0.000003 J in transmission, reception, idle and sleep states respectively. All simulations have been performed using 802.11 CSMA/CA as MAC protocol and all nodes communicate at a data rate of 1 Mbps.

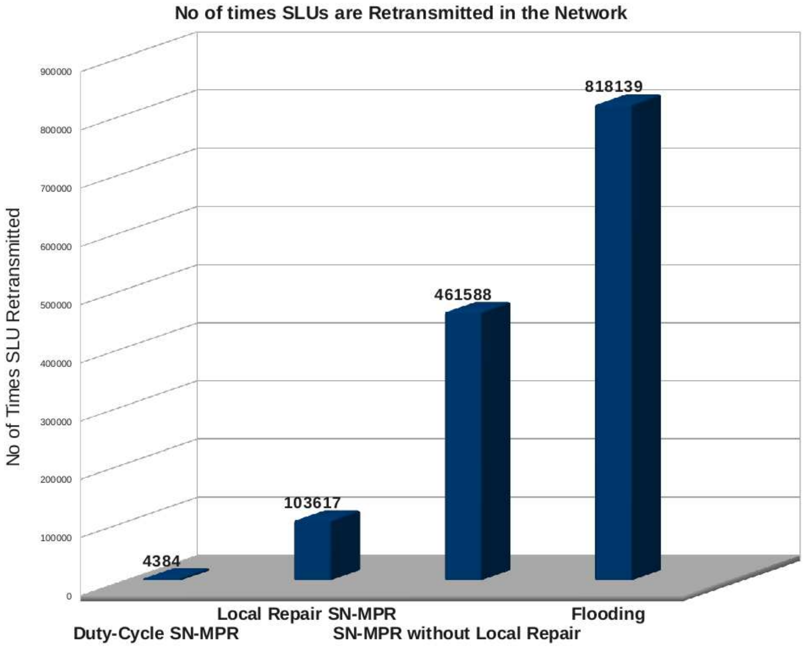


Figure 5.2: Comparison of the Overhead of SLU traffic

5.4.2.1 Control Traffic Overhead

Here, we compare the overhead generated by the control traffic of the duty cycle SN-MPR algorithm. More specifically, we observe the overhead due to SLU messages as they are disseminated network wide. We do not consider overhead of hello messages as only few are exchanged at the network initialization phase or afterwards between the sink and its neighbors when it arrives at new sojourn point. We compare its overhead with the local repair SN-MPR algorithm and pure flooding. In these set of simulations, 400 nodes are randomly deployed in a 1000mx1000m network grid and every simulation lasts 10,000 seconds. The sink generates one location update packet every 5 seconds with the local repair based SN-MPR and flooding algorithms, whereas in duty cycle algorithm sink sojourns for 300 seconds and sends a new SLU when ever it arrives at its randomly selected newer anchor position.

Figure-5.2 shows the comparison of the number of times the SLU message is forwarded by all the nodes during whole simulation. It can be observed that the proposed algorithm has minimum overhead with SLU forwarded 4384 times in comparison to the local repair SN-MPR which has 23.6 times more overhead with 103617 SLU retransmissions. Moreover, we also compare the overhead with SN-MPR algorithm without local repair in which a packet generated by the sink is transmitted to the whole network through MPRs broadcast. We can see that, 461588 SLUs are transmitted in the network when SN-MPR without local repair is used which is 103 times more overhead than the duty-cycle SN-MPR algorithm. Finally, network wide flooding has highest overhead with 818139 retransmissions which is 186 times more than the proposed algorithm. One should note that overhead of the proposed algorithm can vary depending upon the times the sink sojourns at different positions and thus transmits SLU messages. It does not directly depend upon the speed of the sink like the local repair SN-MPR algorithm where the increase in SLU message overhead is directly proportional to the speed of the sink, or upon network wide MPR broadcast or flooding algorithms of which the overhead is totally independent of the sink speeds.

5.4.2.2 Efficiency of the Duty-Cycling

In these an the remaining evaluations one hundred nodes were randomly deployed in a network grid of dimensions 400mx400m, and every simulation run lasts 10,000 seconds. The remaining network parameters are the same as described above. In this subsection we evaluate the efficiency of the duty-cycling, and observe the percentage of lifetime a node's transceiver passes in different communication states. Figure-5.3 shows the fraction of time a node passes in transmission, reception, idle listening and sleep states. We can observe that on the average a transceiver passes only 6% of its lifetime in actually transmitting the data due to relatively low data rates of WSN applications; 64 bytes data packets are generated by all the nodes every 10 seconds. However, on the average nodes pass rather more, 167 seconds in the receiving state which is due to the fact that a node receives the packets at MAC layers even if they are not destined to it, decodes them and verify the packets destination, and then, drops them if packets are not intended for this node.

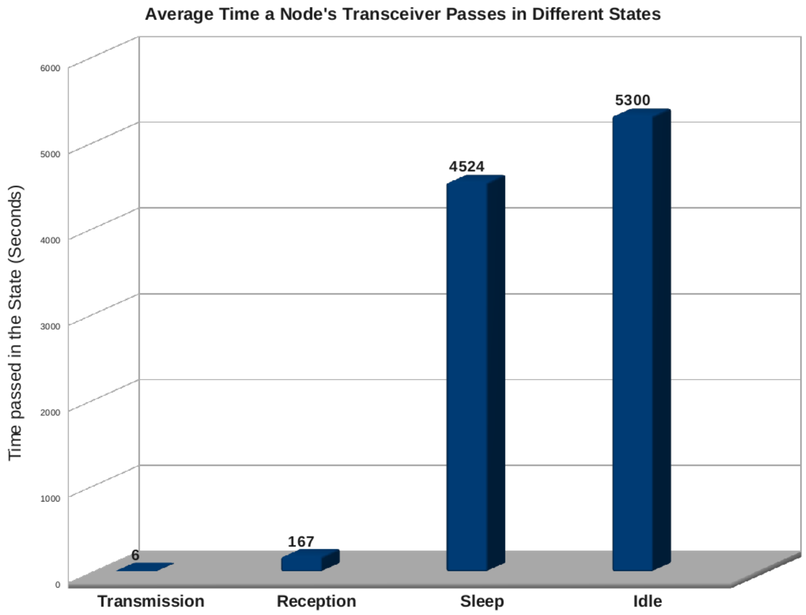


Figure 5.3: Comparison of the Overhead of SLU traffic

One important factor, in duty-cycle algorithm is the average time a node happens to pass in sleep state so that maximum energy can be saved. At the same time, a node can't switch-off its radio all the time as it has to act as relay from time to time depending upon the structure of the routing tree. Thus, there should be a balance between the time a nodes passes in sleep state and staying awake (consuming power in idle, transmission & idle states). This is exactly what we observe in the figure-5.3. On the average, nodes pass about 45% of their lifetime in sleep state and about 54% in the idle listening, transmission and reception states. Thus, nodes keep their respective radios switched-off during almost half of their lifetimes. This clearly shows the efficiency of the duty-cycle SN-MPR algorithm as compared to the local repair based SN-MPR algorithm presented in the previous chapter, in which nodes waste majority of their battery power in idle listening.

5.4.2.3 Energy Distribution Graphs

Generally, algorithms which have unequal distribution of power consumption in a WSN offer lower network lifetimes such routing mechanisms might result in the early death of some nodes which may create disjoint subnetworks making the sink inaccessible to a subset of network. This rapidly makes the WSN application non-usable in spite of the reason that most of the nodes are still functioning. On the other hand, better energy distribution allows the network nodes to consume power almost equally. Thus nodes lose their battery power almost at the same time resulting in longer average network lifetimes as no disjoint subnetworks are created. In active sleep SN-MPR algorithm, whenever a sink is stationary at a sojourn position and has created a data forwarding tree rooted at itself, only a subset of nodes, the MPRs, are relaying the data in that particular tree. When sink creates another data forwarding tree after moving to another sojourn position, the set of MPRs relaying data in that particular tree will be different than the MPRs of the forwarding tree constructed at previous sink sojourn position. Thus, change in position naturally allows the nodes to switch relaying role and thus offer power distribution efficiency. Here, we evaluate the power distribution efficiency of the proposed algorithm.

Since, sink mobility model also affects power distribution, therefore we evaluate the algorithm under random and perimeter sink mobility models. For this evaluation, each simulation run lasts 10,000 seconds.

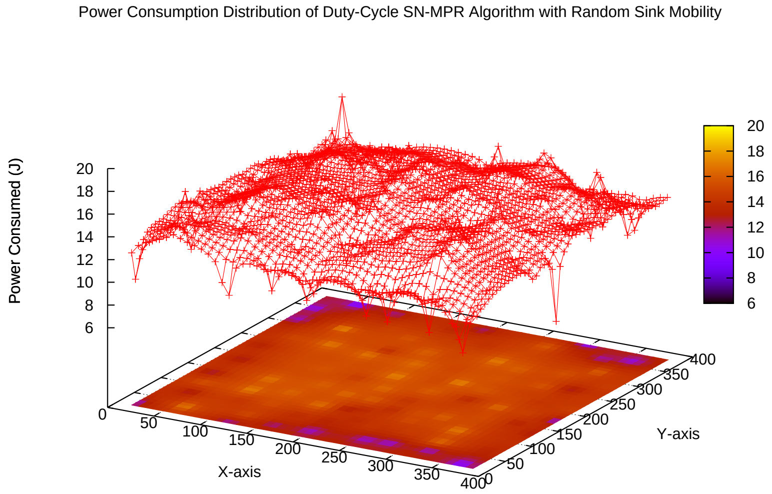


Figure 5.4: Power Consumption Distribution of Duty-Cycle SN-MPR Algorithm with Random Sink Mobility

Distribution of Total Power Consumption with Random Sink Mobility:

First, we evaluate the performance of the algorithm with random sink mobility model. As shown in figure-5.4, the duty-cycle SN-MPR algorithm offers very good power distribution under random sink mobility model. Majority of the nodes consume power almost uniformly in the 16J to 18J range. Although, nodes deployed at the network boundaries consume rather less power than nodes at the center; this is natural as perimeter nodes have lesser relaying responsibilities. Result in figure-5.4 shows that highest power consumed by any node in the network is 20J, whereas, 30J was the highest power consumed by any node (figure-4.10) when SN-MPR algorithm was evaluated in the chapter-4.5.7.5. Thus, even the worst case node consumes approximately 35% less power than the SN-MPR algorithm presented in the previous section. However, 35% economy is the least advantage offered by the algorithm; most of the nodes consume lesser energy than 20J and thus would function for longer duration thereby offering longer network lifetimes. It should be noted that, we simulated both scenarios using the same network topology and utilized exactly the same network parameters.

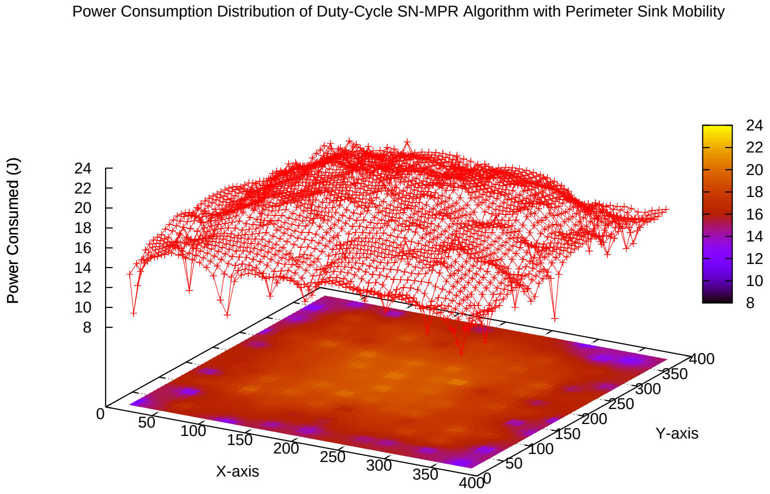


Figure 5.5: Power Consumption Distribution of Duty-Cycle SN-MPR Algorithm with Perimeter Sink Mobility

Distribution of Total Power Consumption with Perimeter Sink Mobility:

Next, the power distribution when the sink follows perimeter mobility model and thus moves at the border of the network is presented in the figure-5.5. As can be observed, the overall energy consumption distribution is again pretty uniform even with this mobility model, but like a similar observation with the SN-MPR algorithm, nodes consume more average power than the than the random sink mobility model, both in the central region and on the perimeter. Higher consumption at the perimeter is due to the fact that nodes deployed near to the perimeter have to relay all the network's traffic when the sink sojourns in their neighborhood. On the other hand, nodes at the network center consume more average energy because they are always on the mid path on the data forwarding tree to relay data towards tree root (the sink) on behalf of the nodes behind them.

5.5 Conclusion and Future Perspectives

In this chapter, we presented a duty cycle aware version of the SN-MPR algorithm which enables the non-relaying nodes to switch off their transceivers whenever they have no data reports to transmit towards the sink. Simulation results show that the nodes running the proposed algorithm consume about 35% less power than the predecessor SN-MPR algorithm in the worst case. Furthermore, our proposal offers better energy distribution which eventually helps in increasing the lifetime of the network.

In the next chapter, we discuss the advantages of utilizing multiple channel communication for data dissemination in wireless sensor networks. We discuss and analyze the existing multi-channel selection protocols proposed specifically for WSNs. Moreover, as the last contribution, we propose a traffic aware channel selection algorithm which allows the network to adapt network capacity according to varying traffic rates.

Chapter 6

TABA: A Traffic-Aware Channel Selection Protocol for IEEE 802.15.4 PHY Based Wireless Sensor Networks

Contents

Almost all the protocols designed for wireless sensor networks consider the presence of a single channel (frequency) for communication due to rather easier coordination to acquire the medium. However, the throughput share of each node decreases with increase in the number of interfering neighbors due to the increased contention. This throughput limitation caused due to contention can be avoided/minimized by utilizing multiple orthogonal channels. Suppose two pairs of communicating nodes AB and CD, all of which are in the interference range of each other. They will have to contend with each other to acquire access to the channel if all four of them are tuned to the same channel which will increase the interference due to collisions and ultimately effective throughput of the network is decreased. However, if two orthogonal channels are available, the pairs AB and CD can tune to different channels each in order to utilize the full bandwidth of the radios.

Majority of the existing routing and MAC protocols in WSNs have been designed on the assumption of the availability of a single channel in spite of the availability of sixteen orthogonal channels in the unlicensed 2.4GHz spectrum in the IEEE 802.15.4 PHY standard, and each channel supports up to 250kbps data rate. These orthogonal channels can be used to allow simultaneous communications in order to increase the effective throughput of the network. In order to exploit the advantages of multi-channel communications, we propose a Traffic-Aware Bandwidth-Adaptive (TABA) channel selection algorithm for heterogeneous wireless sensor networks in this chapter. TABA algorithm is specifically designed for IEEE 802.15.4 PHY wireless sensor networks. This algorithm enables nodes to not only choose interference free channels in the neighborhood, but also enables the nodes to adapt channel-widths (bandwidth) to increase or decrease the network throughput according to varying traffic conditions.

6.1 Motivation

Heterogeneous wireless sensor network may consist of a wide range of sensors ranging from simple temperature, pressure detecting sensors to more complex audio-visual multimedia sensors [AMC07]. Due to this heterogeneity, the relay nodes have variable traffic rates depending upon the type of traffic they are relaying, and this traffic load also variates with time depending upon the presence or absence of events. Traditional single channel communication protocols cannot provide sufficient throughput due to channel interferences caused by nodes in the same geographical region. However, multiple channel communications can increase network throughput by allowing concurrent transmissions in the shared wireless medium. Existing sensor platforms like MicaZ [Mot12] are equipped with a single half-duplex transceiver which can operate over multiple channels. Generally, multimedia traffic has stringent throughput and delay requirements which cannot be ensured by the low rate IEEE 802.15.4 technology. For instance, the traffic rate requirements of some nodes might be beyond the capacity of a standard 2MHz wide channel of IEEE 802.15.4. IEEE 802.15.4 [IEE03] PHY has sixteen 2MHz wide channels in 2450MHz band, and there is 5MHz inter-channel spacing between the central frequencies of adjacent channels as shown in the figure-6.1a. The boundaries of adjacent channels do not overlap as 5MHz inter-channel spacing leaves a 3MHz guard band between them. Thus, if this 3MHz guard band is used intelligently the network throughput can be enhanced.

Recently, the mechanism of adaptive channel bandwidth selection was proposed by Chandra et. al. in [CMM+08]. They proposed an adaptive channel width based algorithm for 802.11 based networks, where, in addition to fix 20 MHz bandwidth, communicating nodes n_i and n_j variate channel widths to 5, 10 and 40 MHz for different variable traffic requirements. Under low throughput requirements, n_i and n_j select a narrow width channel which results in longer communication range and lesser power consumption. On the other hand, when higher throughput is desired, nodes increase the bandwidth by bonding together adjacent channels. This variable channel width criteria could also prove to be very efficient in heterogeneous WSNs, since they generate variable data ranging from small scalar temperature values to bandwidth demanding audio-visual traffic.

6.2 Related Work

In this section, we discuss the issues which make multi-channel communication in WSNs different from other existing wireless technologies, and we also provide a brief classification of the multichannel protocols proposed specifically for WSNs. Moreover, we also discuss the pros and cons of each of the classified categories.

6.2.1 Unique Characteristics of WSNs

Many multichannel protocols have been proposed for wireless networks, especially mesh networks. However, most of the existing algorithms cannot be used for communication in WSNs due to a number of reasons.

- First of all, existing works consider multi-channel assignment to multiple radios as each access point in mesh networks is equipped with multiple radios as opposed to the WSNs which usually have a single half duplex transceiver. Moreover, algorithms designed for Ad hoc networks cannot be used as they usually consider an additional transceiver for exchanging control traffic which is not possible in WSNs.

- Power limitation is a stringent factor in WSNs as replacing or recharging battery might not be possible due to harsh environments while it poses lesser or no problem at all in cases of Ad hoc and mesh networks respectively. Moreover, WSNs are also limited in processing capabilities and have limited memory.

- WSNs are equipped with limited bandwidth transceivers which can support up to 250 kbps as in case of micaZ [Mot12] or yet lower rates of 19.2 kbps in mica2 nodes. Contrarily, ad hoc networks support much higher rates.

- WSNs may consist of hundreds of thousands of densely deployed nodes as compared to rather smaller ad hoc networks. Limited bandwidth combined with scalability poses unique issues which are not faced by ad hoc and mesh networks.

Keeping in view these differences, some multi-channel protocols have been proposed specifically for WSNs. A brief classification of these mechanisms, and their pros and cons will be discussed in this section. We classify the channel selection algorithms according to the channel selection criteria in the section-6.2.2. Then, we classify them based on whether channels assignment is done *statically (fixed)*, *dynamically* or in a *hybrid* fashion in the section-6.2.3

6.2.2 Channel Assignment Classification Criteria:

We can classify existing channel assignment protocols designed for WSNs into the following four categories;

- *Node-based multi-channel assignment:* In node based channel selection protocols like MMSN [ZHY$^+$06] and TMMAC [ZZH$^+$07], a node selects its own channel in order to minimize the local interference by using two-hop neighborhood information. In node-based scheme, a node's selected channel might be different from its neighbors which obliges the communicating pair to switch to the same channel. This switching requires accurate time and channel synchronization as the neighbor pair interested in communication has to switch to the same channel at the same time.

- *Flow-based channel assignment:* In this scheme, a single channel is assigned to all the nodes along the path from the source till the destination node, the sink in WSN case. This scheme avoids frequent channel switching as all nodes along a particular flow communicate on the same channel. However, flow based channel assignment has two limitations. Firstly, nodes belonging to same flow may interfere with each other during communication thereby limiting the network throughput. Secondly, assigning a unique channel to every flow in order to create multiple node disjoint interference free paths is complicated, especially if flows change frequently in the network; channel assignment cycles should be executed for every newly created flow.

- *Topology-based channel assignment:* Some protocols like TMCP [WSHL08] try to minimize network wide interference. For instance, the TMCP protocol divides the whole network into multiple disjoint sub-trees and then assigns a unique channel to each sub-tree. Data generated by a node is then forwarded in its corresponding sub-tree on the assigned channel. TMCP is different from flow based channel assignment as multiple communicating flows may exist in a single disjoint subtree in which all nodes are tuned to the same physical channel. Similar to the flow-based channel assignment, dividing the network into multiple disjoint trees is complex and proved to be NP hard by the authors of [WSHL08]. Moreover, it is quite possible that a members of a particular sub-tree have relatively higher interference because the nodes which detect an event belong to that same sub-tree, whereas other sub-trees have little or no traffic at all. In this case, topology-based channel assignment will give sub-optimal results and thus will not be very efficient.

Also, a node-based channel assignment scheme like MMSN, described above, is also topology-aware but MMSN tries to minimize local interference by using only 2-hop neighborhood information.

- *Routing-based channel assignment:* Multi-channel assignment may or may not be routing-aware, irrespective of any one among the aforementioned three categories it belongs to. Generally, multi-channel communication reduces network interference but assigning channels without taking traffic information into consideration can result in sub-optimal scheme. For instance, MMSN [ZHY$^+$06] minimizes interference in 2-hop neighborhood without considering traffic loads. It is quite possible that nodes tuned to the same channel may have very high traffic rates and suffer interference, where as neighbors tuned to different channels have no traffic at all. A traffic aware channel selection scheme will not suffer from this problem as is proposed by Wu. et. al. in [WKZM09].

6.2.3 Channel Selection Mechanism

Based on when and how the channels are selected, the existing protocols can be broadly classified into the following categories;

- *Fixed Channel Assignment:* In this approach, the radio is assigned a fixed channel by a centralized or distributed algorithm, and then nodes do not switch channels during network lifetime as in TMCP [WSHL08], [CZSB02], [GGM06]. Fixed channel assignment is rather simpler to implement but nodes may suffer from interference issues during traffic bursts if a most of the traffic is being carried by nodes on the same communicating channel.

- *Dynamic Channel Assignment:* In dynamic assignment protocols like Y-MAC [KSC08] and [WWF$^+$09], channels are assigned to links on run time by negotiating frequencies and/or time slots for synchronization. Channel selection may be done on per packet basis or occasionally depending upon factors like current traffic rates and/or interference conditions. These protocols reduce network interferences but are complex due to their requirements of accurate time synchronization and frequent frequency selection to exchange traffic.

- *Semi-Flexible Channel Assignment:* In this approach, fixed channels are assigned to the nodes for reception or transmission, and then, nodes switch their channel to the neighbor's channel in order to communicate with them as in TABA [YS11], MC-LMAC [IvHJH11], MMSN [ZHY$^+$06], [CHH$^+$06], [LHA08].

In MMSN [ZHY$^+$06], nodes gather two hop topology information from neighbors, and then, available channels are assigned to balance channel utilization in two hops. Unfortunately, MMSN does not take into account the routing information while assigning channels. It is feasible if all nodes have equal traffic rates, but this distribution is not optimal for realistic scenarios, as node's traffic at any instant t depends upon its position in the network and absence/presence of events. For medium access, MMSN uses slotted CSMA protocol where all nodes contend for the channel at the beginning of each time slot. Moreover, MMSN has a dedicated broadcast channel and all nodes tune to this channel at the beginning of each time slot.

Wu. et. al. in [WSHL08] propose a static tree-based multichannel assignment protocol (TMCP) which divides the network into disjoint multiple trees each operating on an independent channel. Thus, TMCP offers multiple interference free flows in the network. However, similar to MMSN, TMCP does not consider routing information for channel assignment. As stated earlier, it is possible that some trees have high traffic loads resulting in bottleneck condition, while other sub-trees have little or no traffic at all. Also, partitioning network into disjoint sub-trees has complexities especially for large scale networks.

Recently, Yu. et. al. [YCF$^+$10] proposed a traffic-aware Game-based Channel Assignment Algorithm (GBCA) which takes into account both, topology information and routing information. In GBCA, higher degree nodes select channels prior to their lower degree neighbors to acquire better spectrum, because authors suppose that nodes having higher degree have comparatively more relaying load and thus suffer or cause more network interference. However, GBCA algorithm is feasible for homogeneous WSNs where every node has similar traffic generation rates. The supposition of prioritizing high degree nodes during channel selection will not be valid for heterogeneous WSNs like bandwidth demanding multimedia WSNs, or even event-based homogeneous networks. Thus, a realistic traffic-aware and topology aware strategy needs to be proposed.

In our TABA protocol, channel assignment is both static and dynamic in nature; channel assignment is static as every nodes reserves its central frequency (channel number) and maximum required channel width at network initialization based on its estimated traffic rates. Afterwards, TABA has dynamic behavior as; a) nodes switch to different channels for transmission and reception, and b) nodes can variate their channel widths according to their current traffic rates. It is to be noted that, once a node has selected a channel on which it wishes to communicate with its neighbors, it won't change it; only the bandwidth of the channel can be altered. These characteristics should make TABA very efficient as access to wireless spectrum is fine tuned according to traffic requirements. On the other hand, channel selection mechanisms proposed by protocols like GBCA [YCF+10], [CHH+06], TMMAC [ZZH+07], [LHA08], MMSN [ZHY+06], TMCP [WSHL08] cannot maximize the network throughput, and thus cannot fully utilize the advantages of multi-channel usage as channel assignment is not traffic-aware.

6.3 TABA Algorithm

This is a distributed algorithm where nodes independently take channel selection decisions based upon the limited information they have about the network.

6.3.1 Working Principle:

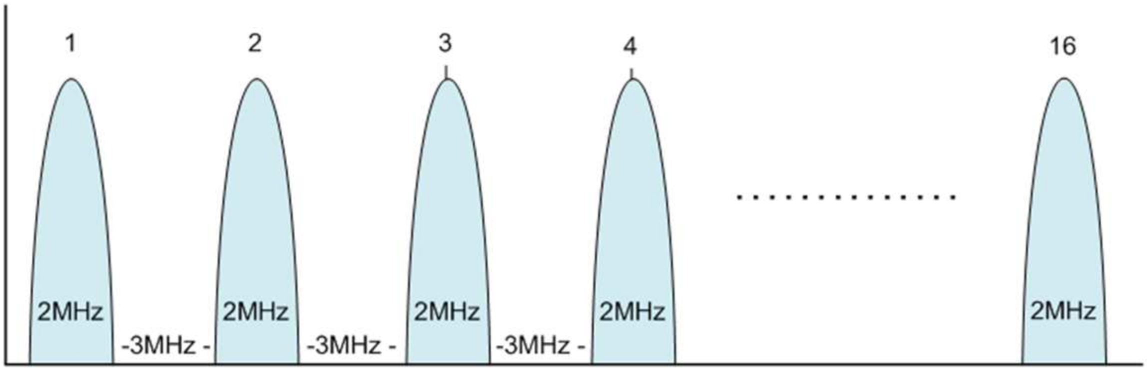
We consider a network consisting of a sink and N nodes which are organized into tree-based topology with sink as root; at network initialization, the sink broadcasts a packet to the network via pure flooding and then the nodes can used the reverse paths of the sink's broadcast packets to construct the reverse routing tree. Moreover, nodes also exchange hello messages to discover their one hop and two hop topology. We are supposing that, in this network, every node n_i knows:

(a) The minimum and the maximum traffic a node n_i may generate, and also the minimum and the maximum traffic n_i may relay on behalf of its successors in its subtree.

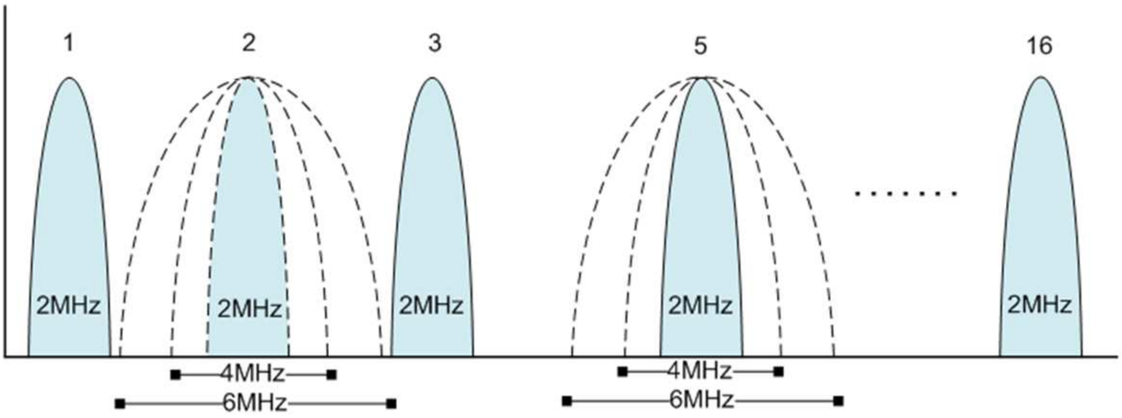
(b) Its one-hop and two-hop neighbors calculated via exchange of *Hello* messages

(c) Its predecessor and successor(s) in the tree

Traffic Generation Rate of Sensors: In a heterogeneous wireless sensor network, nodes may be equipped with different types of sensors. Moreover, some nodes may also be equipped with multiple sensor types each having different tasks to perform, and thus they will generate data reports of different sizes. Furthermore, each sensor may have different QoS requirements. Now, from the type of sensor(s) a node n_i is equipped with, it can estimate its own minimum and maximum data generation rates denoted by r_{i_min} and r_{i_max} respectively. Let r_{i_min} be the rate at which n_i is obliged to generate a data report after some maximum time span even in the absence of any event. Moreover, let r_{i_max} be the



(a) Channel distribution of IEEE 802.15.4 PHY spectrum with 3MHz guard band



(b) TABA's adaptive channel-width choices

Figure 6.1: Channel Distribution of IEEE 802.15.4

rate at which n_i generates reports at its highest capacity; r_{i_max} depends upon the type of traffic a sensor generates and its periodicity, both of which can be pre-calculated from the profile of the sensor(s) a node is equipped with.

Hello Messages: In TABA, nodes also exchange *hello* messages to discover their two hop neighborhood. A *hello* generated by a node n$_i$ contains the following detailed information:

- address of the source n$_i$.
- its minimum and maximum required traffic rates λ_{i_min} and λ_{i_max} as defined in the next paragraph.
- its depth l in the tree which n$_i$ can determine easily from the Time-To-Live value of the broadcast packet flooded by the sink.

- the ID of its predecessor and its successors in the tree.
- the channel number selected by n_i and its width.
- the list of one hop neighbors already discovered by n_i and the above mentioned three points (a,b & c) they have announced in their *hello* messages.

Estimation of Minimum and Maximum Traffic Rates: Every node n_i at depth l, denoted as $n_{i,l}$, sends this traffic profile to its predecessor $n_{j,l-1}$, where $i, j \epsilon \{1, 2, .., N\}$ and $l \epsilon \{1, .., height_{tree}\}$. Thus, a node $n_{i,l}$ can estimate its minimum and maximum required transmission rates denoted as λ_{i_min} & λ_{i_max} respectively from the equation-6.1 and equation-6.2 respectively.

$$\lambda_{i\_min} = \sum_{j \epsilon successor(i)} \lambda_{j\_min} + r_{i\_min} \tag{6.1}$$

where $\sum_{j \epsilon successor(i)} \lambda_{j\_min}$ is the minimum traffic the successors of n_i may send to it for relaying towards the sink and r_{i_min} is the minimum traffic generated at n_i by its sensors combined together.

$$\lambda_{i\_max} = \sum_{j \epsilon successor(i)} \lambda_{j\_max} + r_{i\_max} \tag{6.2}$$

where $\sum_{j \epsilon successor(i)} \lambda_{j\_max}$ is the maximum traffic successors of n_i may send to it for relaying towards the sink, and r_{i_max} is the maximum traffic generated by n_i.

Initially, all nodes tune to the same channel and exchange beacons to discover neighborhood at different channel widths. We use discrete channel widths β, 2β, 3β and 4β where β=2MHz. 4β is the maximum channel width choice in 802.15.4 for utilizing the 3MHz guard band without interfering with the adjacent channels. Let $N_{i,w\beta}$ be the neighbor set of n_i at width w where $N_{i,\beta} \geq N_{i,2\beta}$ because for same transmission power P_t, transmission range decreases with increase in channel width. Once every n_i has calculated $N_{i,w\beta}$ for all channel widths w, the beacon exchange process terminates. For the same transmission power P_t, the transmission range decreases with increase in channel width and vice versa. Due to this characteristic, we come across two choices;

1. *Same Transmission power over all Channel Widths:* Nodes use same radio power for transmitting packets over any channel width; Under such circumstances neighborhood set will be different at different channel widths, which means neighbor discovery process will be executed multiple times once for every channel width.
2. *Channel-width aware transmission power:* Approximately same transmission range, and thus, same neighborhood set can be maintained for different channel widths by increasing/decreasing transmission power with increase/decrease in channel width

Algorithm 4 : Channel selection algorithm at node n_i

```
Input: A sink-rooted tree where $n_i$ knows; its two hop neighbors and their levels, predecessor $n_{i,p}$, successors $n_{i,s}$, $\lambda_{i\_min}$ & $\lambda_{i\_max}$
Output: A traffic-aware channel , its width and slot assignment
Wait (till all l-1 level & high priority neighbors send beacon) do
    if (all high priority neighbors selected ch) do
        Select $ch_{c,w}$ s.t. (a) & (b) are true
        (a) if Capacity($ch_{c,w}$)$\geq\lambda_{i\_max}$ //provided b) is true
                select $ch_{c,w}$
            else // no channel available in which adjacent guard band can be used
                $n_i$ selects $ch_{c,1}$ //choose an available standard 2MHz channel. In case of conflict,
                                         //use even-channel selection technique. Note: all nodes using channel $ch_{c,1}$
                                         //use standard 2MHz channel.
        // Adjacent channels boundaries do not overlap
        (b)$(ch_{c-1,w\frac{max}{2}} \cap ch_{c,w\frac{min}{2}} = \emptyset)$ &&
            $(ch_{c+1,w\frac{min}{2}} \cap ch_{c,w\frac{max}{2}} = \emptyset)$
        Broadcast Beacon($ch_{c,w}$)
    else
        Listen to high priority neighbors beacons
    done
done

//Slot Assignment to Successors(i)
Successor of $n_i$ sends slot request and current required data rate
    $n_i$ assigns $slot_{num}$ & channel width to $n_j$
    // if $n_i$'s successor retransmits higher/lower traffic rate request then $n_i$ will increase/decrease the channel width assigned to the request sender
```

respectively. Effective transmission range for combinations of transmission powers, channel width and encoding schemes can be found by repetitive tests in a given environment, though, effective transmission range also depends upon a lot of environmental factors and interference from other technologies such as wifi. For the moment, it is being assumed that nodes will keep the same transmission range by variating transmission powers. The case of different neighborhood sets with change in channel widths will be treated in the upcoming work.

Channel Selection Process: Now, the channel spectrum and its width selection process starts from the sink moving in the breadth first manner. By now, every node knows its two hop neighbors and their depths, its predecessor and successors, and λ_{i_min} and λ_{i_max} respectively. A node n_i at level l waits till level *l-1* nodes in its two hop neighbors have not sent their channel selection decisions. Once a node n_i has received channel selection decisions from all *l-1* neighbors in its 2-hop via *hello* messages, channel selection starts at the level l. One should note that non-leaf nodes at level l have higher priority in decision making as they have higher relaying nodes. In case of conflict, the node having highest $\lambda_{i,max}$ in the neighborhood has higher priority. At level l, a non-leaf node n_i selects an unoccupied channel $ch_{c,w}$, where w is the minimum channel width chosen from $\{\beta, 2\beta, 3\beta, 4\beta\}$ that is sufficient to accommodate maximum incoming traffic rates at n_i

i.e. $capacity(ch_{c,w}) \geq \lambda_{i\_max}$. One important thing is, the boundaries of $ch_{c,w}$ should not intersect with adjacent channels' boundaries already selected by neighbors, as a neighbor might already have selected an adjacent channel's guard band for its use. Once $ch_{c,w}$ is selected, n_i broadcasts this information to its neighbors. Then, the next non-leaf neighbor at level l choses an interference free unoccupied channel spectrum and widths and transmits it to the neighbors via a beacon. Once all non-leaf nodes at l have selected channels, then leaves at l select channels because they have lower traffic requirement. Once all neighbors of a node at same level have selected channels, next $l+1$ level nodes start making channel decisions according to the above described process. This process stops once all nodes have finalized spectrum and width selection decisions.

6.3.2 Personal Discussion

Every node n_i knows its reception channel

$$ch_{c,[w_{min},w_{max}]}$$

. According to the supposition, nodes will initially communicate on one control channel to exchange tree structure information, traffic requirements, and then, select a channel and min and maximum bandwidths on which they will communicate. Once channel selection process is complete nodes need to exchange TDMA slots, frequency and current channel width. This requires the communication pair to switch to the same channel.

Problem and available solutions: Every node will have to switch to the same channel to reserve slots. Both, source and destination pair should switch to the same channel at the same time. A channel can be assigned exclusively for control traffic exchange so that nodes can synchronize among themselves; All nodes can switch to the same control channel at the beginning of the TDMA control frame to discover neighbors, reserve slots, and negotiate channel width. Nodes which don't want to communicate will switch-off their radios at the end of TDMA control frame, where as other nodes will wake-up/switch to the negotiated channel in their respective time slot(s).

6.3.3 Channel Access Mechanism

Since, the communicating node pair not only needs to switch to the same channel, but channel width should also be the same. CSMA/CA does not seem to be a feasible option for TABA due to synchronization problems; Switching to the same channel for negotiating channel parameters and sending data reports is infeasible, even if a dedicated control channel is used. Therefore, we use TDMA mechanism to access channel, where every predecessor assigns slots to its immediate successors for data reception. All nodes start communication at their respective selected channel c and at w=β=2MHz. Lets consider communication between a parent n_p and its successor n_s. If at instant t, traffic rate λ_t at n_s increases such that n_s cannot transmit this data to n_p in the slot assigned to it at current channel width, then n_s informs n_p about the change in traffic rate. If n_p has unassigned slots then it will reserve these slots for n_s, and then n_p informs n_s about the additional slot assigned to it via a beacon. In case this is not possible, n_p will decide to receive data from n_s at higher bandwidth by selecting an appropriate channel width it had selected during channel selection phase. It then transmits this new channel width $w\beta$ & slot s to n_s. At the beginning of the slot s, both n_s and n_p tune their radios to channel $ch_{c,w\beta}$ with width $w \times \beta$, and n_s transmits data reports to n_p at higher throughput. At the end of the slot s, both these nodes may tune radios to another appropriate channel and width for communicating with other neighbors or may decide to sleep if no communication is planned in the slot $s+1$. This mechanism enables nodes to increase/decrease throughput according to varying incoming traffic rate. It is possible that only one successor of n_p demands higher bandwidth while all others require standard 2 MHz channel. In this case, only n_p and n_s will change channel width in their concerned slots while other successors having lower traffic rates will keep on communicating on the standard 2MHz channel. Thus, only the sub-branches of the trees which have traffic requirements beyond the capacity of the stanadard 2 MHz channel will variate the channel width.

6.4 Discussion

A number of factors will be analyzed and taken into account before making channel decisions. Firstly, bandwidth variation may cause interference on adjacent channel communications, especially if nodes are geographically very close to each other; Minimum distance thresholds for different channel widths will be found to avoid interference. Secondly, hardware delays are involved when a node switches channels or only changes width while remaining at the same channel. Also, communicating nodes need to resynchronize themselves after they modify their channels or bandwidth. Thus, it may not always be feasible to switch channels and vary bandwidths. We will analyze the impact of these factors on network performance so that feasible and unfeasible conditions for decision making can be identified. Thirdly, as also dicussed above, network topology changes by varying channel width because increase in channel width reduces the effective transmission range. This factor will be thoroughly analyzed in the upcoming work.

6.5 Platform Implementation

In the beginning, the goal was to implement the TABA algorithm on Crossbow's micaZ nodes [Mot12] to do experimentation on a real platform, instead of testing its performance in a simulated environment. Our research group has crossbow's MicaZ sensor nodes which are equipped with a IEEE 802.15.4 standard-based CC2420 wireless chip [Ins12b]; CC2420 is a half-duplex wireless radio capable of communicating over one of the 16 channels specified in the 802.15.4 standard.

We had opted to implement the algorithm on a real platform in order to first test the conditions under which the bandwidth could be increased without causing interference to the nodes tuned to the adjacent channels. For instance, it is a know fact that communicating pairs tuned to two partially overlapping channels might still be able to successfully if the nodes are separated by a certain distance, even though they might still be in each others transmission range if they are tuned to the same channel.

However, after implementing the basic functionalities of the protocol like exchanging *hello* messages and altering channels, it was discovered that micaZ platform's manufacturer, Crossbow cooperation, does not provide access to the programmers to alter the default 2 MHz channel bandwidth. Due to this unfortunate reality, experimentation based performance evaluation could not be realized as channel width variation is the backbone of the TABA algorithm. This algorithm can be still be implemented on a real platform but this requires access to the software programmable radios like the ones constructed by the Ettus coorporation [Com12]. However, unfortunate for us, we do not have access to these software programmable radios at the moment.

6.6 Conclusion and Future Work

In this chapter, we proposed a distributed traffic-aware channel selection algorithm for heterogeneous WSNs. This algorithm enables nodes to dynamically modify channel parameters according to increasing or decreasing traffic rates. Initially, an attempt was made to implement the proposed algorithm on micaZ sensors [Mot12], but unfortunately the channel width of the 802.15.4 cannot be modified on these chips. Due to this reason, the TABA algorithm is being currently implemented in the GloMoSim Simulator [Lib12] for performing in-depth analysis.

Chapter 7

Conclusion and Future Perspectives

Contents

In this thesis, we have addressed the energy efficient data dissemination issue in both small and large scale wireless sensor networks. In the beginning, we study the power consumption in wearable health monitoring networks and analyze the power consumption effect in single hop and multi-hop communication scenarios to see which of the two options is more energy efficient in case of short range networks. Moreover, we have proposed two data dissemination algorithms for large scale wireless sensor networks in which the sink is mobile. One of these algorithms, SN-MPR, is designed for applications which have rather stringent data delivery requirements; this algorithm minimizes energy consumption in the network by limiting sink location update messages to those nodes which are affected by sink mobility; at the same time sink ensures continuous connectivity with the sensor nodes. The second among these two data dissemination algorithms, the duty-cycle SN-MPR, further minimizes the power consumption of the network by enabling the non-relay nodes to switch-off their respective transceivers when they don't want to communicate.

In addition, we propose TABA, a multi-channel assignment algorithm for heterogeneous wireless sensor networks. The objectives of proposing TABA algorithm are to minimize power consumption caused due to network interferences at higher traffic rates, and enhance network throughput by allowing multiple concurrent transmissions.

7.1 Contributions

In the first part of this thesis, we address the energy issue in WBANs. In fact, recent advances in technology has led to the development of small, intelligent, wearable sensors capable of remotely performing critical health monitoring tasks and then transmitting patient's data back to health care centers over wireless medium. But to the day, energy remains to be a big constraint in enhancing Wireless Body Area Networks lifetime. Some recent literature on WBANs proposes multi-hop sensor to gateway data relay as more energy efficient than single hop communication. There are studies which argue contrarily. In this context, we conduct a study which analyzes the single vs multi-hop energy consumption effect for real short range sensor devices in the given context. The results show that deliberate reduction of transmission range to induce multi-hop scenario is not energy efficient.

In the second part of this thesis, we address the energy efficiency in the context of data dissemination mechanisms in large scale WSNs, and propose two data dissemination protocols for applications in which sink is mobile. We consider sink as a mobile entity because static sink based protocols suffer from energy hot spot problems; nodes closer to the static sink quickly lose their battery power due to excessive relaying and die, making the network inaccessible to the sink in spit of the fact that majority of the nodes are still functioning. In this particular context, this thesis contributes two mobile sink based data dissemination algorithms. As a first contribution in this part, we propose a distributive energy-efficient sink location update algorithm, named SN-MPR, which uses a combination of multi-point relay broadcast [CJ03] and a local path repair mechanism by means of which sink's location update packets are forwarded only to those nodes which are affected by the sink mobility i.e. change in sink position changes those nodes' route towards the sink as compared to its position in the previous sink location update message. The rest of the nodes whose routing paths do not change due to sink mobility do not rebroadcast sink location update messages. This combination of local repair technique and MPR broadcast mechanism minimizes the energy consumption of the network and sink mobility.

As a next contribution in the second part of the thesis, we propose a duty-cycle aware version of the SN-MPR algorithm to further minimize energy consumption in the unnecessary utilization of radio resources. In fact, transceiver is the biggest energy consuming component in a wireless sensor platform and consumes battery power of the order of magnitude much higher than the other electronic components such as processor, sensor(s) and memory. Moreover, transceiver remains in idle listening state most of its lifetime which consumes power which is relatively equal to the power consumed by radio in receiving a packet. Our proposed duty-cycle SN-MPR algorithm allows all non-relay nodes to switch-off their respective transceivers when communication is not desired.

To validate the performance of the above described SN-MPR and the duty-cycle aware SN-MPR algorithms, we used Network Simulator 2 for performing simulations. Since, OLSR protocol [CJ03] also uses MPR mechanism for broadcasting, we modified an existing implementation of the said protocol called UM-OLSR [Fra09] to implement both these algorithms. For duty-cycle SN-MPR, necessary changes were also made in the MAC layer module of the Network Simulator 2 to control transceiver's duty cycle and the energy record keeping functionality. The simulation results show that both of these algorithms significantly reduce the power consumption of the network when compared to classical MPR flooding.

In the third and final part of this thesis, we address multi-channel assignment problem in the context of energy efficiency and network capacity for IEEE 802.15.4 based heterogeneous multimedia WSNs, which require data transfer higher rates as compared to scalar sensor network applications. In fact, majority of the existing data dissemination protocols for WSNs have been designed to work on a single channel in spite of the fact that single channel communications suffer from capacity constraint problem due to interferences caused by frequent collisions, which also results in energy wastage. On the other hand, multi-channel assignment strategies can minimize power losses due to packet collisions and multiple retransmission retries. Moreover, concurrent multiple transmissions over multiple channels also increase the throughput of the network. In addition, proper coordination among nodes can enable them to economize power consumption by switching-off their transceivers for longer durations as nodes do not have to wait for longer duration to gain access to the channel due to lesser number of neighbors operating on the same frequency. Most of the existing WSN platforms like micaZ [Mot12], mica2 [Cooa], telosB [Coo12b], imote2 [Cooc] are equipped with a half-duplex transceiver which can operate over multiple channels. In order to profit from the advantages offered by multi-channel communication paradigm, some recent works address multichannel data dissemination, but these algorithms cannot ensure QoS to rather higher data rate multimedia heterogeneous WSNs as they have been proposed for low rate homogeneous sensor applications, and also these schemes consider fixed channel widths. Thus, in order to address the energy issue and at the same time enhance network throughput, we propose a Traffic-Aware Bandwidth-Adaptive channel assignment algorithm (TABA) for applications which have higher traffic rates. The TABA algorithm enables the nodes to not only choose interference free channels in the neighborhood but also to adapt channel's bandwidth to increase or decrease throughput according to varying traffic conditions.

7.2 Future Prospects

For the moment, SN-MPR and duty-cycle SN-MPR algorithms consider only a single mobile sink, however, some applications may require multiple data collecting sinks in the network. It would be interesting to extend these two algorithms for such multiple sink scenarios as it would give rise to some new research issues; in the first place, inter-sink coordination is required to efficiently divide the terrain to be monitored as it would be ineffective if multiple sinks gather data from the same region. In the second place, sinks need to coordinate to exchange the monitored information among themselves which could be either over a single hop if high power transmissions are used or over multiple hops by using the sensor nodes.

Moreover, in this thesis the performance of SN-MPR and duty-cycle SN-MPR has been evaluated through simulations. However, it would be interesting to see the behavior of both algorithms on real platforms.

The TABA algorithm needs to be evaluated on a real test bed. Attempts were made during the thesis to implement TABA on Crossbow's micaZ nodes, however, the realization of this platform was not possible due to the limitations of the CC2420 transceiver's hardware. In fact, channel's bandwidth variation is the backbone of the TABA algorithm, however, the default 2 MHz bandwidth of the available sixteen channels of these CC2420 transceivers installed on micaZ platforms [Mot12] cannot be modified. To evaluate the algorithm's performance, we plan to use off-the shelf software programmable radios like the ones constructed by Ettus [Com12] as they allow the modification of channel's bandwidth.

Sensing events are generated in simulation environments either at regular intervals or with some probability which might not reflect the behavior of a real sensing application scenario. In order to study the behavior of all the three contributions of this thesis under real environment, traces captured by real events on existing platforms can be used in the future evaluations as this will enable the in depth analysis of the protocols under realistic conditions.

Appendix A

List of Publications

- **Under Progress**

  1. Y. Faheem, S. Boudjit, K. Chen: Energy Efficient Multi-Point Relay Routing Protocol for Mobile Sink Wireless Sensor Networks, Wiley Wireless Communications and Mobile Computing Journal *(submitted)*
  2. Y. Faheem, S. Boudjit: Duty-Cycle SN-MPR Algorithm for Mobile Sink Wireless Sensor Networks, Elsevier Journal of Network and Computer Applications *(submitted)*

- **Published Work**

  1. Y. Faheem, S. Boudjit: TABA: A Traffic-Aware Channel Selection Protocol for 802.15.4 Based Wireless Sensor Networks, *in Proceedings of the 12th ACM international symposium on Mobile ad hoc networking and computing (MobiHoc)*, Paris, 2011
  2. Y. Faheem, S. Boudjit: Traffic-aware Adaptive-Bandwidth Channel Selection Algorithm for Wireless Sensor Networks, *5th IWSOS workshop*, Karlsruhe, Germany, 2011
  3. Y. Faheem, S. Boudjit and K. Chen: Dynamic Sink Location Update Scope Control Mechanism for Mobile Sink Wireless Sensor Networks, *in Proceedings of 9th Wireless On-Demand Networks Conference (WONS)*, Italy, 2011
  4. Y. Faheem, S. Boudjit: SN-MPR: A Multi-Point Relay Based Routing Protocol for Wireless Sensor Networks, in Proceedings of 3rd IEEE/ACM Int'l Confer-

ence on Green Computing and Communications & Int'l Conference on Cyber, Physical and Social Computing (CPSCom/WISARN), Hangzhou, China, 2010

5. Y. Faheem, S. Boudjit: ”Wireless Body Area Networks: Information Dissemination Analysis”, *in Proceedings of* 3^{rd} *IEEE HealthINF Conference*, 20-23 Jaunuary, 2010, Valencia, Spain
6. Y. Faheem, S. Boudjit and K. Chen: Data Dissemination Strategies in Mobile Sink Wireless Sensor Networks: A Survey,*in Proceedings of* 2^{nd} *IFIP Wireless Days Conference*, Paris, France, 2009

Other Publications

1. Y. Faheem & J. L. Rougier: Loop avoidance for fish-eye OLSR in sparse wireless mesh networks, *in Proceedings of the* 6^{th} *international conference on Wireless On-Demand Network Systems and Services (WONS)*, IEEE Press, 2009, 215-218

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List of figures

List of tables