Process Control over Wireless Sensor Networks

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Abstract

A significant growth was witnessed in the filed of Wireless Sensor Networks (WSNs), the previous decade. Advances in hardware miniaturization coupled with increased processing capabilities and memory capacity have extended the application domains of WSNs. In light of this, standardization organizations led by academia and industries initiated activities for the design of protocols such as IEEE 802.15.4 and IETF RPL (Routing Protocol for Low power and Lossy Networks). IEEE 802.15.4 defines physical and media access layers for WSNs while IETF RPL defines the functionality of the routing layer.

This thesis investigates research issues in wireless sensor networks and network controlled systems that control micro-biological processes for water treatment plants. By choosing a process model that can relate to an industrial process, feasibility of control over IEEE 802.15.4 and RPL protocols is evaluated for stability with regards to network delay and packet loss. Settling time and overshoot are measured to indicate control performance. Control messages related to routing and routing table lengths are measured to indicate network stability and scalability. The system model used is a centralized discrete controller controlling a thermal processes running on the sensors. This model is chosen for representing wide industrial networked control systems while adding a WSN dimension based on IEEE 802.15.4 and RPL.

The main contribution of this thesis is an experimental study where both the network and controller performance is validated while utilizing commercial off-the-shelf sensor platforms. The results from this experimental work include first the use of established theorems for analyzing control using WSNs. Moreover, the ability of IEEE 802.15.4 and RPL to provide stable communication that is reliable enough for actual industrial control implementation is validated.

Acknowledgments

First and foremost I would like to express my sincere gratitude to my advisers Prof. Carlo Fischione and Dr. George Athanasiou for letting me conduct this thesis under their supervision. Your expertise in control and networking has been invaluable and a lot I have learned from. I thank you for the continuous assistance, understanding and patience you have granted me. It has been a great inspiration for bringing this thesis work to conclusion.

Many thanks goes also to colleagues Yuzhe Xu and Meng Guo, both PHD students who have shared their knowledge and time to lend a helpful insight in clarifying problems along the thesis work.

I also would like to use this opportunity to extend my gratefulness to my family, friends and all who has been at my side during this thesis work and the course of my study. All your words and supports have strengthened me in many ways.

Contents

List of Figures

List of Tables

Acronyms and Abbreviations

6LoWPAN IPv6 Low power Wireless Personal Area Networks.

ARPA Advanced Research Projects Agency.

BLIP Berkeley Low-power IP stack.

CAP Contention Access Period.

CFP Contention Free Period.

CSMA-CA Carrier Sense Multiple Access with Collision Avoidance.

DAO Destination Advertisement Objects.

DIO DAG Information Object.

DIS DAG Information Solicitation.

DODAG Destination Oriented Directed Acyclic Graph.

DSN Distributed Sensor Network.

ETX Expected Transmission count.

GTS Guaranteed Time Slot.

HBN HYDROBIONET.

ICMP Internet Control Message Protocol.

LLN Low power Lossy Networks.

MAC Media Access Control.

MBR Membrane Bioreactor.

MEM Micro electromechanical.

MRHOF Minimum Rank Objective Function with Hysteresis.

NCS Network Controlled System.

OF Objective Functions.

OS Operating System.

PID Proportional-integral-derivative controller.

PRR Packet Reception Ratio.

RO Reverse Osmosis.

RPL Routing Protocol for Low-Power and Lossy Networks.

RSSI Received Signal Strength Indication.

WBN Wireless Biosensor and Actuator Network.

WINS Wireless Integrated Network Sensors.

WSN Wireless Sensor Network.

Chapter 1

Introduction

Wireless Sensor Networks (WSNs) is one of the most exciting and growing branches of wireless communication. As predictions show the market is soon to cross the billion dollar mark [2]. Our world is going toward autonomous, sustainable and environment conscious systems with technologies which can monitor the environment, provide valuable and timely measurements. WSNs enable such drives in a non-intrusive manner yet with extended coverage of area thanks to their underlining distributed and miniature nature.

In addition when combined with Network Controlled Systems (NCSs) where by feedback and control decisions are communicated using a wireless medium, they create the potential to be applied and revolutionize many application areas. Concepts like Smart buildings, Smart industries, Internet of things are all but becoming common.

1.1 Background and motivation

Origins of WSN can be traced back to the beginning of 1980s research on Distributed Sensor Network (DSN) backed by Advanced Research Projects Agency (ARPA).[1] Operating System (OS) suited for communication from CMU and helicopter tracking application at MIT were a couple of the pioneering works [3]. At the time such initiatives faced the obstacle of underdeveloped sensing and communication platforms.

[1] The precursor to the current DARPA, the US military advance research unit.

In the late 1990s advances in wireless technologies, very large scale integration of components and Micro electromechanicals (MEMs) systems revived the attention given to WSNs. Notable projects included, the Wireless Integrated Network Sensorss (WINSs) at the rock well science center UCLA [4] and the famous Smart dust project, sensing nodes with grain size at University of California at Berkeley [6].

In continuation, the past decade has been accelerated growth period for WSNs in every aspect. From the hardware perspective advance in miniaturization and integration of sensors, processors and actuators including widely available of-the-shelf platforms such as micaz and telosB were achieved. In terms of software development OSs targeting embedded systems and sensor networks such as TinyOS and Contiki have evolved into existence. Accompanying communication protocols have been standardized, including IEEE 802.15.4 Media Access Control (MAC) and Routing Protocol for Low-Power and Lossy Networks (RPL).

The academia has also been actively engaged in tackling new challenges that accompany WSNs and NCSs. Some works include sampled system control and stability [8], network life time,coverage and architecture [7], co-design methodologies for control and networking [12, 13, 11], networking protocol evaluation and optimization [10]. In general the surveys [15, 14] present the researches around WSNs while [16] summarize NCSs researches.

The ultimate goal and vision of WSNs field is to make sensor networks a fabric of social life. Minute sensors will be embedded in every conceivable manner to provide accurate timely information to sinks nodes. These nodes interested with the information will enable proactive response hence improving the user experience, quality of life as well as fortunes spent in industries and manufacturing. In [18] picturesque vision for the year 2050 is introduced.

Aside from visionary predictions recent times some actual practical projects worth mentioning have been implemented. To name a few large scale deployments, habitat monitoring [22], structural monitoring project of the golden gate bridge [23, 21], health care [24], large scale water monitoring [19], and the HYDROBIONETs (HBNs) for large scale plants which the basis for this thesis.

The aim of HBN is to utilize as well as pioneer state of the art in WSNs and NCSs for water treatment plants. Among others it involves integrating standard communication protocols, optimizing and designing control systems and designing special sensor units. More importantly the main motivation and uniqueness of this master thesis arises in setting out to evaluate the holistic effect of both wireless communication protocols (IEEE 802.11.4 MAC & RPL) and a designed controller (PID) unlike other related works. The master thesis work [38] though done well, its scope was only on RPL. The paper [20] demonstrates actual WSN used in monitoring water treatment process similar to this thesis but lacks controller and protocol parameter evaluations. The work in [1] important work of comparing RPL with other routing protocol is done. While the methodology of evaluating the networking is similar with this thesis it was not aimed at any application nor have controller implementation.

1.2 Problem statement

Motivated by the predicted tremendous growth in this field, the interesting applications, engaging challenges of WSNs and the specific requirements of HBNs project, this thesis was carried out with two aims. The first aim is to review the topics of WSNs and NCSs with HBNs and industrial water treatment processes in mind. The second is to evaluate feasibility of networked control using IEEE 802.15.4 and RPL. In this regards the performance of a control system built on top of these protocols will be analyzed.

In more concrete words the unique contribution of this thesis is the practical evaluation of a WSN built on IEEE 802.15.4 and RPL as used for process control. This entails actual experimental work both on controller and networking side relying on off-the-shelf sensor platforms. Some questions addressed following the undertaken work include:

- What types of wireless sensors and network topologies suitable for water treatment plants?

  Various topological options were scrutinized and suggestions are made to incorporate multi-tier architecture.

- Is a simpler feedback controller over the established protocols such as IEEE 802.15.4 and RPL for application in water treatment plants possible?
  A Proportional-integral-derivative controller (PID) controller designed using matlab and feedback system implemented on sensor nodes.

- How is the performance of such a controller implementation is affected by constraints of protocols and the application area?
  The effects of network delay and packet drop thoroughly analyzed in a practical setup with the conclusion that satisfactory system performance (network stability, controller settling time & controller overshoot) are achieved.

- Are there tangible outcomes from such implementation of WSNs and feedback controller that scale to HBNs in large scale water treatment plants?
  It is shown network built on IEEE 802.11.4 MAC and RPL can be scaled but require a well structured topology design to begin with.

The rest of this document is organized as follows. In Chapter 2 WSNs are described from a general perspective followed by water treatment plants and the HBNs project. In chapter 3 the protocols IEEE 802.15.4 and RPL are presented. The chapter closes with pointing the reasons why it is plausible to consider them for the project. Chapter 4 will be mainly describing the PI controller design and theoretical basis for implementing and evaluating a NCS. Chapter 5 will cover the setup and experimental scenarios along with interpretations of results. Chapter 6 will sum up the work undertaken and closes with proposed future works.

Chapter 2

Wireless sensor networks

WSNs can broadly be defined as system of tiny sensing and processing units distributed spatially and communicating through wireless technologies. These system of sensors will be measuring physical and environmental parameters and in a cooperative manner transmit the information to a central location for further storage, analysis and decision.

Recent advances in hardware have opened doors for actuation to co-exist side by side with sensing in these networks, hence a more expressive definition of Wireless sensor networks will be nodes wirelessly networked for sensing, processing, control and actuation purposes.

WSNs once deployed the nodes are expected to form an ad-hoc network which ensures a multihop path to the sink/central node(s). This enables WSNs to exist in diverse environments and function autonomously with no or little maintenance requirement with the added benefit of no precondition on pre-existing network infrastructure. Applications which require large sensor deployment numbers, wide coverage area, limited accessibility are among those suited for WSNs.

In this chapter first components of WSNs will be described. Then HBN project will be presented. Lastly sensors platforms used in WSNs research and those required by HBNs are described.

2.1 Component of the system

A WSN system comprises of the nodes as the center stones, the operating system running on nodes, the communication and networking protocols and the desired applications.

2.1.1 Sensor nodes

A basic sensor node composition consists of five basic hardware as shown in the block diagram below.

Processor/Controller module: Executes all the calculation and processing tasks. Operating and application software codes run on it while coordinating other resources and components.

Transceiver module: Concerned with converting data in between bit stream, bytes or frames from microcontroller to and from radio waves of the wireless channel. WSNs utilize predominately radio frequency (RF) in the frequency spectrum 433 MHZ - 2 GHz in half duplex mode and with no requirement on line of sight communication.

Memory module: Provides for the storage needs of a sensor node in three forms. A RAM with minimal read write time that is used for intermediate data storage for calculation results, sensor readings and received packets. An EEPROM where data is written and erased in bytes and suited for long term storage such as program codes. A FLASH with higher capacity that only allows writing in blocks of bytes. Though primarily used to store log and configuration data, it can also hold intermediate data when RAM is burden but with the disadvantage of slow access time and high energy expenditure.

Power supply module: The mechanisms for power supply in sensor nodes are either non rechargeable primary batteries or energy scavenging from the environment. While incorporating primary battery is easier and the prevalent method, in the many deployment scenarios replacement is impossible thus the later method of energy scavenging necessary. Photo voltaic recharging based on solar cells, thermoelectric generators based on temperature differences and electromagnetic or electrostatic generators based on mechanical vibrations are among the possibilities to recharge secondary batteries. The main limitation of these approach is technologies are not mature enough to enable recharging at very low current levels and efficiently manage intermittent charging cycles. Both of which inherent to power scavenging techniques.

Sensor/actuator: Sensors as the first interface to the physical world, they convert physical signal to electrical, do signal conditioning if needed and possibly covert to digital output. Section 2.3 provides more about sensors.

Actuators are another interface to the physical world which make possible full control loops. Though they are usually switches and valves, could also be add-ons to sensors for mobility and more.

2.1.2 Operating system

OS for sensor nodes must account for resource constraints, and more restricted nature of programs and processes running on the nodes. Some of the main considerations in OS design and choice include architecture, programming model, scheduling, memory management and protection and API Support [25].

From the above perspective TinyOS[1] is considered a monolithic component based system with static memory allocation and management. It is primary an event driven FIFO OS that doesn't explicitly support real time systems, though have incorporated multithreading and EDF scheduling through time. Regarding communication protocols it has among others IEEE 802.15.4 complaint MAC, RPL and Berkeley Low-power IP stack (BLIP).

2.1.3 Communication Protocols

The communication protocols in WSNs primarily focus on media access (layer 2) and routing (layer 3). In both cases autonomous reliable low data rate communication is the goal. Some of the well known industry standards include IEEE 802.15.4, ZigBee, WirelessHART, ISA100.11a, IETF 6LoWPAN and RPL [30].

[1] TinyOS is the OS of choice for this thesis project.

IEEE 802.15.4: It is the core specification for WSNs which are concerned with low power low data rate networks and on which most other standards are based on. It defines the physical layer at center frequency is of 868/915 MHz and 2.4 GHz and MAC layer based on Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism. More detailed given in Chapter 3.

IETF IPv6 Low power Wireless Personal Area Networks (6LoWPAN): It is definition of an adaptation layer for the compression, encapsulation and address resolution required to enable IPv6 packet to be sent and received on top of IEEE 802.15.4.

RPL It is a recent standard which followed header compression mechanisms for IP such as 6LoWPAN. It is unique from the numerous routing protocols in WSN in that the support it provides for different application objectives is separated from the actual routing process. More detailed given in Chapter 3.

2.1.4 Application domains

Presenting the diverse application domains in WSNs is well beyond the scope of this document but in general they can be classified as tracking or monitoring [30]. And some of these include smart grids, smart buildings, environmental monitoring, structural monitoring and industrial control and automation which includes HBN.

Industrial control and automation: By placing sensors and actuators at points closest to processes with minimal intrusion more powerful monitoring, processing and control is achieved in industrial plants. Temperature, pressure, flow level density and vibration are some of the process variables that can be monitored and controlled. In addition health of machinery, stocks of inventory can be tracked. Some attractive qualities include no wiring, less corrosion and burning damages hence easy maintenance and reduced associated costs, better performance and reliability with the use of increased redundancy.

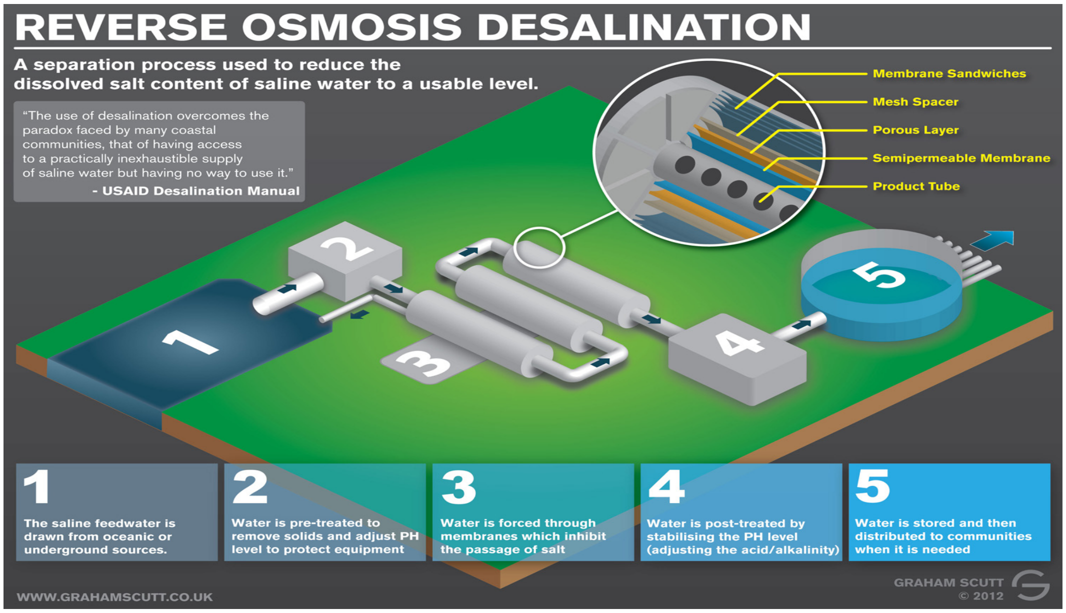


Figure 2-1: Simplified water desalination process with RO. [Source: `http://grahamscutt.co.uk/reverse-osmosis-desalination`]

2.2 Network setup for HYDROBIONETS

2.2.1 Water treatment plants and technologies

Water treatment plants primarily use two technologies depending on the source and intended use of the cleaned water [26].

Reverse Osmosis (RO): RO shown in Fig. 2-1 is a technology used primarily by water desalination plants where the water source is sea water with high the salt content.

In the pretreatment step most of the work is carried out by filtration techniques coagulation, flocculation and granular filtration. The aim is to remove solid, suspended materials. Furthermore continuous or periodic biocide dosing is required in order to eliminate bacteria. Presently this process is controlled by human measurements.

In the main reverse osmosis process high pressure pumps are used to drive water against its natural osmotic tendencies across a semipermeable membrane while it holds salts and bigger contaminants. In an industrial setup membranes are wrapped in cylindrical compact manner with an input for water and outputs for the salty (concentrate) and cleaner water (permeate). Accumulation of bacterial matter (bio-

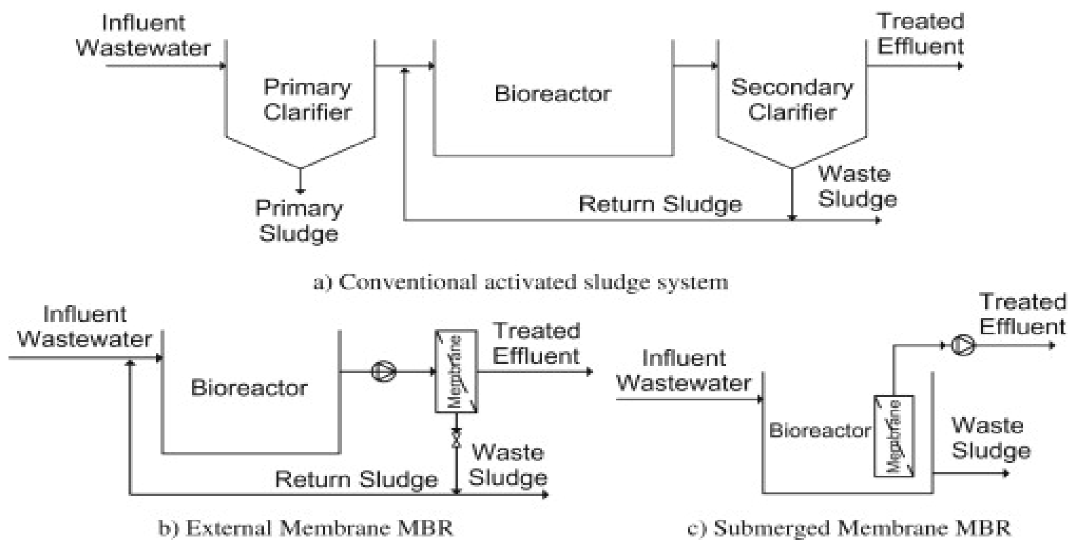


Figure 2-2: Simplified waste water treatment process with MBR [5].

fouling) on the membrane will greatly increase the demand on power to maintain sufficient pressure across the membranes.

Final step in desalination plants is the post treatment also known as hardening. Salts, carbon dioxide, calcium hydroxide and final chlorination will be added to permeate to make it drinkable water.

Problem statement in RO: Controlling the dosing of chemicals and frequency of cleaning process so that cost is reduced life time of RO membranes improved.

Membrane Bioreactor (MBR): MBR is a technology that is used to reclaim water for non-potent uses from waste water. It combines conventional activated sludge treatment with low-pressure membrane filtration, Fig. 2-2.

The pretreatment section is responsible for removing bigger inorganic wastes and biocide dosing is performed to help the filtration process

The aeration zone section is responsible for transferring air bubbles for the bacteria that is expected to metabolize organic matter. The aeration in this stage involves finer air bubbles.

The membrane section is responsible for passing the reclaimed cleaner water using low pressure micro-filtration or ultra-filtration membranes. For membrane section there is also the need for aeration to keep the pores in membranes open but in the form of course air bubbles. The cleaning in MBR systems is performed by combination of chemical shock and back washing. These do not take into account real time information from sensors, thus it is usually performed more than required.

Problem statement in MBR

Control of both coarse aeration process and fine aeration can save energy.

Control the dosing of chemicals and frequency of cleaning process can reduce cost as well as improve life time of filtration membranes.

So how can knowledge of WSN be integrated to existing infrastructure and bring about advantage in the above described application domain? The answer HBN.

2.2.2 HYDROBIONETs (HBNs)

HBN is a project aimed to address the need for a heterogeneous Wireless Biosensor and Actuator Networks (WBNs) applied to autonomous control of large-scale water desalination and treatment plants. This will be achieved by integration of BioMEM sensors and actuators in network nodes and optimization of WSN protocols to create a reliable and long lasting network. At its core WBNs will help solve the problem statements identified in the previous section [27].

The project aims to increase production, decrease energy consumption, decrease production cost and create improved monitoring and visualization system. Sensors capable of indicating concentration of chemicals such as chlorine and bacterial agents will be developed for both RO and MBR plants. The suitable topology and architecture will be studied and researched for networked control over WSN. Networking protocols will be evaluated and optimized to support this control signals to actuator pumps.

Scientific, Economic and Societal impact include:

- acquire knowledge that can be applied to other application domains
- contribute to improvements, standardization of protocols and hardware
- decrease in energy consumption, cost of production and a corresponding increase in competitiveness

- increase in production outputs with minimal environmental impact through efficient energy and chemical usage

To achieve these benefits the main technical goals of the project emphasizes:

- optimization of standard communication and networking protocols for WBNs
- design of cooperative in-network Processing protocols WBNs
- design of multi-sensing and multi-actuation motes suitable WBNs
- development of tools for real time visualization and management including web based

The work of this thesis mainly lies in the first technical goal specifically to study the reliability of network formation in IEEE 802.15.4 and RPL protocols and possible application to control of distributed nodes.

2.3 Sensors and platforms

Based on working principles sensors can be passive or active. Passive sensors are devices which don't actively query the environment and could be resistive, capacitive or inductive [31]. Active sensors those that can emit measurement signals to probe their environment and as expected possess energy source for the signal they emit. Due to energy constraints it is passive sensors which are more suitable for WSNs applications and widely used.

Based on the physical parameters they measure sensors can be grouped into mechanical, thermal, electrical, magnetic, radiation, chemical and biochemical [31]. The last two categories being specially important for HBNs.

Chemical sensors detect chemical elements and compounds by observing signals generated due to a chemical process taking place on a chemically sensitive material of the sensor. They have a chemical sensitive layer, a transducer which generates a signal based on chemical reaction at sensitive layer and electrical circuitry to process the signal into suitable form. These sensors have a huge industrial application as well as medical and health domains.

Biochemical sensors detect presence of biological agents as well as biochemical complexes in the environment. A difference from the chemical sensors will be the sensitivity layer is biological component such as enzyme or membranes. They have similarly wide application domains including health and public safety as well as military.

Two sensors planned for manufacturing for HBNs are biofilm and chlorine sensors are:

- Biofilm sensors which work by giving a capacitance variation proportional to the amount of bacterial agents deposited to the active electrodes of the sensors. The specification include aluminum electrodes in concentric arrangement at 0.08 mm separation with the working electrode at 0.5 mm^2 and counter electrode 1.4 mm^2 on silicon nitride substrate. The sensor will have a response time of 30 sec with measurement dynamic range of $10 - 10^5$ colony forming bacterial units.

- Chlorine sensors which work by polarizing the working electrode to collect the electrons generated from reduction of hypocrite on. The specification include platinum electrodes in concentric arrangement at 0.08 mm separation with the working electrode at 0.3 mm^2 and counter electrode 1.4 mm^2 on silicon nitride substrate. The sensor will have a response time of 20 sec with measurement dynamic range of 0.1-5 ppm HCLO- concentration.

To make this section complete Table 2.1 lists common commercially available sensor platforms.

Table 2.1: Commercial Sensor Platforms.

Name	Microcontroller	Transceiver	Memory[2]	Programming
BTnode	ATmega 128L	TI Chipcon CC1000	64+180KB, 4KB, 128KB	C, BTnut, TinyOS
EPIC	TI MSP430	TI Chipcon CC2420	10KB, 48KB, 2MB	TinyOS
Iris mote	ATmega 1281	Atmel AT86RF230	8KB, 4KB, 128KB	Mote works, TinyOS
MicaZ	ATmega 128L	TI Chipcon CC1000	4KB, 4KB, 128KB	Mote works, TinyOS
TelosB	TI MSP430	TI CC2420	10KB, 48KB, 1MB	nesC, TinyOS 2.x, ContikiOS
TMote Sky	TI MSP430	TI CC2420	10KB, 48KB, 1MB	nesC, TinyOS 2.x, ContikiOS

Figure 2-3: TelosB sensor node.

Among the above telosB 2-3 and TMote Sky have been used later in experiments. The two platforms are chosen in part for the better memory capacity they provide. As both are for all practical purposes similar, telosB will be referred from now on.

[2]RAM, EEPROM, Flash.

Chapter 3

IEEE 802.15.4 and RPL

This chapter discussed the protocols IEEE 802.15.4 and RPL. It present general description, followed by key characteristics and constraints and closes by pointing how they fit in the HBNs project.

3.1 IEEE 802.15.4

The IEEE 802.15.4 protocol is a well known standard which came in to existence in 2003 and updated in 2006 [33, 34]. It supports star and peer to peer topologies with mesh and cluster tree being special cases of the later.

3.1.1 IEEE 802.15.4 PHY

The physical layer defines two services. The PHY data service is responsible for the actual data transfer through radio transceiver. The PHY management service that interface with physical layer's management entity (PLME).

Functionally the physical layer perform radio transceiver control, energy detection, link quality indication, channel selection, clear channel assessment.

Radio transceiver control involves the activation and deactivation of the devices radio. The frequency bands and data rate of a compliant device is shown in Fig. 3-1 with either -95 dBm or -85 dBm receiver sensitivities.

PHY (MHz)	Frequency band (MHz)	Spreading parameters		Data parameters		
		Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
868/915	868–868.6	300	BPSK	20	20	Binary
	902–928	600	BPSK	40	40	Binary
868/915 (optional)	868–868.6	400	ASK	250	12.5	20-bit PSSS
	902–928	1600	ASK	250	50	5-bit PSSS
868/915 (optional)	868–868.6	400	O-QPSK	100	25	16-ary Orthogonal
	902–928	1000	O-QPSK	250	62.5	16-ary Orthogonal
2450	2400–2483.5	2000	O-QPSK	250	62.5	16-ary Orthogonal

Figure 3-1: PHY frequency bands and data rates.

Energy detection (ED) is estimation of a received signal power within the IEEE 802.15.4 PHY bandwidth. It is reported as 8 bit integer using linear mapping. The value is used for signal validation and/or for the network layer channel selection and routing analysis.

Link quality indication (LQI) measurement is also an 8 bit mapping which characterize the strength or quality of a received packet. It could be ED value and/or signal to noise measurement. The network layer and application are the possible users of this measurement.

Clear channel assessment (CCA) imply checking the state of a shared channel. In IEEE 802.15.4 there are three ways to carry out this task. By comparing received signal power with ED threshold, by comparing received signal's modulation and spreading characteristics with that of IEEE 802.15.4 or combination of the two methods.

Preamble ~4 octets	SHR ~1 octet	PHY header 1 octet	PSDU <=127 octets
SFD		PHR	PHY payload/MAC protocol data unit
PHY protocol data unit			

Figure 3-2: Format of PHY data unit.

Figure 3-2 depict the general PHY frame format. It is composed of synchronization filed (SHR), frame length information (PHR), and the physical service data unit (PSDU) which is the payload for the PHY layer. Its size varies depending on the

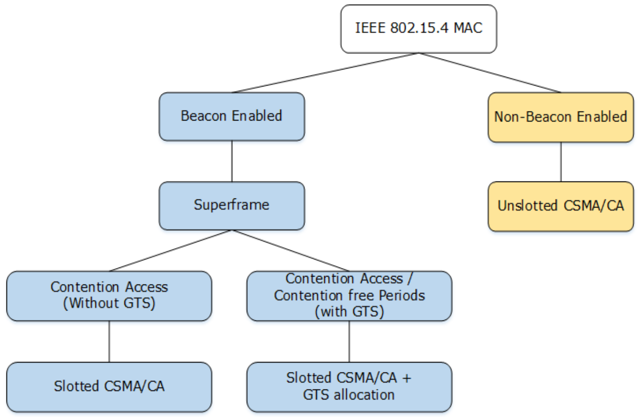


Figure 3-3: Operational modes.

amount of data being transmitted but never bigger than 127 bytes.[1]

3.1.2 IEEE 802.15.4 MAC

The MAC sublayer also provides two services. The MAC data services for actual data transfer access. The MAC management service for accessing mac layer management entity (MLME). IEEE 802.15.4 MAC has two operating modes as shown in Fig. 3-3, with its distinguishing features arising from the use of the Beaconed mode.

Beacon management and superframe format

In a beacon enabled communication network the network coordinator bounds its frames between synchronizing beacons and forcing use of superframe structure.

A superframe is composed of an active and idle portions. Having an idle portion create the potential for a device to go into sleep state and save energy. The parameters that define the duration and structure of a superframe are $macBeaconOrder(BO)$ and $macSuperframeOrder(SO)$.

Generally the active part is composed of three parts the Beacon, the Contention Access Period (CAP) and Contention Free Period (CFP):

- Beacons mandate the use of a superframe structure. They are necessary to synchronize network devices, identify a PAN and describe the superframe structure.

[1]Having 127 byte size limitation necessitate IP adaptation layer 6LoWPAN.

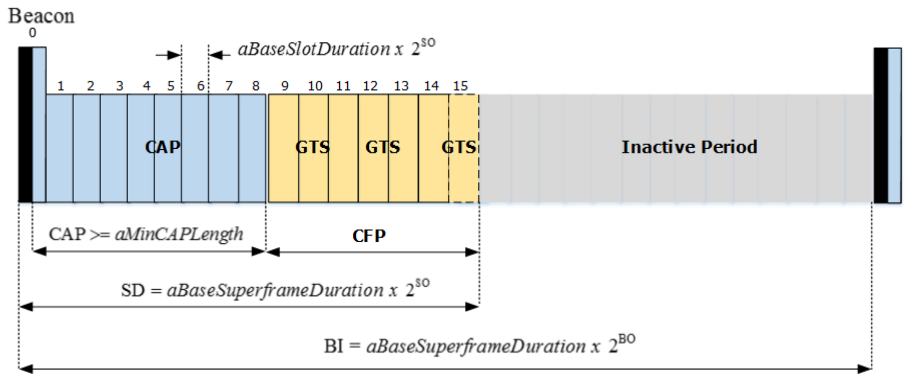


Figure 3-4: IEEE 802.15.4 MAC superframe.

- CAP is the period where contentious access to the channel is possible using a slotted CSMA-CA method. This period has variable size upto a minimum length, $aMinCAPLength$ depending on the beacon and CFP length.

- CFP is the last part of the active period which is composed of contentious allotted slots by the coordinator for network devices which need guaranteed time slots Guaranteed Time Slot (GTS).

Note that GTS management is basically on first come first served basis for nodes and applications that need it but it is hot area of MAC optimization researches due to the reliability and energy saving achieved depending on application.

Channel access and CSMA-CA Algorithm The basic Channel access mechanism in IEEE 802.15.4 is CSMA-CA, Fig 3-5. On top of that the use of a superframe structure adds a time division multiple access feature by assigning guaranteed time slots for devices in CFP.

If a beacon exist and hence superframe structure used, devices which need to transmit data using CSMA-CA start by aligning their backoff period with the start of coordinator beacon frame (slotted). This backoff period is the listen and wait time for channel availability.

NB is the number of times the CSMA-CA algorithm was required to back-off while attempting the current transmission. It is initialized to 0 before every new transmission.

BE is backoff exponent indicating how many backoff periods a device shall wait

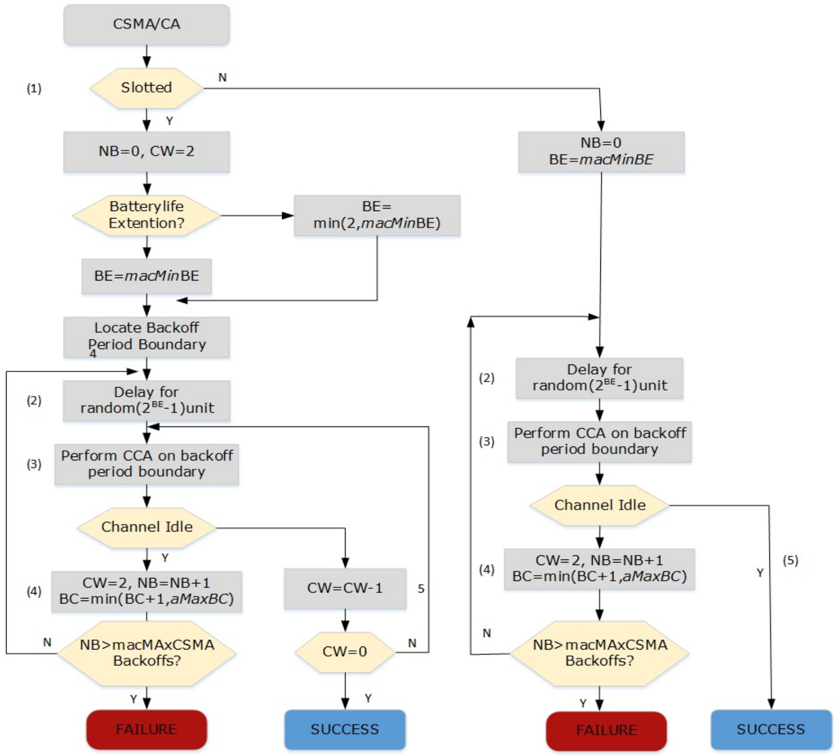


Figure 3-5: CSMA-CA Algorithm.

before attempting to assess the channel. That is when ever a device wants to transmit it enables its receiver and wait a random number of back-off periods between 0 and 2^{BE-1} and only then begins sensing the channel.

CW is contention window length indicating the number of back-off periods that need to be clear of activity before the transmission can start. It is initialized to 2 before each transmission attempt and reset to 2 each time the channel is assessed to be busy.

When ever a channel is busy the process repeats again by incrementing NB until it is less than or equal to $maxBE$, in which case it terminates with a failure.

3.2 RPL

In a network of devices in order to communicate beyond a devices radio sphere there must exist a routing mechanism. RPL is one such layer three protocol which is specifically designed with Low power Lossy Networks (LLN) in mind [32].

The IETF working group ROLL introduced RPL draft in 2010 as an IP routing standard for multihop networking of LLN devices. It followed after header compression mechanisms for IP such as 6LoWPAN opened potential application domains for LLN. And the result was a new proactive distance vector routing protocol which works in a memory, energy and processing power constrained devices and yet support scalability, highly unreliable links, multiple traffic patterns and multiple topologies. Primarily these are possible by the use of range and time limited updates, dynamic metrics and use of Objective Functions (OF) to represent different applications and optimization goals.

3.2.1 Topology formation

The goal of RPL is to form a Destination Oriented Directed Acyclic Graph (DODAG). And the process of graph formation starts with the root node which is an administratively assigned and possibly resource rich device that can act as a gateway.

The root node start by sending occasional DAG Information Object (DIO) message to devices in the vicinity. This message holds among other parameters the DAG Id (DAGID), the sender's rank indicative of its place in the DAG, objective code point (OCP) which indicate the metric for rank calculation and RPL instance ID. RPL instance ID is a way for RPL to differentiate different logical DAG topologies built on top of common physical network/nodes.

Nodes receiving DIO messages from potential parents including the root node will check their configured OCF and will join the DODAG if it matches by choosing a parent with the least cost to the DODAG root, evaluate their corresponding rank based on the metrics used and broadcast their own DIO. The process continues in a hierarchical manner with increase in rank downwards from the root node until leaf nodes are reached.

In the process of topology formation an RPL node in a DODAG is additionally expected to keep track of candidate neighbor set and parent set. A candidate neighbor set is a table of neighbors with lower or equal rank which a node has received DIO message from. And those with lower rank than itself will come to constitute the parent

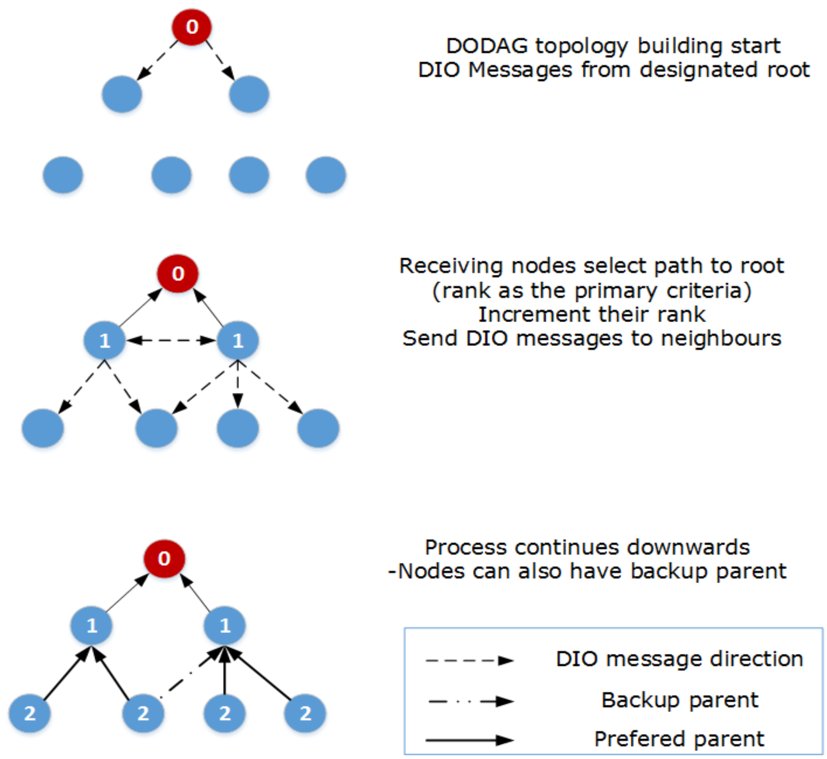


Figure 3-6: DODAG formation.

set out of which the one with best rank will be chosen as the preferred parent. In order to maintain the different tables uptodate and consistent besides waiting for DIO message a node can explicitly request them through the use of use DAG Information Solicitation (DIS).

Once a topology is created situations such as node disappearance, link metrics change or other general inconsistencies may mandate reconfiguration and reformation of a DODAG necessary. In such situations topology formation for the whole DODAG will be initiated again by the root node and will be tracked by DODAG version number in the DIO messages.

The topology created in the above manner is able to support the basic traffic pattern multipoint to point (data collection). RPL also support two additional traffic types. A downward point to multipoint and point to point traffic between devices. RPL support these traffics by use of Destination Advertisement Objects (DAO) which forward route information upwards to parent about nodes that can be reached through the DAO sending node. Depending on the mode of operation chosen, DAO's could propagate until the root node is reached which maps out paths to specific nodes (non-storing mode) or DAO's will be aggregated by storing capable nodes and only prefixes advertised upwards (storing mode).

3.2.2 Loop Detection and correction

RPL implement an on demand loop detection. It implies RPL tries to identify and correct loops and inconsistencies during data transmission and topology changes rather than continuously tracking links and nodes. The main idea behind this design choice is from the assumption LLN nodes are usually susceptible to transient physical link connectivity loss hence unnecessary and waste of resource to perform loop check until there is actual data to transmit.

The main mechanism used in RPL for loop detection is data path validation. It makes use of rank of a node, version number of DODAG and data traffic direction. For instance if a data is supposed to be traveling in the upward direction (decreasing rank) but a node with rank higher than the sender node rank receives the data then it indicate a possible inconsistency calling for a local DODAG (subDODAG) repair.

3.2.3 The trickle algorithm

The trickle algorithms is responsible to determining the frequency of DIO transmissions which are necessary for building and maintaining consistent state about the network. Essentially a node will only send out local multicast DIO messages when ever a DIO message it receives indicate inconsistency or when ever its trickle period expires. Trickle period grows incrementally from a set minimum value to maximum as long as the network is considered stable [9].[2]

The advantage of such an algorithm lies in the combination of the two features. First sending out local broadcast will enable local repair of inconsistencies with out resulting broadcast storms to the bigger network. Further a node acts as a silent listener until its next trickle period as long as the broadcast updates it receive are

[2] In the current TinyRPL implementation from 0.25s - 128s.

consistent with its current information. Secondly the use of an exponentially increasing update period imply less network maintenance packets as long as stability exist. The more converged the network the less need to communicate. Therefor in both cases precious shared bandwidth scarce energy are conserved.

3.3 Implementation and integration for HBNs

As HBNs sets out to produce both new technical understanding and practical implementation from a new application domain of WSN, a number of issues arise as laid out in [26]. Those requirements pertaining to networking, topology and communication are presented below

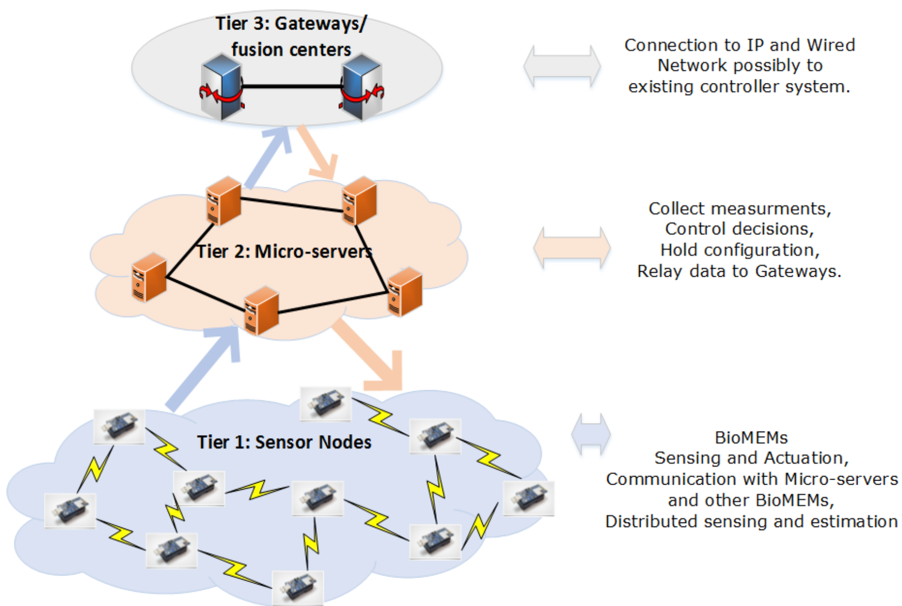


Figure 3-7: Three tier HBN network topology.

Essentially the project propose three level of node devices. The first tire composed of BioMEMs. These are off the shelf standard sensor node platforms such as telosB with suitable sensor and actuators attached to them. Their task will be to perform sensing and communicate with each other and tier 2 nodes to perform (possibly distributed) estimations, consensus and control decisions. The second tire of devices are micro-servers with better resources that could function potentially as critical decision points based on the data they receive for tier 1 nodes. They could hold configuration parameters such as threshold values of chemicals, and biological agents for control decisions they would make. They also can also simply function as the relay points to the optional tier 3 gateways. Tier 3 nodes/gateways are the either the end point where central decision can be made or they are the doors to TCP/IP network which connect to the external controller/application system.

The use of a three tier architecture in the above respect only imply the capability of the node devices. In terms of packet transfer it makes open both flat and hierarchical network depending on the design choice. The advantage with IEEE 802.15.4 and RPL is they support both architectures. Further IEEE 802.15.4 also provides the ability to be extended by a link scheduling algorithm to increase the reliability of transmission in a flat network WSN, which induces greater interference.

The requirement proposal [26] also identify four possible traffic types in HBNs depending the applications that could exist at same instant in time. One type is data collection and actuation from nodes to getaways and back. Second type is hierarchical data collection and actuation where micro-servers lie in between to perform control and aggregation tasks. A third type is distributed sensing and actuation directly between nodes microservers only acting as relays. And finally network and application management between all tires to set protocol and application parameters. For all these possible traffic types again combination of IEEE 802.15.4 and RPL can construct bi-directional network that support two way traffic and further more RPL can construct multiple DODAGs capable of optimizing for the application type suited for HBNs including the different communication demands between the three proposed tiers.

Chapter 4

Network Controlled Systems (NCSs) for water treatment plants

The goal of this chapter is to present NCS, highlight the characteristics in relation to wireless network and finally describe PID design procedure for this thesis work.

NCS is one in which sensors, controllers and actuators exist in a spatially distributed manner. Sensor to controller, controller to actuator loops are reliant on real time communication network which could be either wired or wireless with the later being the focus of this thesis.

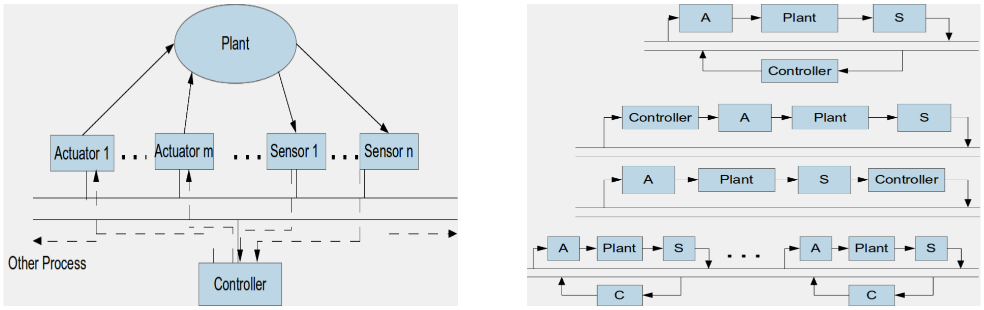
A mathematical characterization for a general linear system in networked control can be given as:

$$\begin{aligned} x(kh+h) &= \Phi x(kh) + \Gamma u(kh) \\ y(kh) &= Cx(kh) + Du(kh) \end{aligned} \tag{4.1}$$

whose controller goal is to bring the solution state to the desired $x^*(k)$

$$x(k) = \Phi^k x(0) + \sum_{j=0}^{k-1} \Phi^{k-j-1} \Gamma u(j) \tag{4.2}$$

Some advantages of WSNs for NCSs include reduced system wiring, ease of system maintenance, increased system robustness, greater scalability and possible integration



(a) Basic NCS. (b) Variation in location.

Figure 4-1: Network Controlled Systems.

of mobile agents

4.1 Characteristics and Constraints of NCS

Among the characteristics of NCSs which are mandatory to take into account include:

Network induced delay: Delays are inherent properties of a networked system. Delay in signal path between sensor and controller, between controller and actuators and also overhead delay in controller calculations. The later depend on factors like system scheduling, controller type and implementation.

IEEE 802.15.4 based NCS at the core exhibit time varying delays which controller designs must account for. It's necessary to minimize these delays much as possible to satisfy conventional controller designs assumptions or as make them predictable and within acceptable margin to incorporate them in the design of controllers.

Jitter: Form network perspective jitter describes the variable nature of delays as mentioned above. But from sampling and synchronization perspective it's superficial unintended variation in the duration in any specified related intervals. It arise from a number of factors that result temporal mismatch in alignment of intervals and synchronization. For the later type of buffers or special hardware structures should be used in order to avoid false sampling, false time outs etc.

Sampling interval: Choice of the sampling interval should be balanced with regards to network capacity. In general the smaller the sampling interval the better for most control applications, but in regards to NCSs which are based on WSNs low data rate is the norm to prolong the life time of participating nodes. It is the case also in protocol such as IEEE 802.15.4, an increase in sample rate beyond some threshold can result in deterioration of the system performance due to the increased network media contention.

Packet Drop: There also exists the case where packets don't reach the intended receivers at all due to node failures and buffers. From real time NCSs perspective in situations where new and old versions of data packet exist it would be could be appropriate to discard older packets.

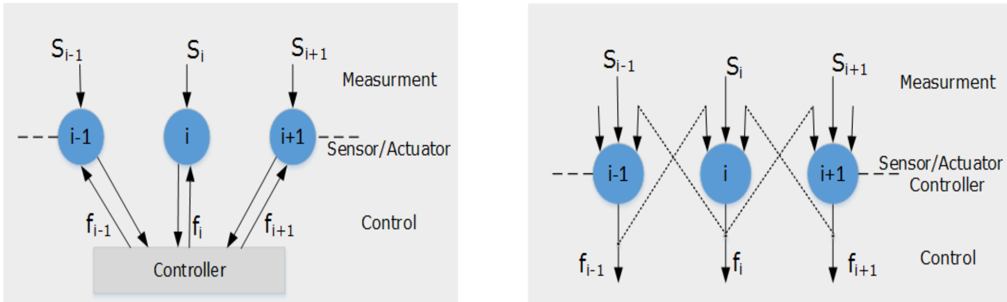
Energy efficiency: A primary factor driving most if not all limitations of control over wireless sensor networks. Controllers which require high reliability with low delay would strain energy usage on nodes through higher data rate and retransmissions. Though distributed control with efficient algorithms help reducing communication costs over longer hops they still entail an increase the in-network processing of data.

Robustness: Control algorithms must be adaptive to the dynamic nature of WSNs topology. Mobile nodes being the extreme example as association to one specific location is a matter of temporal occurrence hence the need for dynamic control hierarchy.

Scalability: One of the great advantages of WSNs is the potential for cost effective large scale implementation as well as growth through the addition of new nodes. This puts a great demand on a control design that is able to handles growth of a network without performance degradation while keeping the burden on nodes to minimum. The scalablity and in general performance of NCS depend on the controller architecture.

In a centralized control data is forwarded to a central node which is able perform large scale data processing and send appropriate signals to respective actuator [36]. Advantages are:

- globally optimal control with faster convergence
- established theoretical understanding to implement and evaluate centralized controllers



(a) Centralized (b) Distributed

Figure 4-2: Centralized verses Decentralized Control [36].

Disadvantages are:

- increased delay due to longer the multihop distance paths
- increased scheduling and processing time on the control side, hence larger sampling interval in the control loop

In decentralized control the controllers are implemented on some or all of network nodes. The knowledge and decision of each node will be on local parameter values. Multiple controllers are involved to collect sensory information, schedule tasks, make control decisions and coordinate actuators [36]

Advantages are:

- make use of the increasing processing powers of sensor nodes
- improve the network life time by reducing the frequency of communication beyond certain range
- reduce delay while reliability is increased in shorter communications paths

Disadvantages are:

- local optima rather than global optima is guaranteed
- convergence to stable state take longer time or iterations

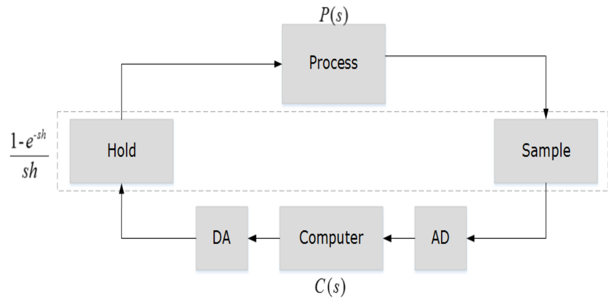


Figure 4-3: Continuous time design of Discrete controller.

4.2 Control strategy using PID

PIDs are by far the most used controllers in the industrial world including water treatment plants. Therefore the controller designed for the thesis is PI controller.

$$u(kh) = P(kh) + I(kh) + D(kh) \tag{4.3}$$

where

$$P(kh) = K\Big(bu_c(kh) - y(kh)\Big)$$
$$I(kh+h) = I(kh) + \frac{Kh}{T_i}\Big(u_c(kh) - y(kh)\Big)$$

Equation (4.3) gives the discrete practical version of PI controller [37]. In this form the gain of the derivative part is limited, only a fraction of the command signal act on the proportional part and no control signal at all on the derivative part.

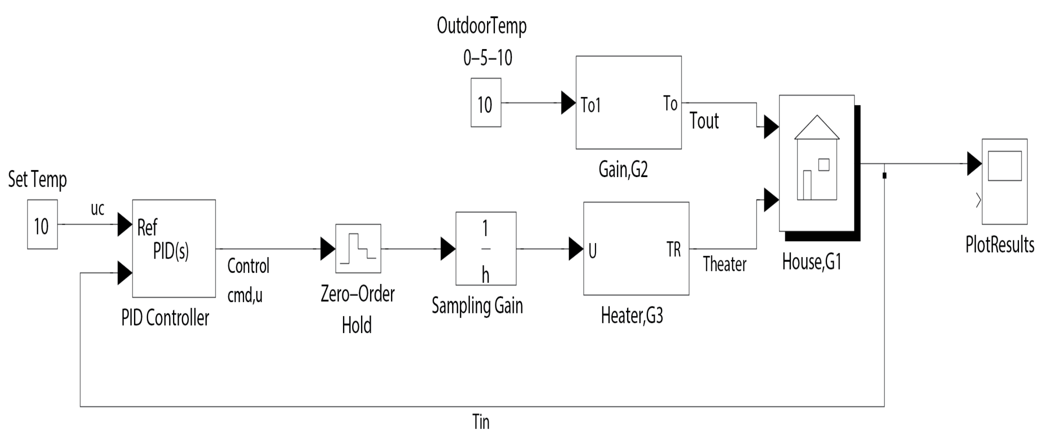


Figure 4-4: Simulation Model of the feedback controlled system.

Designing feedback controller for wireless sensor nodes implies designing a discrete controller for a sampled system. In order to arrive on a discreet PID, we follow the methodology where a continuous controller is designed for the continuous process transfer function and then apply standard discretization techniques Fig. 4-3. The addition of zero order hold and sampling blocks introduce the transfer function ${}^{(1-e^{-sh})}/_{sh}$ to account the large sampling time used in the process model described in next section. Figure 4-4 show the whole system in matlab simulink with the PID block and feedback loop included. The coefficients of k_p and k_i in (4.3) are obtained by simulating and tuning the simulink model constrained to desired performance factors rise time and settling time.

4.2.1 Process selection and State space formulation

The process model which was chosen for evaluation is a house heating system presented below. In this regard the temperature of control of a house is desired and was chosen for a number of reasons. Firstly the idea of controlling the heat output of a heater through its temperature have some correlation to controlling the chemical output of a valve through the valves opening as used in water treatment plants. Secondly heater and house dynamics will be simulated within the sensing nodes hence the desire for a light process model to minimize the processing required on sensor nodes.

In the dynamics of the heat model the contributions for rate change of the room temperature will be from two sources. One source is the temperature difference between the outside temperature and the room temperature. The second is the temperature difference between the heater and the room temperature. The heater being the actuator the control signal coming to it will regulate its temperature by affecting its rate of change. The room, wall, and heater dynamics are represented by the $\alpha_1, \alpha_2, \alpha_3$ coefficients respectively.

$$\begin{aligned} \dot{T}_I &= \alpha_1(T_R - T_I) + \alpha_2(T_O - T_I) \\ \dot{T}_R &= \alpha_3(u - T_R) \end{aligned} \tag{4.4}$$

T_I = room temperature, T_R = radiator temperature

T_0 = outside temperature, u = control signal

$$\dot{x}(t) = \begin{bmatrix} -(\alpha_1 + \alpha_2) & \alpha_1 \\ 0 & \alpha_3 \end{bmatrix} x(t) + \begin{bmatrix} 0 & \alpha_2 \\ \alpha_3 & 0 \end{bmatrix} U(t)$$
$$y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} x(t) \tag{4.5}$$

To model the system in a standard state space representation we identify two inputs and a single output. The first input to the system is our controller signal $u_1(t) = u(t)$ and the second is the outside temperature $u_2(t) = T_O(t)$. We will also identify two states variables $x_1(t) = T_I(t)$ and $x_2(t) = T_H(t)$ given in (4.5). This modeling is to follow formality but in the actual experiment the outside temperature is considered a disturbance and left to a zero value.

$$\dot{x}(t) = \begin{bmatrix} -.11 & .1 \\ 0 & -50 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ -50 \end{bmatrix} U(t)$$
$$y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} x(t) \tag{4.6}$$

$$\dot{x}(t) = \begin{bmatrix} -20 & 1 \\ 0 & .1 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} U(t)$$
$$y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} x(t) \tag{4.7}$$

Two candidate process models are given in (4.6) and (4.7). The first is a stable room temperature model while the second is a model chosen for having unstable open loop transfer function.

4.2.2 Theoretical stability analysis

In this section the stability (limits of) PI controller for the two process will be analyzed with respect to network delay and packet drop.

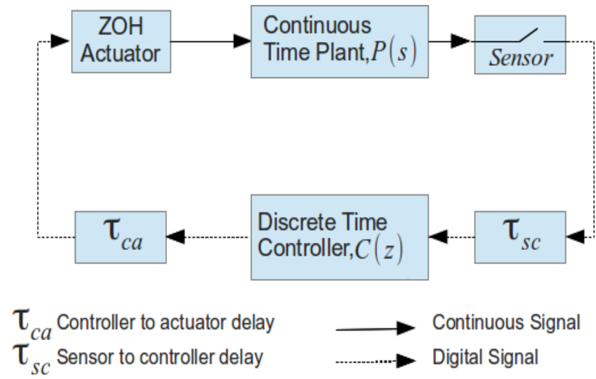


Figure 4-5: NCS model with network induced-delay.

Theorem 1: Stability region with regards to delay and sampling time A general networked control system is shown in Fig. 4-5, with a continuous plant $P(s)$ and a discrete controller $C(z)$ are given in as follows. In [8], if the controller is time-invariant it is argued also the network and controller computational delays can be lumped together in as a total delay term τ.

$$
\begin{aligned}
\dot{x(t)} &= Ax(t) + Bu(t) \\
y(t) &= Cx(t)
\end{aligned}
\tag{4.8}
$$

where

$$u(kh) = -Kx(kh) \quad k = 0, 1, 2, ...$$

$$
\begin{aligned}
x((k+1)h) &= \Phi x(kh) + \Gamma_0(\tau_k)u(kh) + \Gamma_1(\tau_k)u((k-1)h) \\
y(kh) &= Cx(kh)
\end{aligned}
\tag{4.9}
$$

where

$$\Phi = e^{Ah}, \quad \Gamma_0(\tau_k) = \int_0^{h-t} e^{As}Bds, \quad \Gamma_1(\tau_k) = \int_{h-t}^{h} e^{As}Bds$$

Furthermore with the assumption delay less than one sampling time, clock driven sensors and event driven controller-actuator the sampling of the system in (4.8) will result in (4.9). Hence by applying the control input and deriving augmented closed-loop system transition matrix we can check stability of the system for varying τ.

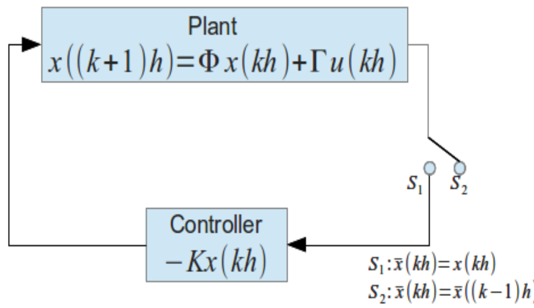


Figure 4-6: NCS model with packet drop.

Theorem 2: Delay jitters and stability For a mixed discrete and continuous system, another way to analyze the maximum tolerable delay variation for stability is given in [29]. For the closed-loop system in Fig. 4-5, with continuous, strictly proper and stable process $P(s)$, and discrete controller $C(z)$ sampled with period h, the system is stable for any time-varying delays

$$0 \leq \delta(t) \leq Nh \quad \text{where} N \in \mathbb{R} \tag{4.10}$$

if the inequality

$$\left| \frac{P_{alias}(w)C(e^{jw})}{1 + P_{zoh}C(e^{jw}} \right| < \frac{1}{\tilde{N}|e^{jw}-1|} \quad \forall w \in [0, \infty) \tag{4.11}$$

$$P_{alias} = \sqrt{\sum_{K=-\infty}^{\infty} \left| P\big(j(w+2\pi k)\frac{1}{h}\big) \right|^2}$$

where P_{zoh} *is ZOH of* $P(s)$, and $\tilde{N} = \sqrt{\lfloor N \rfloor^2 + 2\lfloor N \rfloor g + g}, g = N - \lfloor N \rfloor$ is satisfied.

The infinite summation of Theorem 2 will be numerically approximated and is expected to converge as P is a stable system. Additionally $\hat{N}$ will be the least that can satisfy the inequality among all frequencies.

Theorem 3: Packet loss and stability Given the networked control system shown in Fig. 4-6 where the loss of measurement data is modeled by an opening of the switch, if the closed-loop system with no packet drop is stable then we have two conditions for stability with packet loss [8].

- If the open loop is marginally stable then the system is exponentially stable for all $0 < r \leq 1$.

- If the open loop is unstable then the system is exponentially stable for all

$$\frac{1}{1 - \gamma_1/\gamma_2} < r \leq 1 \tag{4.12}$$

where $\gamma_1 = log[\lambda^2_{max\ closedloop}]$ $\gamma_2 = log[\lambda^2_{max\ openloop}]$ r=packet reception ratio.

Now the goal is to reformulate augmented state-space matrix in order to apply the aforementioned theorems which are based on state feedback control and in doing so we can equivalently assign the PI-controller gains chosen from simulation as the state feedback gains. Continuous time case derivation is available at [28] here the discrete version is formulated. First we introduce a new state $\xi(kh)$ where

$$\begin{aligned} \xi(t) &= \int \big(r(t) - y(t)\big)dt \\ \xi\big((k+1)h\big) &= \xi(Kh) + \big[r(kh) - y(kh)\big] \end{aligned} \tag{4.13}$$

hence our PI-control signal will be

$$u(kh) = K_p\big(r(kh) - y(kh)\big) + K_i\big(\xi(kh)\big) \tag{4.14}$$

The resulting augmented states will enable us to avoid the reference input in the state transition matrix which otherwise require the assumption of starting from steady state.

Combining the discrete version in (4.13), (4.14) and the sampled system with delay in (4.9) and rearranging terms we obtain a closed loop augmented state-space

$$\begin{bmatrix} x\big((k+1)h\big) \\ u(kh) \\ \xi\big((k+1)h\big) \end{bmatrix} = \begin{bmatrix} \Phi - \Gamma_0(K_pC) & \Gamma_1 & \Gamma_0 K_i \\ -(K_pC) & 0 & K_i \\ -C & 0 & 1 \end{bmatrix} \begin{bmatrix} x(kh) \\ u\big((k-1)h\big) \\ \xi(kh) \end{bmatrix} + \begin{bmatrix} \Gamma_0 K_p \\ K_p \\ 1 \end{bmatrix} r(kh) \tag{4.15}$$

Then it suffice to check the magnitudes of the eigenvalues of the closed-loop system to be within the unit circle to characterize the stability of the whole control system. By varying the delay and sampling time parameters we will draw the stability region.

The second task of characterizing the maximum delay variation is done by doing direct numerical calculation using directly as in (4.10) using the transfer functions of the controller and the process.

Lastly in order to characterize the acceptable reception probability of sensor data based on (4.12) we will first find the open-loop and closed-loop state transition matrices of the system. As only packet drop and no delay is assumed, by removing the delayed control state our closed-loop model (4.15) reduces to

$$\begin{bmatrix} x\big((k+1)h\big) \\ \xi\big((k+1)h\big) \end{bmatrix} = \begin{bmatrix} \Phi - \Gamma_0(K_p C) & \Gamma_0 K_i \\ -C & 1 \end{bmatrix} \begin{bmatrix} x(kh) \\ \xi(kh) \end{bmatrix} + \begin{bmatrix} \Gamma_0 K_p \\ 1 \end{bmatrix} r(kh) \tag{4.16}$$

with further manipulation it can be shown a possible open-loop model can be given as

$$\begin{bmatrix} x\big((k+1)h\big) \\ \xi\big((k+1)h\big) \end{bmatrix} = \begin{bmatrix} \Phi & 0 \\ 0 & 1 - {}^{K_i}/_{K_p} \end{bmatrix} \begin{bmatrix} x(kh) \\ \xi(kh) \end{bmatrix} + \begin{bmatrix} \Gamma_0 \\ {}^{1}/_{K_p} \end{bmatrix} u(kh) \tag{4.17}$$

Chapter 5

Experiments and Results

The organization of this chapter is as follows. The first section describes the software environment and coding implementation necessary for the experiments. Then both simulation and experimental set-ups explained. And lastly the actual experimental runs and results are presented.

5.1 Software environment and Code integration

TinyOS, nesC, python and matlab are the softwares used for implementation and experiment purposes. TinyOS 2.x is the OS of choice. It has the protocols needed including IEEE 802.15.4[1], TinyRPL[2] and BLIP. On top of this sensing and simulation application and parameter monitoring interfaces are implemented using nesC.

Python is used to do the PC side implementations. The choice is mainly based on the ease of scripting and an existing support enabling python to receive TinyOS messaging structures. Specifically using python script sensor readings are received, the discreet PI controller calculations are performed and control signal sent back to the nodes. Additionally network parameter log is also received and parsed using python.

Matlab is used to design and simulate the controller using simulink models as

[1] CC2420 MAC implementation is used for experiments which is IEEE 802.15.4 compliant

[2] A 2010 Johns Hopkins University implementation used for experiments.

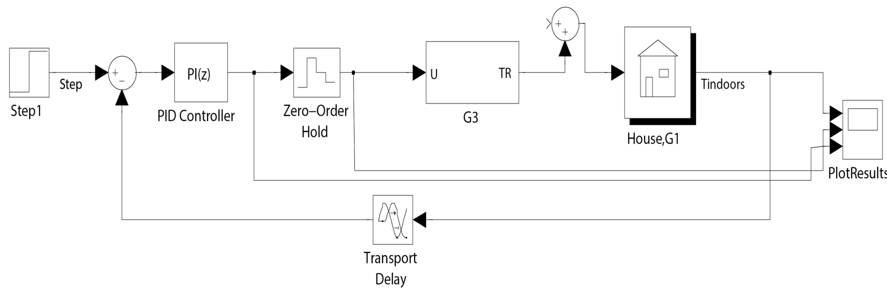


Figure 5-1: Simulink Delay simulation set-up.

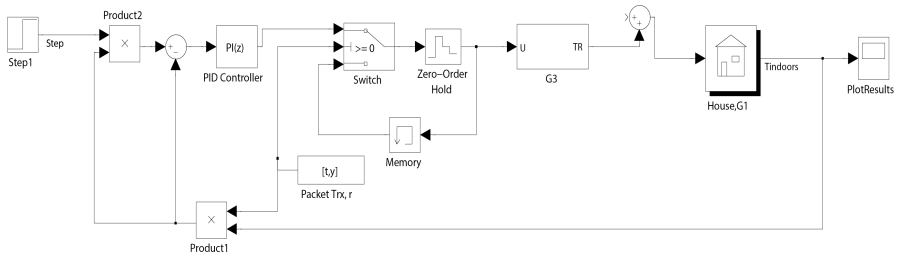


Figure 5-2: Simulink Packet drop simulation set-up.

shown in Fig. 5-1 and 5-2. Matlab scripts are used to visualize the results of the experiments.

5.2 System setup

The simulinks in Fig. 5-1 and 5-2 depict the blocks used in theoretical analysis of controller stability in presence of network delay and packet drop respectively. The feedback path represent the wireless network path, the house the thermal process and the $G3$ block the actuator.

The real world experiments are done using a network of 6 telosB sensor nodes deployed in a home environment in a topology shown in Fig. 5-3.[3] One node acts as the bridge and root to the controller PC (Ubuntu) while others perform sensing and actuation. The topology is guaranteed by topology control[4] as setting the transceiver power to 3 dB relatively translate to 7 m.

[3]Initial topology based on measurement of Received Signal Strength Indication (RSSI) of the environment.

[4]Topology control imply restricting nodes5, 6, 7 from having the root node as their parent

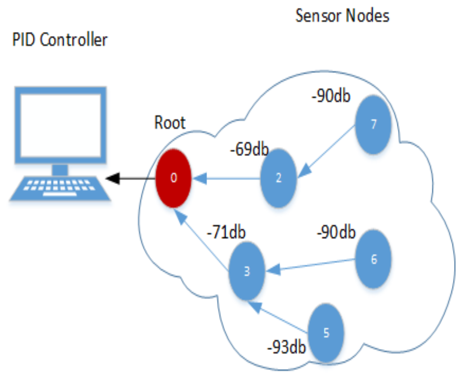


Figure 5-3: Depiction of system setup.

5.3 Results

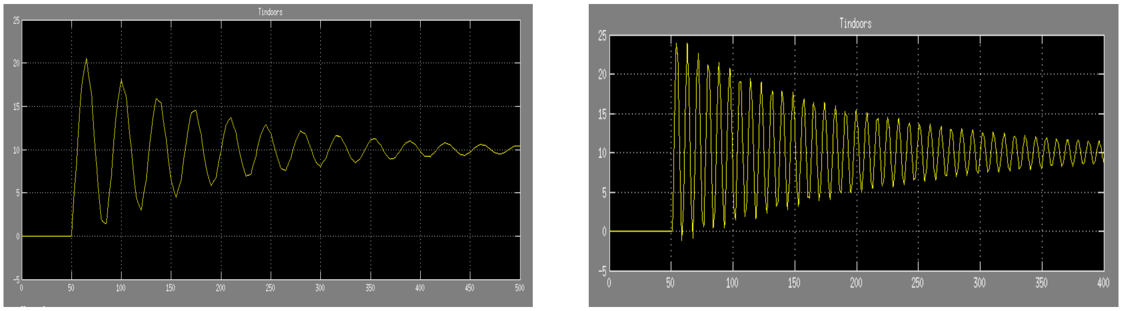
Table 5.1: Process parameters and performances.

	Process I	Process II
$t_{sampling}, s$	5	1.5
$t_{settling}, s$	25	117
overshoot,%	4.82	23
K_p	2.156	15.759
K_i	0.212	0.250

Quantitatively ideal performance of the two control systems from the design of PI controller are given in Table 5.1. These values are $t_{settling}$ 25s (5th sample) and 117s (78 sample), *overshoot* 4.8% and 23% for process I and II respectively. Note that unless specified all values stated are average values for all the sensor nodes while the settling time take account the time measured signal is within 2% of final value.

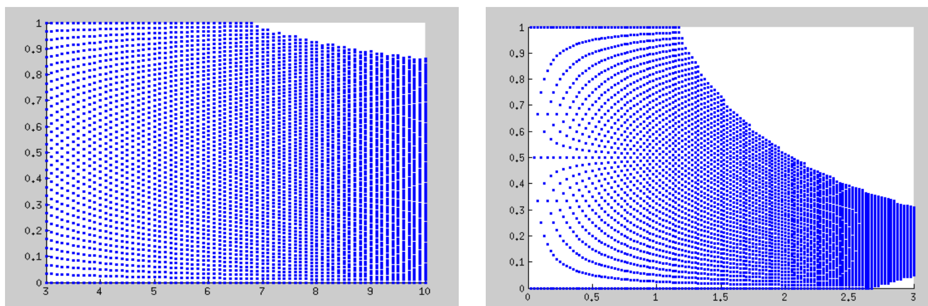
Theoretical results

Following Theorem 1 (4.9) and substitution of actual sampling times, it can be shown the eigenvalue values of the state transition matrix (4.15). The first process always remain within the unit circle for delay upto sampling time, hence always exponentially stable, while the second process enters instability at $\tau = 1.125s$ with eigenvalues $[0.0087 \;\; 1.0087 \;\; 0.0000 \;\; 0.9816]'$.



(a) Process I $\tau = 6s$. (b) Process II $\tau = 1.08s$.

Figure 5-4: Step response with τ_{max} from simulation, step at $t = 50s$.



(a) Process I (b) Process II

Figure 5-5: Stability region for τ/h vs h.

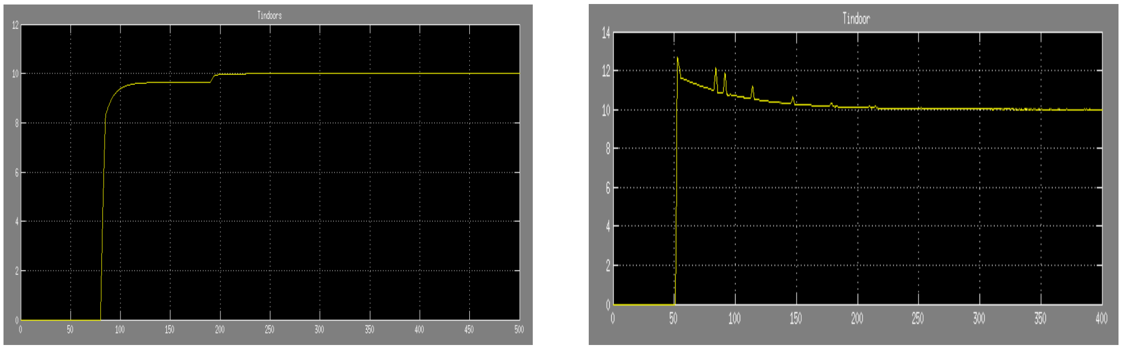
Plots shown in Fig. 5-4 for the simulink delay Fig. 5-1 setup support the above numerical results. The general stability region for the two processes with varying sampling time h and delay τ_k are also shown in Fig. 5-5.

Table 5.2: Maximum theoretical delay.

	Process I	Process II
$\hat{N}$	0.7576	0.4071
N	0.5740	.1658
τ_{max}	2.8698	0.2487

Based on Theorem 2 (4.10) and direct numerical approach, the maximum variable delay is found and the results are presented in Table 5.2.

Lastly based on Theorem 3 (4.12), the minimum packet delivery probability is calculated. The first process is stable for all $0 < r \leq 1$ as its open-loop model in (4.17) is stable with eigenvalues $[0.9311 \quad -0.1663 \quad -0.0145]$. The calculation for the



(a) Process I at $r = 0.1$. (b) Process II at $r = 0.9$.

Figure 5-6: Step response with Packet drop, step at $t = 50s$ with packet drop.

second process is results in $\gamma_1 = -0.0162, \gamma_2 = 0.1303$ and $0.89 < r \leq 1$.

The simulink systems with packet drop probability at these limits are plotted on Fig. 5-6.

Experimental results

Even though based on the same experimental setup outline in the previous section, the scenarios and results below can be grouped in two. In the first group, scenarios I, II and III, network formation and maintenance is observed. Nodes are made to boot up sequentially and form the wireless network while parameters indicating the process and the state of the nodes are logged. In the second group, scenarios IV, V and VI, control loop is included. The sensors send simulated temperature values while the central PC send back the control signal whose value will be affected by the network delay and packet drop associated with the wireless network. Following the theoretical discussion the performance of the system is again measured with the system settling time and controller overshoot.

Scenario I: Parent eviction threshold=2, no topology control, run time=30 min.

Scenario II: Parent eviction threshold=3, no topology control, run time=30 min.

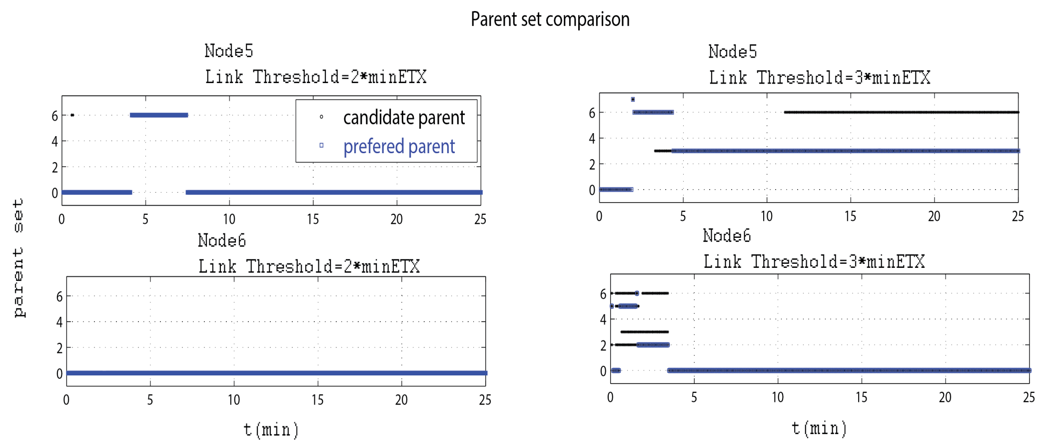


Figure 5-7: Parent set Node5 and Node6, left threshold = 2, right threshold = 3.

The aim of scenarios I and II is to see the effect of Parent eviction threshold value on a nodes parent table. This parameter is important as it is used for calculating Expected Transmission count (ETX) value of a node, which is the expected transmissions required to deliver a message from a sensor node to the root node. ETX_ HOP will be used to determined if a node can be considered as a candidate parent for a node in question. From the plots in Fig. 5-7 increasing the threshold enables deeper nodes to have more candidate parents thus robust to network for failures.

Scenario III: Network nodes failure, parent eviction=3, with topology control, run time 65 min.

The goal of this experiment is to observe the network stability during node failures. To achieve this node2 will be off at $t = 10min$ and on at $t = 20min$, similarly node3 will be off at $t = 30min$ and on at $t = 40min$. The resulting state of the leaf nodes is depicted in Fig. 5-8. We can observe three points from the results.

Firstly in terms of network connectivity having a backup clearly improve a nodes connectivity to the network as is the case for node7 at the instant node2 fails ($t =$

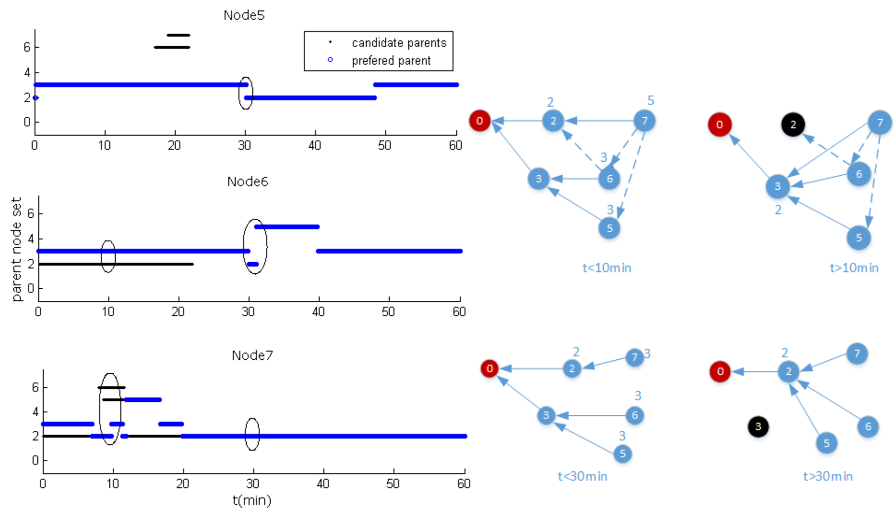


Figure 5-8: Parent set for nodes

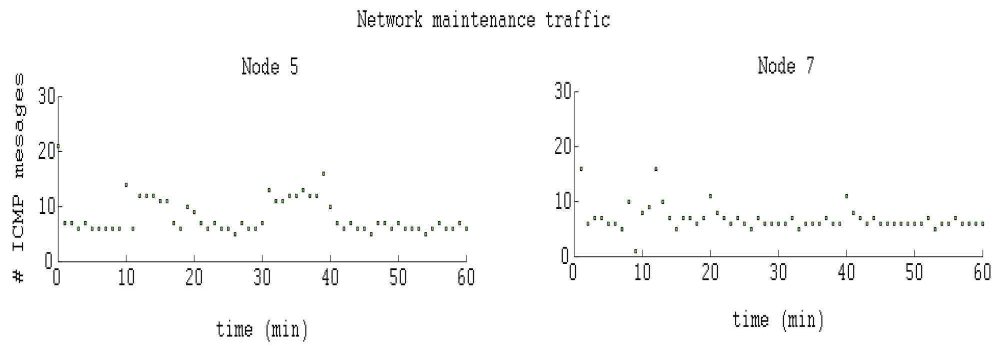


Figure 5-9: RPL ICMP messages count.

$20min$). Conversely due to the nature of RPL design a node doesn't need to actively monitor a link status unless required as is clearly shown by node6 keeping its candidate parent node2 even if it has failed. The direct implications are less energy and rejection of irrelevant/intermittent network changes from a node's perspective.

Secondly the process of maintaining the network is achieved by RPL Internet Control Message Protocol (ICMP) messages which is according to the exponentially decaying trickle algorithm as confirmed by Fig. 5-9. For the points in time nodes fail, there exist a spike in ICMP messages which in time decrease in frequency as network stabilize. The implications are rapid response for network building but with minimal network bandwidth and energy utilization during network maintenance.

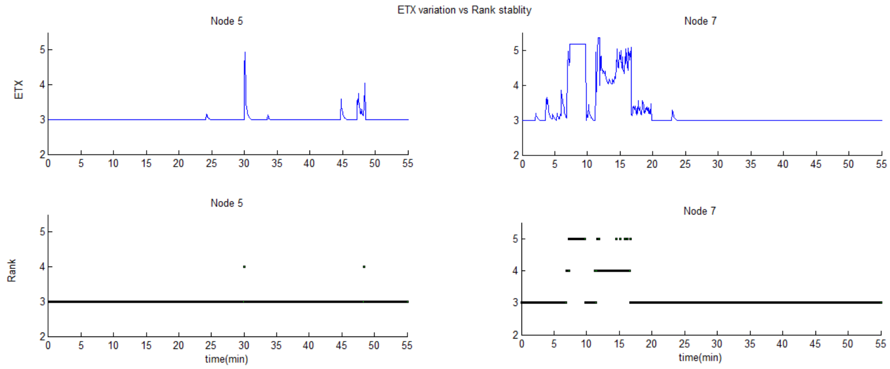


Figure 5-10: ETX vs. Rank.

Thirdly and lastly Fig. 5-10 highlight the resistance of a RPL node for wireless link ETX variation through a stable rank value. This of course confirms the advantage of using the selected routing metric Minimum Rank Objective Function with Hysteresis (MRHOF).

Table 5.3: Network layer performance indicators.

(a) ScenarioI

	Node2	Node3	Node5	Node6	Node7
PRR%	-	-	-	-	-
avg.delay	-	-	-	-	-
avg.DIO/min	0.8667	0.5333	0.8000	0.5333	-
avg.DIS/min	0	0	0.0333	0	-
avg.DAO/min	8.4000	5.9000	5.5333	6.5000	-

(b) ScenarioII

	Node2	Node3	Node5	Node6	Node7
PRR%	-	-	-	-	-
avg.delay	-	-	-	-	-
avg.DIO/min	0.8667	0.5333	1.0333	1.0667	0.5333
avg.DIS/min	0	0	0.0333	0	0.0333
avg.DAO/min	6.3667	11.4333	6.4667	6.2000	6.2000

(c) ScenarioIII

	Node2	Node3	Node5	Node6	Node7
PRR%	-	-	-	-	-
avg.delay	-	-	-	-	-
avg.DIO/min	0.4923	N/A	0.8615	0.7692	1.0923
avg.DIS/min	0.0154	N/A	0	0	0.0154
avg.DAO/min	14.2000	N/A	7.1692	5.8154	5.6923

Table 5.3 summarize quantitatively the network performance for scenarios I,II and III. The empty spaces indicate not applicable values as the control loop is not yet integrated. For scenario I node7 fails due to battery failure while for scenario III node3 data is not applicable as it is simulating node failure.

Scenario IV: Control with no delay and packet drop out. Time run 15 min, parent eviction threshold=3, $uc = 20$.

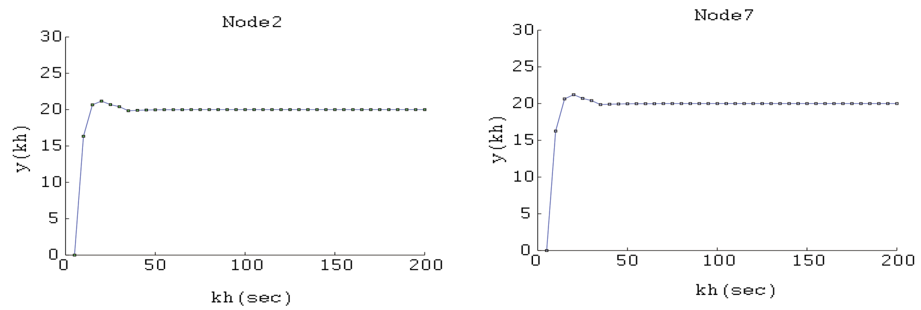


Figure 5-11: Sensor readings from Node2 and Node7 for process I with p=0,d=0.

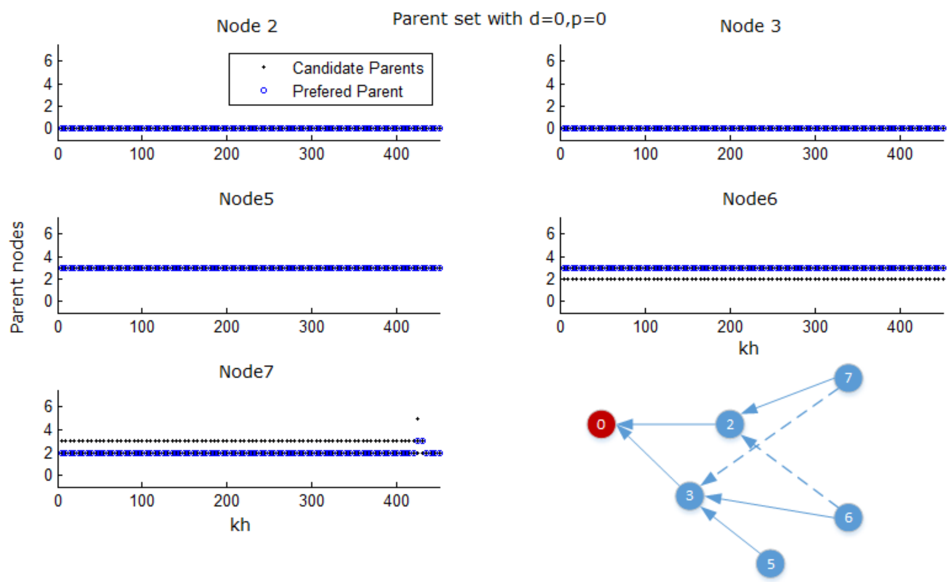


Figure 5-12: Parent set for nodes.

As Fig 5-11 shows NCS performs almost equal to the theoretical prediction. The control system per performance indicators obtained from experiment are; for process I $t_{settling}$ is at 30s (6th sample) with 5.85% overshoot, for process II $t_{settling}$ is at 122s (81th sample) with 34.24% overshoot. These and Fig. 5-11 indicate well acceptable results especially in view of the slow dynamic house temperature system. The deviation from the theoretical is attributed to the minor delay present in the actual control loops 0.1243s and 0.1471s respectively. The effect of delay is more visible on the overshoot and more pronounced on the second process with faster sampling time.

Scenario V: Control with delay, no packet drop out. Time run 10 min, parent eviction threshold=3, $uc = 20$.

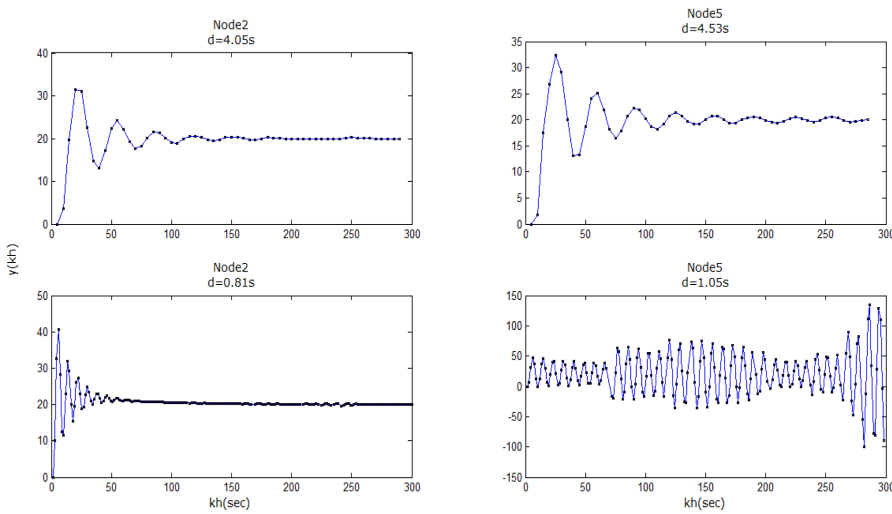


Figure 5-13: Control with packet delay, process I *(top)*, process II *(bottom)*.

In this scenario an extra delay is added to bring the system delays close to the maximum stability limit as calculated from the theoretical results. In this regards process I is expected to be stable for delays upto the whole sampling time (5s) while process II has the limit at 1.125s. As it can be seen from Fig. 5-13, regarding stability it can be argued the theoretical values give a good indication of the delay limit. In line with the previous experiment, delay has pronounced effect on the second (faster system), resulting instability at 1.05s <1.125s. At delay of 0.81s this process also shows stability with settling time of 121.5s (81th sample) but with overshoot of 103% which is probably unacceptable for practical implementation. Another observation of this results is for process I with larger sampling time, though the system is stable to delays close to the sampling time as the theory suggest, the settling time is greatly affected. In this case the system can only achieve settling times of 125s (25th sample) and 255s (51th sample) as compared to the 25s (5th sample) ideal case.

Scenario VI: Control with packet drop out and no delay. Time run 15 min, parent eviction threshold=3, $uc = 20$. Results shown for the two process and two nodes in Fig. 5-14.

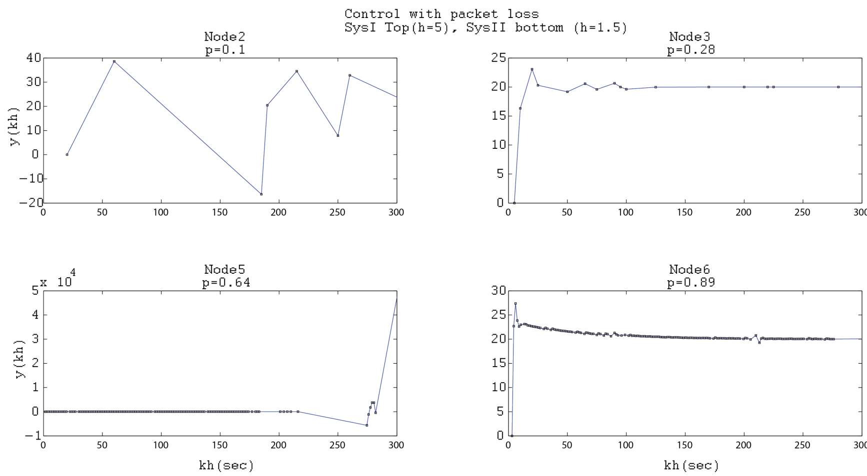


Figure 5-14: Control with packet drop, process I *(top)*, process II *bottom*.

In this scenario the sending probability of the sensor nodes is varied to observe the effect on the controller. From the theoretical argument in theorem 3 (4.12), process I is expected to be stable even in the presence of packet drop while process II has its limit at 89% packet loss probability. Correspondingly the results of this scenario also come close to confirm this, Fig. 5-14. Particularly stability of process I at 28% (node3) but with instability at 10% which can be explained with the argument the time spacing of the dropped packets at such a low reception rate.

Scenario VII: Control with node failure. Time run 20 min, parent eviction threshold=3, $uc = 20$, two process models. Node2 t=5 min off, t=10 min on, node3 t=15 min off, t=20 min on.

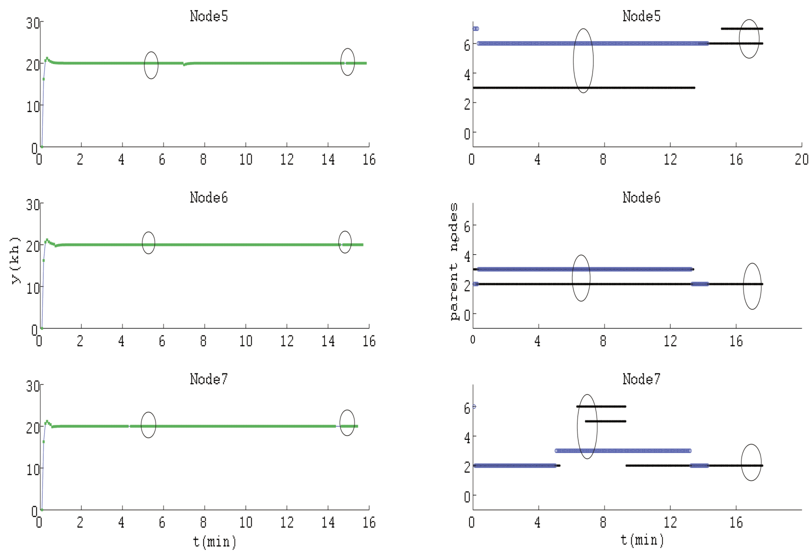


Figure 5-15: Control with node failure for process I.

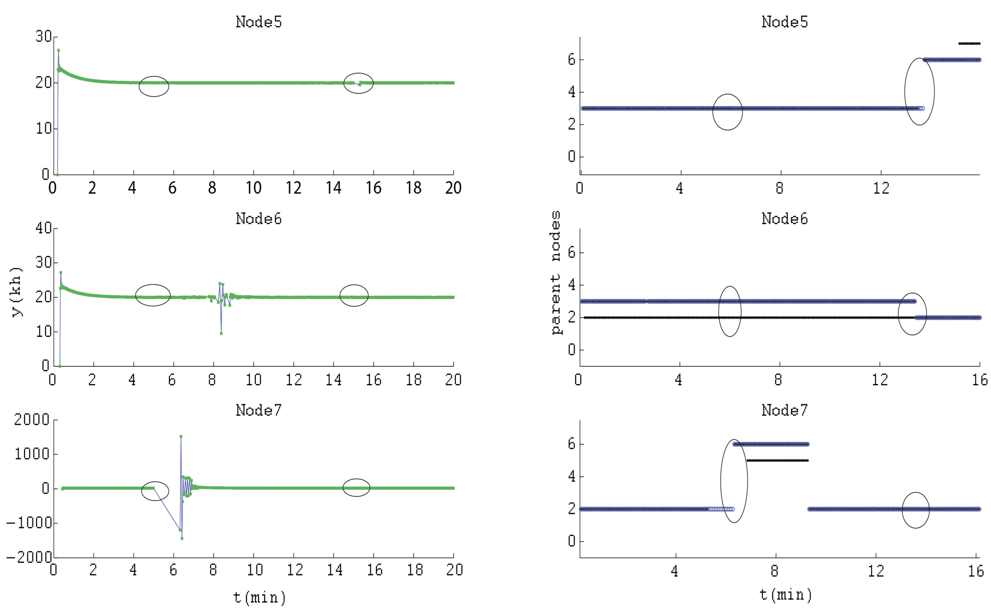


Figure 5-16: Control with node failure for process II.

This last scenario aims to observe any effect node failure has on control performance which actually resulted no visible impact as shown in Fig. 5-15 and 5-16. Two plausible argument for this are failure of nodes happens after the systems stabilized and further the nodes that use the failed nodes as default switch instantly to the back up parents, a point for further study. What ever the case, the wireless network proves itself reliable for supporting control system which is one of the goals this thesis set out to investigate.

Table 5.4: Network statistics with control loop.

(a) scenario IV for process I

	Node2	Node3	Node5	Node6	Node7
PRR%	1	1	1	1	.98
avg.delay	0.1044	0.0865	0.1473	0.1157	0.1677
avg.DIO/min	1.4579	1.3458	0.7290	0.7324	0.7290
avg.DIS/min	0.0561	0	0.0561	0	0.0561
avg.DAO/min	11.6075	17.8318	6.0000	5.9155	6.0000

(b) scenario VII for process I

	Node2	Node3	Node5	Node6	Node7
PRR%	1	N/A	0.9947	0.9842	0.9526
avg.delay	0.082	N/A	.1901	.1406	.1591
avg.DIO/min	1.06	N/A	0.73	1.18	1.18
avg.DIS/min	0	N/A	0.0561	0	0
avg.DAO/min	16.40	N/A	5.97	11.94	6.08

(c) scenario VII process II

	Node2	Node3	Node5	Node6	Node7
PRR%	1	N/A	.99	.94	.91
avg.delay	.1	N/A	.15	.21	.21
avg.DIO/min	1.05	N/A	1.23	0.86	1.64
avg.DIS/min	0.05	N/A	0.05	0	0.05
avg.DAO/min	17.8636	N/A	5.8182	8.2727	5.6364

Table 5.4 gives the comparison of network statistics between scenario IV and VII. As mentioned previously the measurements for node3 are not applicable as it is the one simulating node failure. From the listed values it is observed high reception ratio and the state stability in even in the case of node failure, adding to the viability of the control system for both systems.

A final observation is DAO messages sent by the remaining parent nodes (which substitute failed nodes) noticeably increase. Table 5.4 (b,c) in comparison with (a). In this specific case node2 will be the remaining parent node for nodes 5, 6, 7 when node 3 fails. This situation is explained as DAO's must be forwarded to the root node creating the possibility of network traffic load on nearest to root nodes. In general this should be given importance specially in large scale deployments as the percentage of network traffic will be significant for the node and also imply greater energy demand or short life span.

Chapter 6

Conclusion and Future works

With the goal of creating a better understanding of standard WSNs protocols a small sized practical sensor network is implemented. A control system is also designed and integrated to evaluate the viability of IEEE 802.15.4 MAC and RPL to support feedback control in industrial processes with HBN in mind.

The task of implementing a sensor network involved studying the TinyOS, IEEE 802.15.4 and RPL which followed with implementing interfaces for RPL necessary to monitor the state of nodes and the network such as routing and parent tables. Additionally modification to obtain desired network topology were integrated in the protocols.

From the controller perspective a PID controller is designed and theoretically analyzed using established theorems regarding NCSs. The process chosen was a house thermal control, whose relevance to HBN comes from resembling the control of chemical dosing in water treatment plants. A fictitious process but with faster system dynamics was also experimented with for comparison purposes.

The last part of the thesis entailed experimenting with different scenarios which are grouped into evaluating networking and controller performance. The experiments are done on a test bed of six sensor nodes and a central controller PC. From these a number of observations and conclusions were made.

It was shown parent eviction threshold has a direct impact on parent set a node can have. It is noted the exact tuning of this parameter depends on the actual deployment intended as a balance between the wireless environment quality and desired sensitivity of a node to link qualities. In relation to this point, a form of topology control (limiting the possible parent set of nodes according to their distance of deployment) can and should be integrated in the design of the sensor network to have a better and stable inter-connectivity between nodes. This point was supported with higher Packet Reception Ratio (PRR) achieved for the system as compared to preliminary experiments with plain implementations.

Regarding the RPL ICMP messages which are indicative of the networking load of the system, it was seen the trickle algorithm working as expected, exponentially decreasing number of ICMP messages as long as node interconnection remain stable. In the situation of a node failure, as expected the DIO reset occurs thus spikes in number of RPL ICMP messages occurs. An interesting observation which follow this situation is the significant load increase on the remaining parent nodes. An implication from this observation is the need for redundant distribution of nodes closer to root nodes if the network is to scale as in HBNs.

The study of the performances of controller in the different scenarios also confirm the viability of applying feedback controller over the protocols IEEE 802.15.4 and RPL. Introducing the wireless network doesn't introduce unexpected phenomena on the theoretical control system only the requirement that real implementation need to be conservative than theoretical predictions. The study of the results in the presence of network delay was shown to affect the system with faster dynamics more which is greatly reflected on percent overshoot. The practical implication of this is if the WSN is expected to introduce delay close to the system limit then viability of the system need to be guaranteed by the use of multitiered network topology as explained. Last but not least the study of the results in the presence of packet drop has revealed for the theoretical stability prediction to hold the underlining packet loss probability must be uniformly distributed. From industrial deployment such as in HBN perspective systematic interference must be checked to avoid unpredictable behavior of the control system.

Finally despite the work done, there is always room for improvements. Some possible followup works include:

- Evaluation of the protocols with more detailed deployment scenarios. This entails industrial deployment setup with larger network size. In the process parameters can be tuned and optimized.
- Implementation of new objective functions. Such implementations enable different application level priorities such as security or node's resource prioritization.
- Implementation of distributed control, specially study the advantages for large networks. Thus data aggregation and localized control are possible interesting topics.
- Comparison work between WirelessHART and IEEE 802.15.4 MAC + RPL. Even though the later protocols are studied in this thesis it can be beneficial to study the former also as it is designed for industrial processes in focus.

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