LOW LATENCY MAC (LLMAC) PROTOCOL FOR INDUSTRIAL WIRELESS SENSOR NETWORKS

CHAPTER 1

1.1 INTRODUCTION

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Industrialization refers to modernization of old methods that were used to be hand crafted. As we can realize the growing demand to supply imbalance in today's world due to increased population, industries are replacing these old methods to meet the needs of increased population. Introducing number of engineering innovations in industries helped to improve production and demand-to-supply balance. Increase in population demands for increase in quantity of goods to be supplied to consumers that was not possible with ordinary handcrafted methods. Reliable and well-timed production of goods for consumer was not possible using old hand crafted methods. Machines have been deployed in industries to produce reliably in well-timed manner.

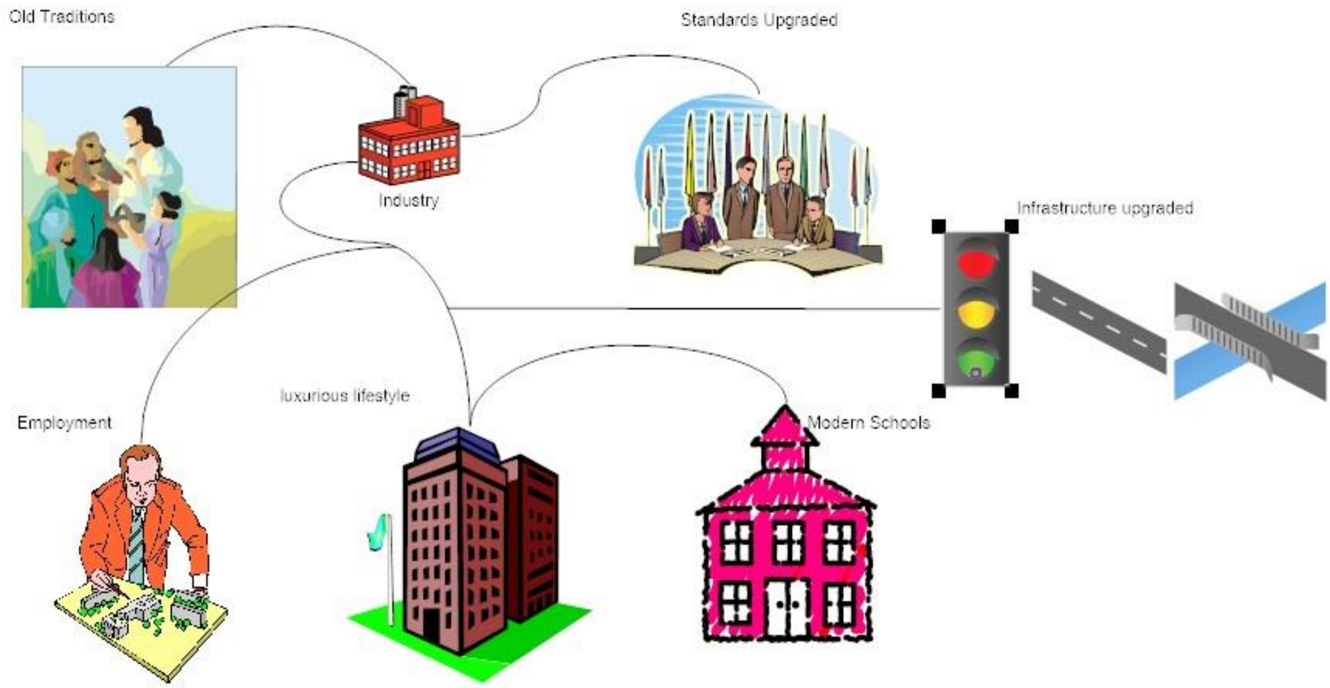


Figure 1-1 Effects of industrialization

This elevated status of society as shown in figure 1-1 but also brought some environmental issues.

To make the industries ecofriendly, it is a good effort to introduce devices to monitor health of equipment and prevent any harmful leakage to environment. Certain monitoring techniques has been introduced up till now that are either wired or wireless. Wired networks in industries are used to be complicated fixed infrastructure. These are not reliable as the damage need to get repaired urgently and it is not efficient, cost effective for a wired structure to be replaced in costly and time consuming manner. Wireless networks for monitoring can be more appropriate for an industrial environment as it allows reconfiguration, relocation, replacement autonomously.

Today's competitive world and emerging complexities of industrial automation scenarios demands improved efficient networks for industrial domain. Wireless Sensor Networks (WSNs) are brought to serve monitoring purpose because of their low cost deploy ability. Intelligent and simple systems are required to encounter the challenges such as throughput, latency, QoS etc., so, Industrial Wireless Sensor Networks (IWSNs) were brought into effect. The cooperative nature of IWSNs provides numerous benefits over old wired industrial monitoring and control systems, including self-organization, swift placement, flexibility, and inherent intelligent-processing capability. For these purposes, WSN is contributing in creating a highly reliable and self-healing industrial system that swiftly cooperate with real-time events using applicable actions [1].

1.2 MOTIVATION

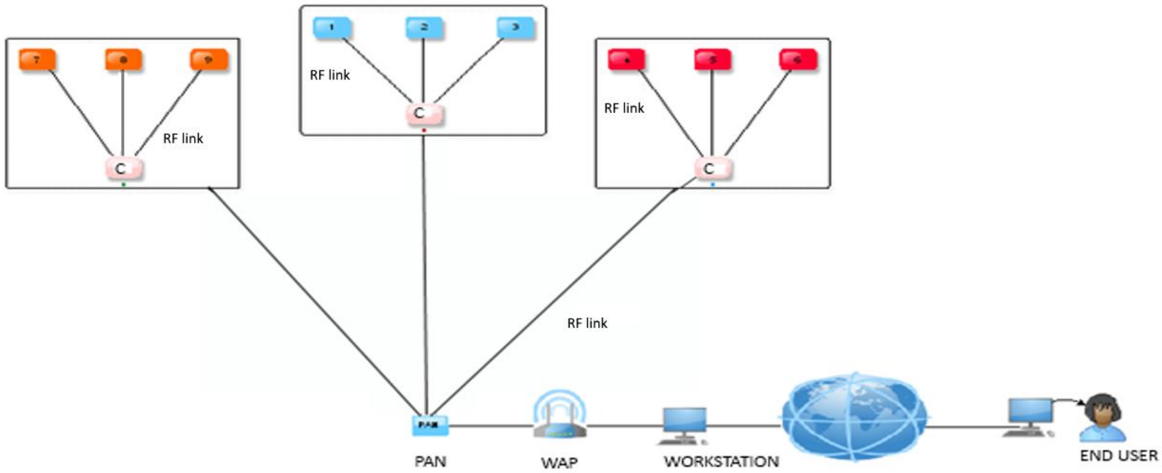
Wireless sensors network has an increasing demand for industrial automation as the harsh industrial environments demands to get the system monitored periodically to avoid any harm to expensive machineries installed there. When it comes to Industrial Wireless Sensor Networks (IWSNs), they need to possess certain capabilities to encounter the challenges such as large scale deployment, latency, throughput, reliability etc. Sensor data has to be real-time. Data communicated with long latency (due to processing or communication) are used to be useless and lead to incorrect decisions in the monitoring system. To improve latency, bandwidth reservation can help in reducing interruptions and through coordinator, scheduling can also be done. For channel efficiency, throughput need to be optimized. Collisions destroys packets and adversely effects reliability.

Certain state of the art protocols are proposed till now which are providing promising solutions in accordance with industrial environment but they have their own limitations in terms of latency and some other constraints, as explained in detail in chapter 2.

To encounter those limitations, specifically latency, a simple protocol, LLMAC(Low Latency MAC) for IWSN, is proposed in this thesis. It takes into account GTS mechanism of 802.15.4, network coding and data aggregation to attain low latency, optimized network lifetime and optimized throughput. Rest of the details are included in next section.

1.3 PROBLEM STATEMENT AND DESCRIPTION

The proposed architecture enables IEEE 802.15.4 to work in multi-cluster scenario and supports large number of nodes as shown in figure 1-2. This resolves the inherent challenge of scalability and synchronization for IEEE 802.15.4 standard. The proposed architecture also addresses the reliability and robustness requirement which are at the core of industrial wireless networks. In this architecture, the heads of clusters can either directly connect with the sink or through multi-hop depending upon channel conditions and route information.



PAN=PAN coordinator (mains powered); C=Coordinators; WAP=Wireless Access Point;

1,2 …. 9=end nodes

Figure 1-2 LLMAC architecture

The chief benefit of using such a methodology is, in case of failure of a cluster head, the network will still be functioning. In order to obtain low latency and avoid redundant data from the network, aggregation of data is performed at coordinator nodes in the proposed scheme. Aggregation typically comprises of the grouping of data from many sensors at coordinator nodes and transmission of the aggregated data to the sink node. Furthermore, in order to reduce latency and enhance reliability, network coding is also used along with data aggregation. Figure 1-3 gives the further detail and insight of these techniques that are proposed with the architecture to further enhance the capacity of IEEE 802.15.4.

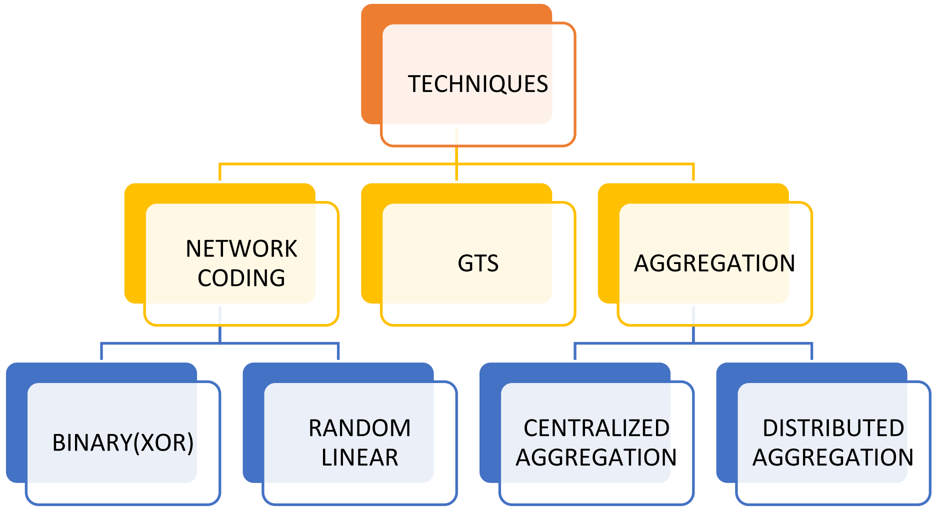


Fig 1-3: Proposed techniques for LLMAC

1.3.1 DATA AGGREGATION

Data aggregation technique is used to collect and transmit data to sink node using an energy efficient method. Sensor nodes are normally associated with power constrained devices as most of them are battery powered, hence methods and algorithms are required to overcome this issue and increase network lifetime.
Usually, sensors are deployed in large scale. Typically, in industrial applications, more than 1000 sensors at short distances are present, correlation of data exists among them and redundant data causes unnecessary consumption of power as well as collision of data packets in the network. By using data aggregation technique, aggregating node collects data, removes redundant information and send aggregated data to sink node. This, in turn improves network lifetime, data accurateness, and decreases latency of the network.
Aggregation will remove redundant data that reduces packet size and in turn, would provide an optimized value of low latency.

1.3.2 GTS

Guaranteed Time Slots (GTSs) are used in beacon-enabled mode of 802.15.4. GTSs occupy contention free period in active potion of super frame which are 7 slots and reserved for certain nodes. This will help in attaining low latency. Rest of the details will be included in chapter 3.

1.3.3 NETWORK CODING

It is a procedure in which intermediate nodes combine packets from different nodes to decrease number of transmissions over the link. There are two major classifications of network coding; XOR and Random Linear(RL). In the proposed idea, 802.15.4 uses super frame with small packets, by using network coding with data aggregation and GTS, number of transmissions can be further reduced by mixing packets and sending coded packets to destination nodes.

1.4 BRIEF DESCRIPTION OF WORKING

Request is sent from PAN coordinator to coordinator node if it has data to send. It also has frame that has to be relayed through coordinator to 1, 2 and 3 containing requests for1, 2 and 3 to send to PAN coordinator. It is working on beacon-enabled mode of 802.15.4. PAN coordinator is working for synchronization using beacon frame, coordinators does the same too.

1.5 THESIS ORGANIZATION

The thesis is organized as follows: chapter 2 for literature review, chapter 3 for analysis of GTS mechanism, chapter 4 for evaluation of proposed algorithm NCAMAC(Network Coded-Aggregated MAC) protocol which is a part of main proposed technique i.e LLMAC (Low Latency MAC protocol for Industrial Wireless Sensor Network) . Chapter 5 is complete evaluation of LLMAC. Chapter 6 will conclude overall thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 OVERVIEW

Electronic devices are adaptable and easy to use. These can be used to measure both static and dynamic signals. Sensors are electronic devices used to convert a physical parameter to an electric output. They can be used through wired or wireless devices which can then form a network to monitor an area [8]. Future of digital world now relies on internet and integration of devices with internet to generate and consume information as shown in figure 2-1. It includes information from all living being, things etc. A controller device (may be a computer or any gadget) responds to information and process it. The target of thesis is industrial environment monitoring, so moving towards this, we need to monitor machine health, entity observation, environment cleaning etc. It depends on certain parameters like battery efficiency, throughput, reliability, security and latency. Latency range varies from application to application. For industrial domain, typical range is around 10 ms, for process control, it's in seconds, and for asset monitoring, in minutes [6]. Wireless Sensor Networks (WSNs), as depicted in figure 2-2, are attaining greater attention in today's world. Due to their low cost deploy ability and mobility, systems are moving towards it. There is no need for physical medium as electromagnetic waves are used. Though, wired networks has been into function from several years and working really good but they have their own limitations. When it comes to Wireless Sensor Networks, WSN in most applications, need to be deployed in large number and could be easily detachable without disturbing the whole network to save cost. Complex installation of large network doesn't make it reliable to work, system need to be energy efficient, reliable and safe. Additionally, they have to possess ability of self-configuration to compete with the encountered environment. Several standards, mechanisms and techniques has been introduced in past years to enhance and make it more efficient and some protocols were proposed specifically for industrial safety critical environments. Application-specific designs makes it easier and reliable to be adequate in attaining target of requirement.

Wireless Sensor Network has an increasing demand for industrial automation as the harsh industrial environments demands to get the system monitored periodically so as to avoid any harm to expensive machineries installed there.

Industrial Wireless Sensor Networks (IWSNs) need to possess certain capabilities to encounter the challenges as detailed below:

(i) Dynamic topology/link failures: These are due to the malfunctioning of nodes. Malfunctioning could be there due to interference, highly corrosive environments, vibrations etc.

(ii) Resource Constraints: Due to small size and battery, resources like energy, memory and processing are limited.

(iii) QoS Requirements: Sensor data has to be real-time. Data communicated with too much latency (due to computations or communication) are used to be useless and lead to incorrect decisions in the monitoring system.

- Latency: In design of any adhoc wireless communications without any fixed infrastructure, with mobility, latency is a major issue. Low interruptions can be attained by bandwidth allocation, time division or may be using some communication control mechanism. The later two mechanisms requires the presence of a coordinator to inspect and avoid bottle neck network issue.

- Throughput: Throughput is the important performance consideration of any wireless network. In case of wireless networks, it becomes of prime importance as it directly influences channel efficiency. Due to lot of interferences and collisions, packet errors at physical layer occurs and throughput is destroyed at MAC layer due to collisions. To avoid this, mostly CSMA/CA implemented at MAC.

(iv) Large Scale deployment: No predetermined network architecture is there. It requires the IWSNs to create network connections on their own.
(v) Reliability & Robustness: They are required at industrial level as data and packet losses may lead to inevitable losses [1].

Wireless ad hoc networks utilizes multi-hop transmission of packets but also able to operate without any organization sustenance. Mostly formed using heterogeneous devices and additional capability is their mobility, that's why, also denoted as Mobile Adhoc Networks(MANETS). Industrial Wireless Sensor Networks(IWSNs) are deployed in industries to monitor equipment in order to assure required performance. There are certain protocols available which are of use in industrial automation such as WISA, Wireless HART, ISA100.11A etc. These protocols provide promising solutions for the existing challenges in industrial environment such as latency, scalability, reliability etc. but at the cost of complexity /scalability issues as most of the protocols are based on mesh/ tree topology [5]. In some protocols, failure of one link may take down the complete network [5]. Wireless HART is developed on mesh and according to [2], mesh networking among multiple nodes makes the system model much more complex than that of a typical MIMO system in WLANs. The ISA100.11a standard is constrained in supporting resource constrained devices and large-scale networks [4].The proposed approach will offer a simple protocol for low latency MAC in harsh industrial environment where complexity may cause losses.
In context of real time performance, some constraints do apply when it comes to Industrial Wireless Sensor Networks(IWSNs). The protocols mentioned above for IWSN have variable performance value as depicted in table 1. In this section, we will take an overview of implementation and enhancement of these protocols in real-time real life world, the review from different papers is included.

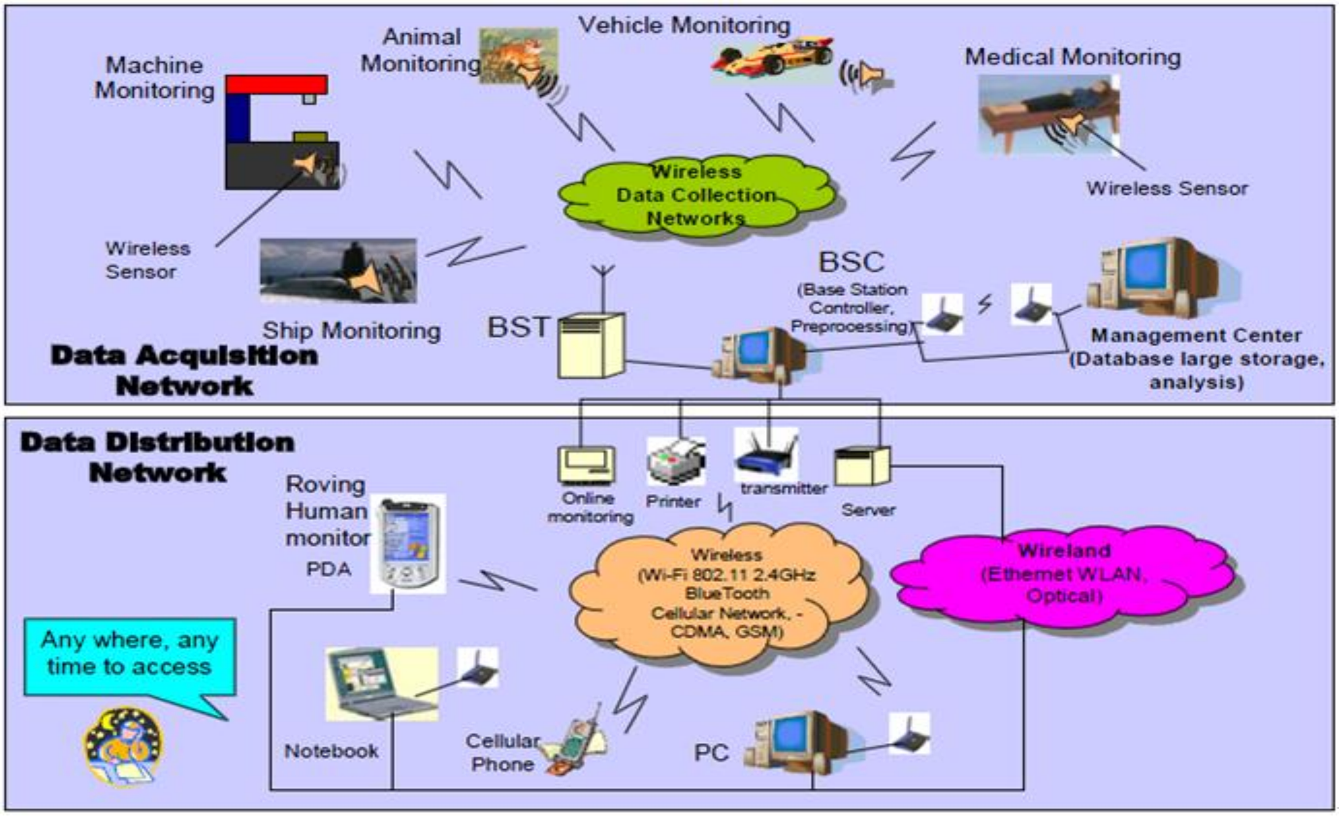


Figure 2-1 Example of wireless networking

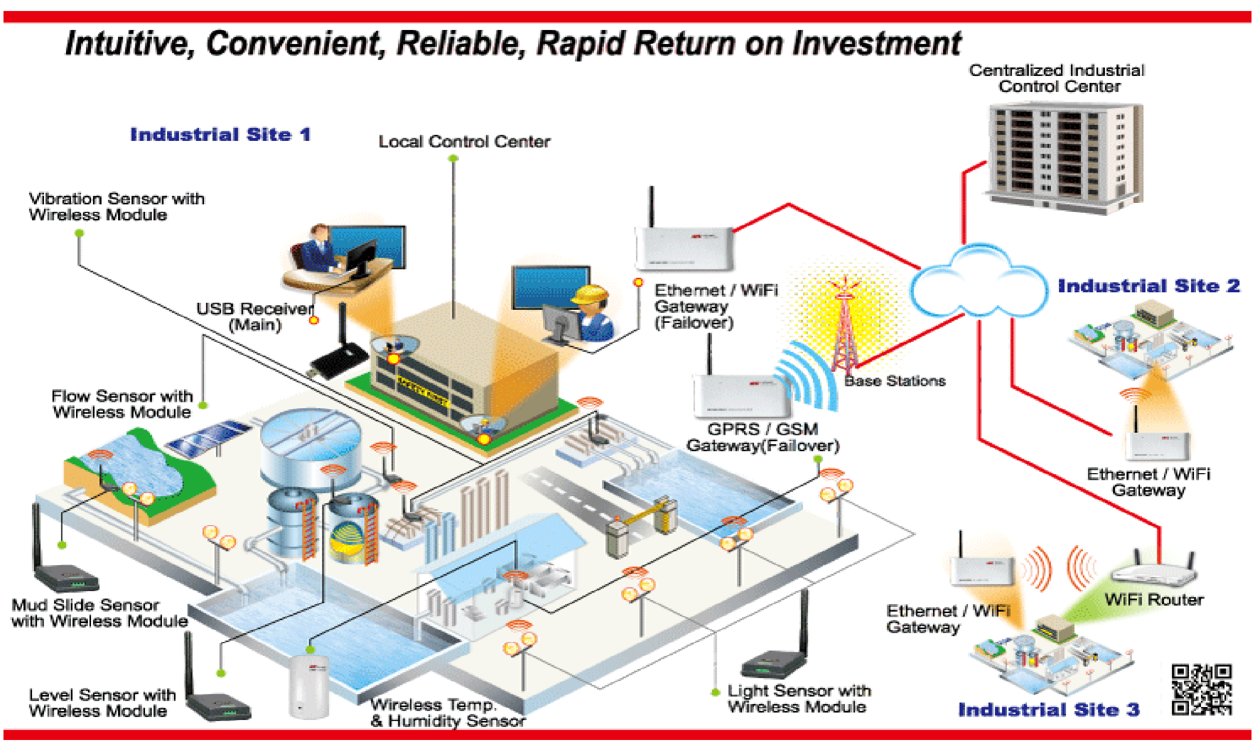


Figure 2-2 Example of Industrial Wireless Sensor Network(IWSN)

2.1.1 IEEE 802.11

This protocol is defined over physical and MAC layer. It is used for implementing in 2.4, 3.6,5 and 60 GHz band for Wireless LAN (WLAN) scenarios. The protocol has two modes: Distributed Coordination Function(DCF) and Point Coordination Function (PCF). The DCF don’t use any controller or coordinator. The access criteria is defined using CSMA/CA with carrier sense or with virtual carrier sense. The PCF uses an access point (controller or coordinator) to control transmission/reception procedure. It transmits a beacon control frame that contains parameters and invitations. The leading benefit of using IEEE 802.11 includes it’s wide use and high data rates . It supports TCP/IP and it can easily be connected to internet.

The major drawback, why we can’t use it for wireless sensor network applications, is its power consumption. Besides, it includes the large overhead in control and data packets which creates latency issues.

2.1.2 IEEE 802.15.1

It is basically used for Mobile Personal Area Networks and ranges up to 100 m (normally it is 10 m). It is used for communicating data over small area. It is a packet based protocol with a master-slave structure. Slaves cannot connect directly to each other, master has control over all slaves. One master may communicate to up to seven active slots in a piconet and 255 non-active slaves. A piconet can communicate using one full duplex channel with 64 kbps master-slave and another 64 kbps slave-master through the basic rate. Figure 2-3 demonstrates an example of scatter net.

The advantage of using Bluetooth is its low-cost hardware. Compatible with mobile phones and laptops.

The drawback of using Bluetooth in WSNs is due to its topology i.e cluster based. Master node acts as cluster head. If node failure occurs at head, the network will disconnect partially or completely. Other drawbacks include power consumption and limited address space. WISA technology is based on IEEE 802.15.1.

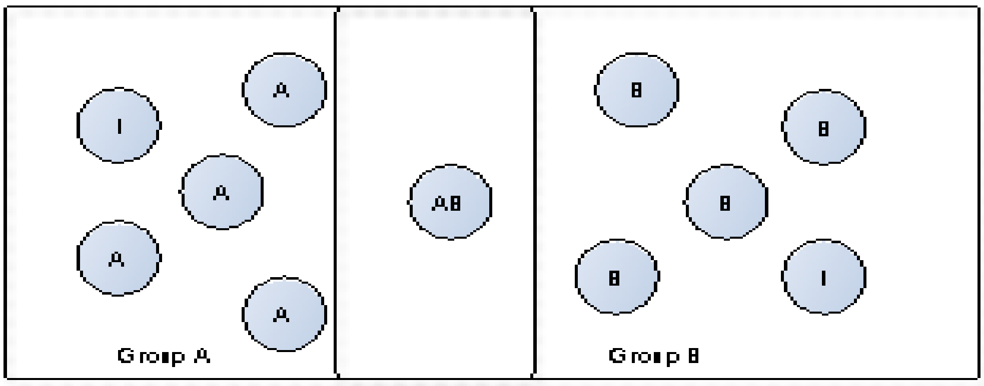


Figure 2-3 Bluetooth scatter net.

Figure 2-3: Shaded circles are master nodes in two different piconets, A and B. Blue circles show slaves belonging to each piconet. Active slaves are labelled according to the network they belong to, inactive slaves have label I. AB is a slave belonging to both piconets. The figure shows coverage areas of both master nodes.

2.1.3 WIRELESS INTERFACE TO SENSORS AND ACTUATORS (WISA)

Sensors and actuators are employed in industries to monitor machines. They require power cabling which could be a source of automation failure as there is a significant number of the sensors and actuators open to harsh industrial environment connected via cabling. At field device level, wires are the source of problem.

Wireless technology was then introduced to minimize the losses introduced by cabling. As for wireless interface to be reliable, it need to satisfy two constraints: Wireless communication for real time communication and wireless power supply.

None of the existing wireless systems/standards satisfies the necessary balance of requirements for the described sensors and actuators as field devices. These constraints are latency vs. data rate, reliability, power consumption and also node density vs. range. Therefore a customized wireless technology is mandatory to fulfil the requirements. The new wireless technology used is based on IEEE 802.15.1 (physical layer) and is called WISA (Wireless Interface to Sensors and Actuators).

According to the ABB corporate research Norway, their proposed design has following features for factory automation. Some of them are listed as under:

- Simultaneous transmission and reception of radio signals; i.e. full-duplex operation.
- Transmit and receive antennas at the input module are swapped every 2 ms to provide a diversity of radio propagation paths against fading and shadowing effects.
- Deterministic frequency hopping to combat broad band interferers.
- Five simultaneous communication channels are available for free access and immediate acknowledgement of 120 devices.

The overall specifications makes WISA a worthy choice as it offers a dynamic solution for industrial automation problem. The only drawback is its topology which makes it complex, a cellular network topology for efficient use of bandwidth.

2.1.4 IEEE 802.15.4

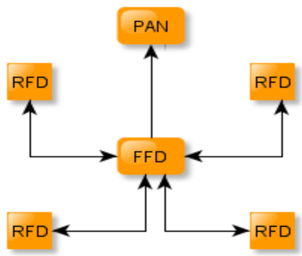
IEEE 802.15.4 is a low power, low data rate wireless communication standard. It forms the basis for low-rate wireless personal area networks. It offers low transmitter power, low power consumption, low cost. It is a MAC and PHY layer protocol. It operates on 2.4 GHz band. This protocol supports two type of devices:

Full Function Device (FFD): It can work as a coordinator that connects the network to other networks. It can connect with any other device.

Reduced Function Device (RFD): RFD only communicates to a FFD.

The main advantage of using 802.15.4 for industrial WSN is designing with inexpensive hardware.

The drawback of 802.15.4 for WSNs is its star topology as shown in figure 2-4a which is merely suitable for the clustered architecture, needs all RFDs close enough to FFD for communication. It also allows peer to peer topology as shown in figure 2-4b. Like 802.15.1, 802.15.4 arbitrary deployment does not assures device position [6]. Power consumption is also a drawback. It is a real time, robust and reliable communication protocol only for limited address space and not suitable for large scale deployment of sensors at industrial level. Unbounded delays make it inappropriate as it is CSMA/CA based technology and does not guarantee specific bound for maximum delay, making it non-suitable for time critical industrial application. When used in beacon enabled mode, delivery ratio is low due to random access method and synchronization introduced by the periodic beacon. While in NBE mode, a low delivery ratio is due to simultaneous transmission from all nodes [4].



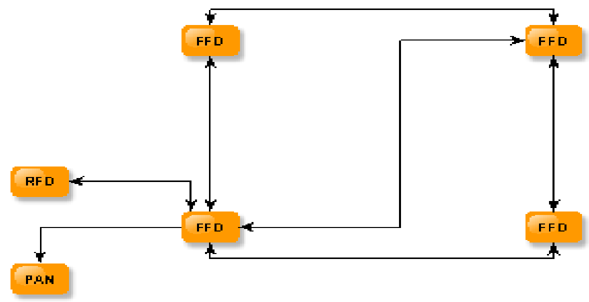


Figure 2-4(a) 802.15.4 topology Figure 2-4(b) 802.15.4 topology

Figure 2-4(a) : Star topology

Figure 2-4(b) : Peer-to-Peer topology.

WSNs usually encounter interference and multipath fading phenomena. IEEE 802.15.4 takes single channel methodology with no predetermined frequency hopping mechanism, cannot protect from their effects. Network will be unstable and might collapse.

2.1.5 WIRELESS HART

It is 802.15.4 based protocol. Wireless HART targets sensors and actuators for monitoring in industrial environment. The protocol functions in PHY, MAC, network, transport and application layer. PHY layer uses 802.15.4 and MAC utilizes TDMA and channel hopping (for system data bandwidth & robustness) to minimize interference. It has a centralized network operation structure. Factors influencing the latency includes routing, scheduling and the network extent [6]. The main advantage of using wireless HART is its robustness to industrial harsh environments. The network architecture for wireless HART is given in figure 2-5.

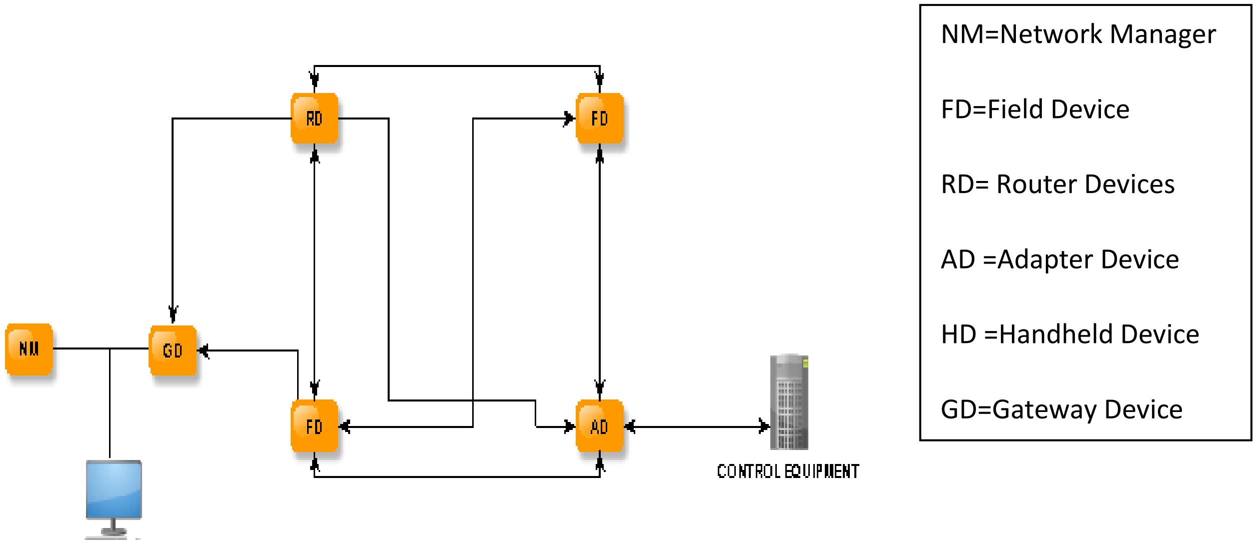


Figure 2-5 Wireless HART network architecture

The downside of using wireless HART is ,if NM fails, it will take the whole network down, though it allows a backup node as well but at a time, only one active NM is allowed. Power consumption issue is also there as it works on star as well as mesh topology for direct communication to gateway. Multi hop communication in a mesh topology introduces complexity in synchronization making it non-reliable for large industrial wireless sensor network construction.

2.1.6 ISA100.11a

It is 802.15.4 based protocol. It is designed taking into consideration flexibility, compatibility of protocols, support of multiple applications, error detection, channel hopping, determinism, security. It corresponds to process automation and shares several features with Wireless HART. Physical layer is used over low power, low rate wireless networks and MAC utilizes CSMA, channel hopping, channel blacklisting and TDMA. Network architecture is shown in figure 2-6. ISA100.11a differs from wireless HART in the way it uses time slots i.e. shared time slots. Sharing of time slot is attained using CSMA/CA algorithm employing priorities for control access. It supports mesh, star-mesh or star topologies, non-routing sensor devices, communication to a plant network via a gateway, nodes interoperability, data integrity, secrecy, validity, replay and latency protection, coordinating with other wireless networks, robustness in the presence of interference [7].

The main advantage of using ISA100.11a is that it can directly connect with different industrial wired networks such as wired HART, Field bus and profibus.

The disadvantage of using ISA100.11a is, it increases complexity, as it employs two network managers. It employs centralized approach which introduces technical ease but incapable to handle sudden changes under industrial environments. The large scale of the deployment needs to exploit distributed methods to assure that the system continues its optimized performance.

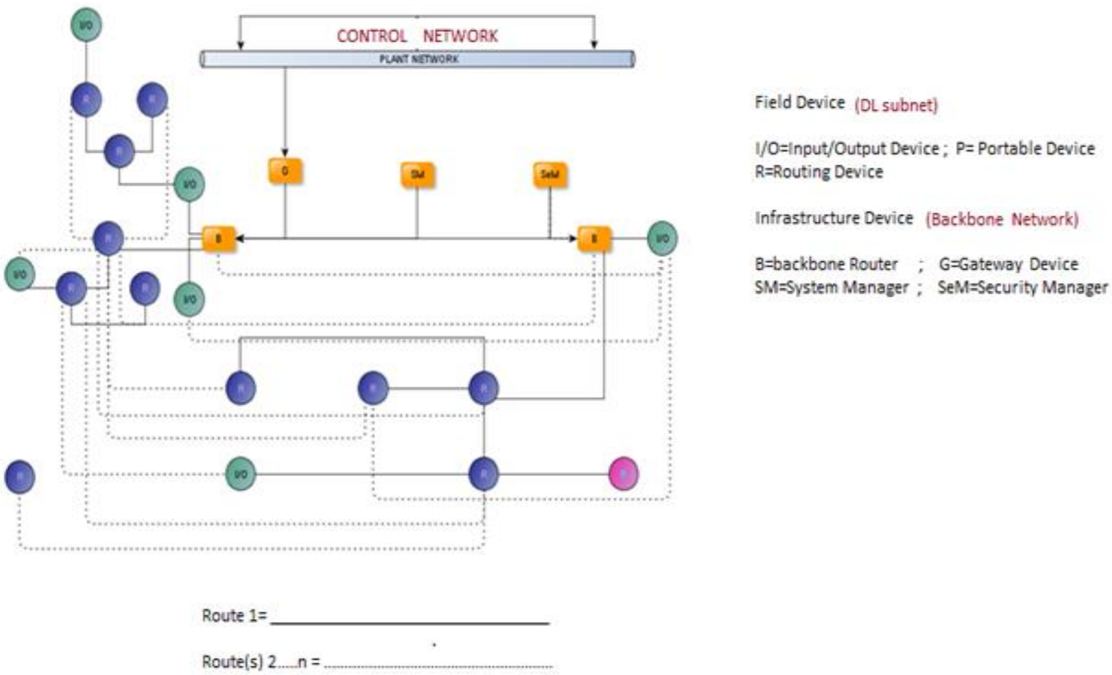


Figure 2-6 ISA100.11a network architecture

Summary of performance of some available protocols is given in table 2-1:

Performance Matrix	WISA	WIRELESS HART	ISA100.11A	802.15.4	802.15.4e
Number of devices	120	30K devices	ISA100.11a uses IPv6 and, as such, has much larger address space.	10	100
Layers/ Modes	802.15.1 based Unspecified	802.15.4 Timeslotted/graph and source coding, connectionless service HART 7	802.15.4Time slotted/ IETF IPv6 and 6LoWPAN/connectionless UDP service	802.15 CSMA/CA,	RFID blink, ACMA,LLDN, DSME,TSCH
Complexity	Yes	Yes	Yes	Yes	No
Topology	Cellular-network based	Inherently mesh but supports star as well	Mesh	Peer-to-peer or star	Star/peer-to-peer (Depends on mode selection)
Real Time	Yes	Yes (for limited address space)	Yes (for limited address space)	Yes (for limited address space)	Yes
Safety critical	Reliable, Robust	Reliable, Robust	Reliable, Robust	Reliable, Robust (for limited address space)	Reliable, Robust
Throughput	Not for pure data throughput but rather for reliability	At transport layer, throughput is maximized using network manager	Backbone routers limits throughput into and out of a single subnet to the throughput of one radio.	for applications requiring relaxed throughput	Increase throughput for industrial requirement by minimizing unwanted collisions using time slotting

Table 2-1 Comparison of protocols

Now, taking a complete survey of all the given different protocols available up to the time, it is clear that these protocols produces promising solutions to wireless networking problems, yet they introduce system complexity and in turn introduces latency issues at the cost of reliability(as in mesh networking) in most of the protocols.

802.15.4 protocol is considered for applications without special requirements in reliability, strength, relevance and scalability, however it provides a level of robustness and reliability for limited address space. This makes it unsuitable for industrial and healthcare fields.

To overcome these limitations, a network architecture is proposed based on enhancement using combination of GTS, aggregation and network coding to evaluate three key parameters throughput, latency and network lifetime. First, we will analyze 802.15.4 in general in next chapter.

CHAPTER 3

ANALYSIS OF 802.15.4 ALONG WITH GTS MECHANISM

3.1 INTRODUCTION OF 802.15.4

According to standard document, 802.15.4 is conceived for applications requiring limited power and relaxed throughput [9]. It operates on several bands such that 2.4 GHz ISM band,915 MHz and 868 MHz . Output powers ,depends on local regulations, are given as 2.4 GHz ISM band , 915 MHz and 868 MHz [13].The raw data rate is 250 kbps for certain applications but also adjustable to requirement of sensors and automation purposes (around 20 kbps)[9]. These are used for industrial monitoring, wireless sensor networks, intelligent farming etc [13]. It is conceived for applications for low cost, low power, low rate Personal Area Networks (PANs). PAN is formed by one or more PAN coordinator and optionally, by one or more sub coordinators or coordinators, that serves for the set of nodes in the network. Two distinctive devices can participate in a network; Full Function Device (FFD) and a Reduced Function Device (RFD).FFD works as a PAN coordinator and RFDs are conceived for minimal resource and capacity device like sensors or a light switch and associated to a single FFD at an instant. The main goals include simplicity of devices establishment, unswerving information exchange, to a great degree minimal effort, and a sensible battery life, while keeping up a simple and adaptable protocol. Standard is capable of optional allocation of GTS to 7 devices at a time. Wireless PAN can be formed by two or more devices communicating on a same physical channel including at least one FFD as a PAN coordinator. Due to dynamic propagation characteristics, no predefined coverage area exists for WPAN because moving from station to station causes to change or decrease signal strength/link quality.

3.2 TOPOLOGIES

Supported topologies are star (single hop), mesh and cluster tree approach.

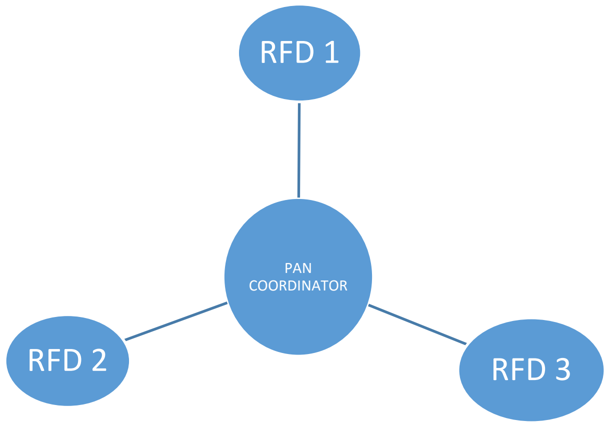


Figure 3-1a Star topology

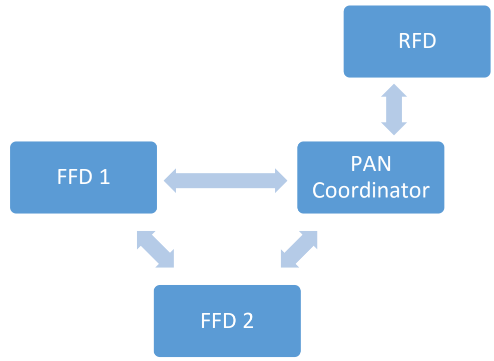


Figure 3-1b Peer-to-peer topology

For direct communication, device uses extended address of 64 bit within PAN or short addresses assigned by PAN when device contacts. PAN coordinator are mains powered while devices are battery powered. Elaborating star network in figure 3-1a, it is illustrated in standard document of 802.15.4 that a FFD can establish its own connection after it has been activated. All star networks works independent of other star networks. In a peer to peer topology, as shown in figure 3-1b, every device is capable of communication to any other device within its communication vicinity.

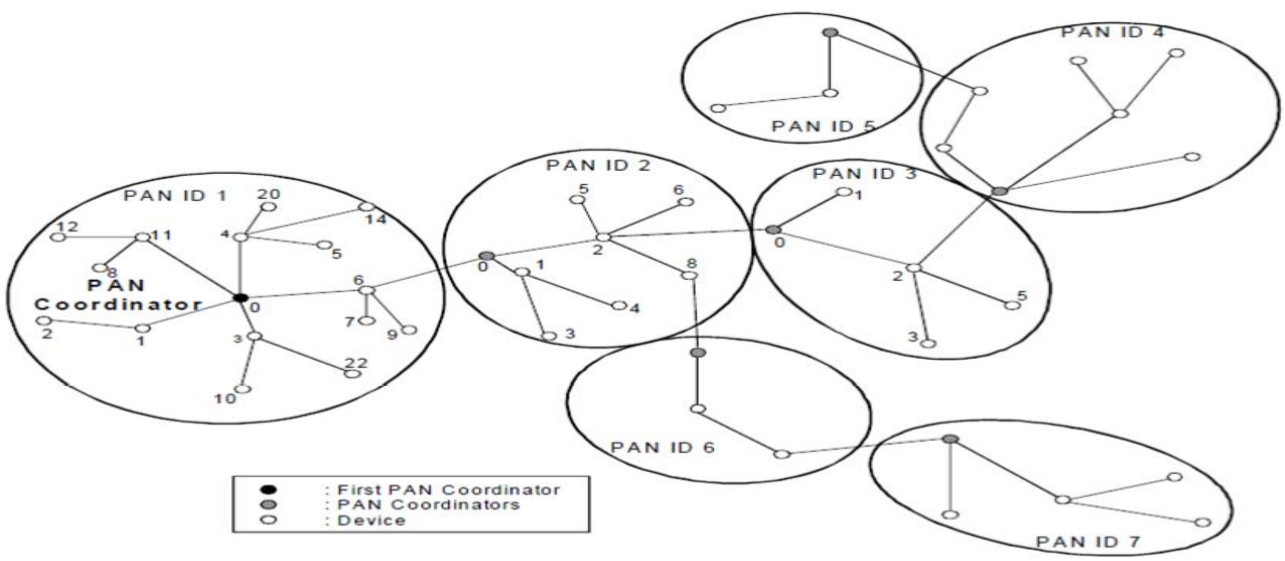


Figure 3-1c Cluster tree network

Third topology is cluster tree as shown in figure 3-1c. Large networks can be formed by forming mesh of multiple clusters which can increase coverage area but increases latency as well which is not favorable for industrial requirements.

3.3 GENERAL ARCHITECTURE OF 802.15.4

802.15.4 is composed of layers responsible for one part of the network and also responsible for the services to the higher layer to it as shown in figure 3-2 .

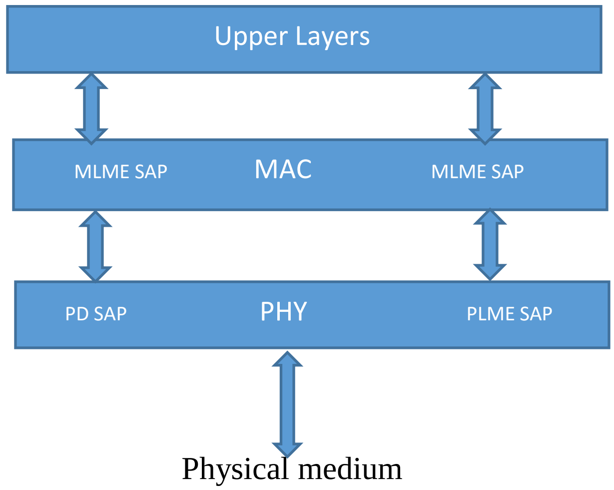


Figure 3-2 LR WPAN device architecture

PHY (Physical layer) consists of RF transceiver along with its low level control mechanism. It provides services for PHY physical data service and PHY management service and enables transmission and reception of Physical Protocol Data Unit (PPDU). Main Features include turning on and turning off of radio transceiver, CCA (Clear Channel Assessment), channel selection, Energy Detection(ED) and Link Quality Indication(LQI).

The MAC (Medium Access Control) sublayer provides services for MAC data service to transmit and receive packets across PHY data service and MAC management service interfacing to MAC Sublayer Management Entity (MLME) Service Access Point (SAP). Main features include frame authentication, association and disassociation, GTS management, beacon management, acknowledged frame delivery and channel access.

Upper layer comprises of network layer providing configuration services and routing. An application layer provides functions to the device but these upper layers descriptions are outside scope of this standard.

3.4 WORKING OF 802.15.4

Two channel access schemes are used: BE (beacon enabled) and NBE (Non-Beacon enabled). BE mode uses super frame structure that is bounded by beacons. Beacons are synchronization frames generated periodically by the coordinator nodes as shown in figure 3-3a . Three types of data transfer modes exist: device to coordinator, coordinator to device, peer to peer transfer. In star network, only two modes are possible, device from coordinator or device to coordinator.

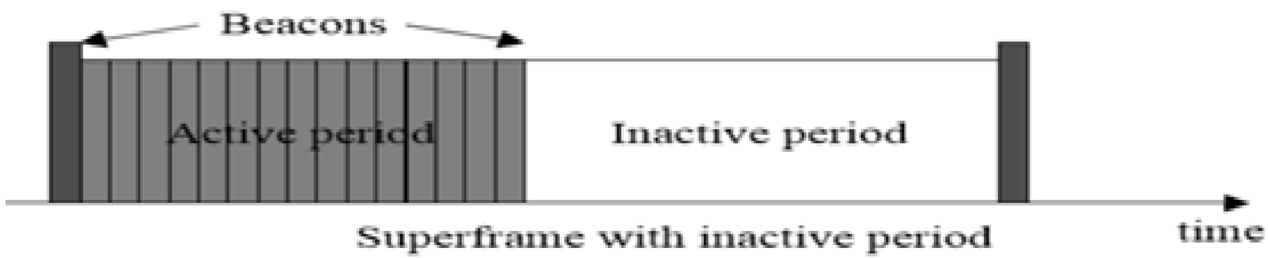


Figure 3-3a Structure of Super frame

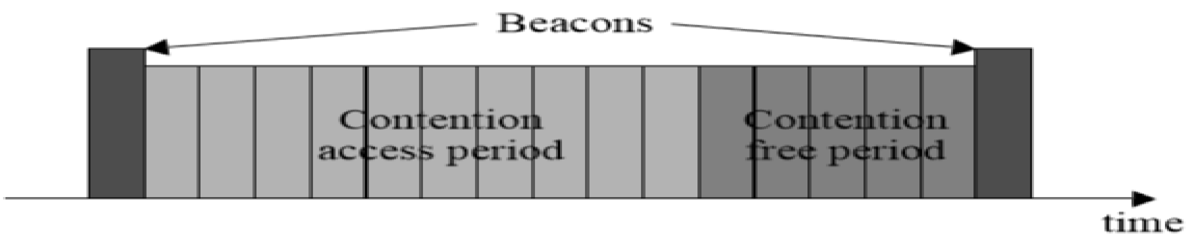


Figure 3-3b Structure of the active periods with GTSs

Transmission, process and reception of information on 802.15.4 depends on following parameters.

1. Beacon Interval (BI) is the interval between two consecutive beacons and is defined by Beacon Order (BO) parameter as shown in (a).

   $BI=15.36.\ 2^{BO}$ (0<=BO<=14) .... (a)

2. A super frame comprises of active and inactive period. In active period, communication between nodes occur while, in inactive period, it goes in low power sleep mode to save energy. Superframe Duration(SD) comprises of active period and Superframe Order(SO) parameter is used to define its size as shown in (b).

   $SD=15.36.\ 2^{so}$ (0<=SO<=BO<=14) .... (b)

3. Active period is further divided into Contention Access Period (CAP) and Contention Free Period(CFP) as shown in figure 3-3b. During CAP, Slotted CSMA/CA is used. For improving probability of successful delivery, CSMA/CA and other mechanisms are used. As defined in standard , "The IEEE 802.15.4 LR-WPAN utilizes two sorts of channel access mechanism, subject to system arrangement. NBE PANs utilize an unslotted

CSMA-CA channel access scheme. Each time a device wishes to transmit data frames or MAC instructions, it is bound to follow for a random period. In the case that the channel is observed to be idle, after the arbitrary back off, the device transmits its information. In the case that the channel is observed to be occupied after the random back off, the device is bound for another arbitrary period before attempting to get to the channel once more. Acknowledgement frames are sent without utilizing a CSMA-CA Algorithm".

4. BE PANs utilize a slotted CSMA-CA channel access scheme and the back off periods are adjusted to the begin of the beacon. The back off times of all devices inside one PAN are adjusted to the PAN coordinator. Each time a device wishes to transmit data frame during the CAP, it finds the limit of the following back off period and after that bounds itself for an arbitrary number of back off periods. On the off chance that the channel is occupied with, taking after this arbitrary back off, the device waits for another random number of back off periods before attempting to get to the channel once more. On the off chance that the channel is idle, the device starts transmitting on the following accessible back off period limit. Acknowledgement and beacon frames are sent without utilizing a CSMA-CA scheme [9].
5. ALOHA mechanism is conceived for small applications in which a device can send without sensing a media which is not suitable for industrial environment.
6. Acknowledgement frame is optional in standard. If the data acknowledgement is not received, device assumes it unsuccessful and retries sending data frame.

3.5 LITERATURE REVIEW

In [7], the performance constraints for 802.15.4 are explained. 802.15.4 is based on CSMA/CA algorithm, so unbounded delays during transmission/reception are likely to occur. Synchronization introduced by periodic beacon and CSMA/CA algorithm produces a low delivery ratio, making it non-reliable. For sensor and actuator networks, it is not suitable as interference and multipath fading are very common in industrial environment. It works on single channel and there is no predetermined frequency hopping to counter multipath fading. Network will encounter instabilities and might collapse. For mesh and tree topologies, intermediate relay nodes are required to turn on their radio all the time causing power consumption.

In [10], an enhancement for IEEE 802.15.4 is proposed for dense wireless micro sensor networks. Authors evaluated the potential of 802.15.4 radio for use in ultra-low power sensor node operating in a dense network. While conducting experiment with 1600 nodes transmitting 1 byte every 8 ms, average power consumption was 211 µW. Energy per bit decreases with increase in packet size. This provided high energy efficiency but latency also got increased. In [11], performance of standard is simulated. It is concluded while examining reliability of point to point communication with real 802.15.4 hardware by measuring RSSI,PER and run length distribution for both indoor and outdoor environments, evaluating MAC in NS2, they showed that simulated throughput is incomparable with maximum capacity. By relatively increasing small back-off order, throughput is increased. Low duty cycles to achieve low power consumption will cause to increase latency. Higher-level protocols which make use of 802.15.4 are ZigBee, MiWi Mesh and MiWi P2P,Wireless HART (industrial automation) , 6LoWPAN and ISA100.11a [12].

3.6 GTS MECHANISM

GTS (Guaranteed Time Slot) allocation is an optional feature of 802.15.4. Up to seven slots are dedicated in a superframe in CFP in beacon enabled mode in which each slot can be dedicated to device ,subject to the space available, to operate on channel as shown in figure 3-3b. Allocation is performed by PAN coordinator to communicate between device and PAN coordinator. A particular GTS can occupy one or as per requirement, more than one slots. Data frame shall use short addressing. Management information for GTS should be contained in PAN coordinator and PAN coordinator should be capable of storing the management information such as length, starting slot, direction (transmit/receive) and associated device address. Direction and address should uniquely identify each GTS. Rest of the details can be found in [9].It also allows deallocation and reallocation mechanisms in standard. Once the GTS is requested and decided to be deallocated , it shall not be used by device and stored characteristics should be reset. This will make the superframe fragmented. To solve this issue, GTS reallocation is performed by shifting other GTSs to fill in the gap created by deallocation, thus utilizing and preventing the superframe from having empty slots and in turn increases size of CAP. The GTS expiry also occurs in certain conditions as explained in [9].

In [13], an author studied effect of varying number of slots for GTS for 802.15.4 protocol performance at radio level. Effect of interference at radio level and number of slots allocated to GTS was also carried out additionally with and without existence of path loss ,using Omnet++ and Castalia. Results showed that with up to three GTS selection, more packets are received by sink node even with presence of interference at wireless communication channel.

In [14], Fault detections and monitoring of motors, measurement of quantities like vibration, temperature and current, at early stage using wireless communication based on 802.15.4 protocol with GTS mechanism in beacon-enabled mode is proposed. According to them “This guarantees the data transmission and a synchronous acquisition, which are serious elements in a monitoring system based on a wireless sensor network”. Data received by coordinator node is stored and examined using LabVIEW. The system comes out to be easy in installation, autonomous and inexpensive to maintain. It works good for sensor networks and preventive measurements for three phase rotating machinery.

3.7 EVALUATION USING MATLAB

802.15.4 permits optional use of superframe configuration defined by the coordinator. It is bounded by beacons and composed of 16 timeslots of equal duration. It is composed of active and inactive portions. Active period is composed of Contention Access Period (CAP) and Contention Free Period (CFP). CFP is composed of GTS that are helpful in low latency applications and during CAP, the devices intending to communicate uses CSMA/CA or ALOHA protocol, dedicating one slot/GTS. Designing with a coordinator, we are using 200 nodes with 7 GTS slots keeping them high for a period. During next, remaining slots are kept active. Block diagram of complete process is shown in figure 3-4.

For network lifetime calculation in thesis, we have used an author’s code [29]. This code was working well and when enhancement is done by including GTS, network coding and data aggregation and changing some steps in code, we got some better results than original code. Comparison is given in figures for network lifetime at the end of chapter 5.

3.7.1 BLOCK DIAGRAM

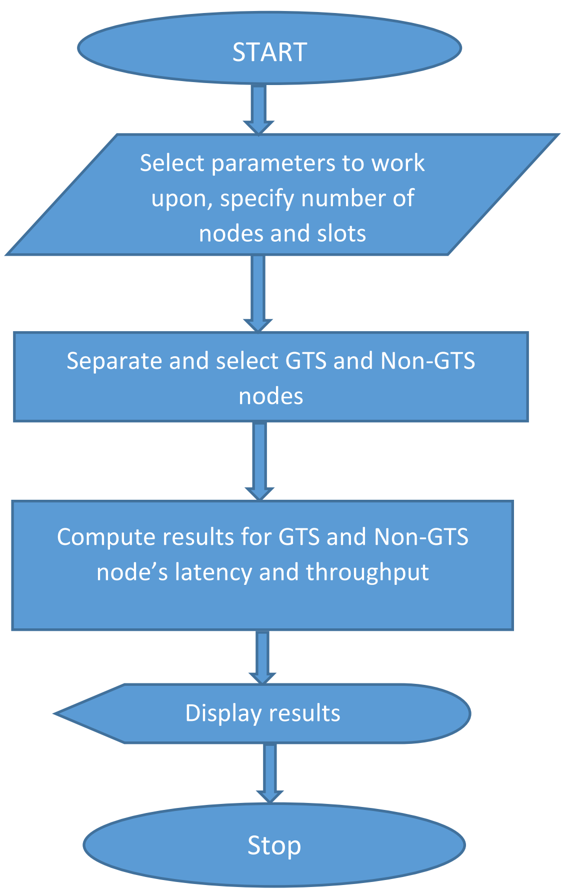


Figure 3-4 Block diagram of GTS evaluation

3.7.2 PSEUDOCODE FOR LATENCY AND THROUGHPUT USING GTS MECHANISM

loop1

Set k // k=Number of iterations for assigning GTS slots

set nn // nn= Number of nodes

set ns //ns=Number of slots

if nn>k

Increment nn

else nn≤ k

Generate GTS nodes

Compute remaining nodes

endif

if ns>k

Increment ns

else ns≤k

Generate GTS slots

Compute remaining slots

endif

end loop1

Set R //Data rate

Set S //Packet size in bits

Initialize q=0 // q=queueing delay; for first packet, q=0

loop2 // Latency and throughput for GTS

Set q

Compute S1 //Packet size in bits

Compute probability

Compute individual latency

for r<=specified value //r=iteration for GTS

Compute overall latency

Compute throughput

increment S1

increment q

if r>specified value

break

endfor

endloop2

Display individual latency,overall latency and throughput

loop3   // Latency and throughput for Non-GTS nodes

Set q

Compute S2   //Packet size in bits

Compute probability

Compute individual latency

for q<=specified value

Compute overall latency

Compute throughput

Increment S2

Increment q

if q>specified value

break

endfor

endloop3

Display individual latency,overall latency and throughput

3.7.3 RESULTS

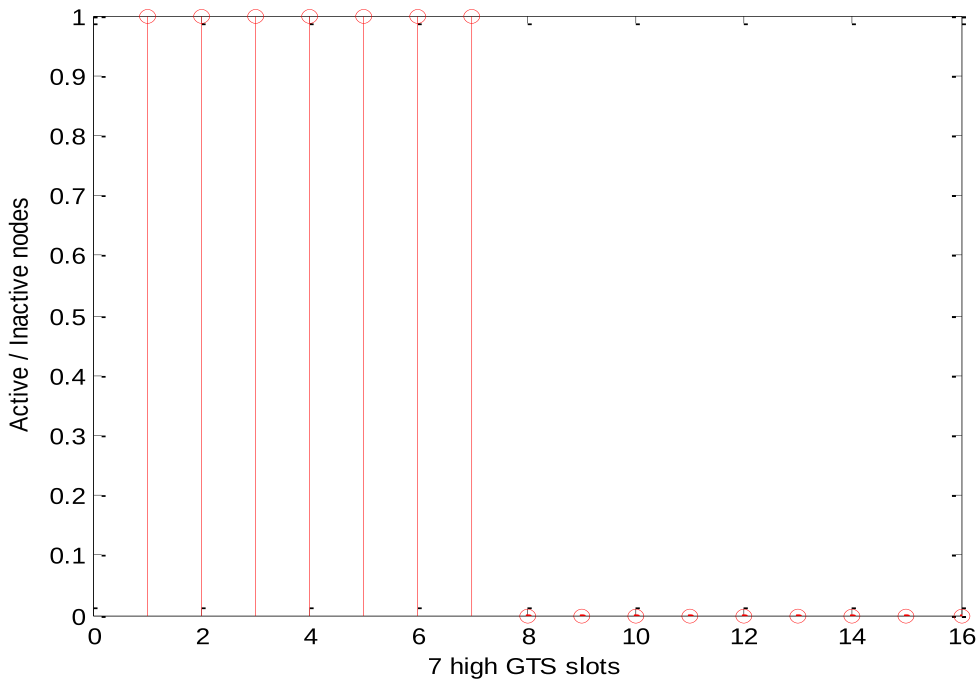


Figure 3-5 Slot allocation for GTS

Figure 3-5 shows reservation process of Guaranteed Time Slots(GTS) & high slots in red lines shows seven nodes are assigned specifically for slots in superframe in active period while rest of 9 slots are available for other nodes as shown in figure 3-6. Nodes are assigned on the basis of the importance of area which is monitored , also based on the energy a node contains. Those seven nodes have to be placed near most critical equipment in industry. Rest of the nodes are placed near less critical equipments. Nodes communicating in GTS has privilege to access contention free in their respective slot of duration 0.96 ms. For rest of 193 nodes, they will compete to access remaining 9 slots of CAP using CSMA/CA.

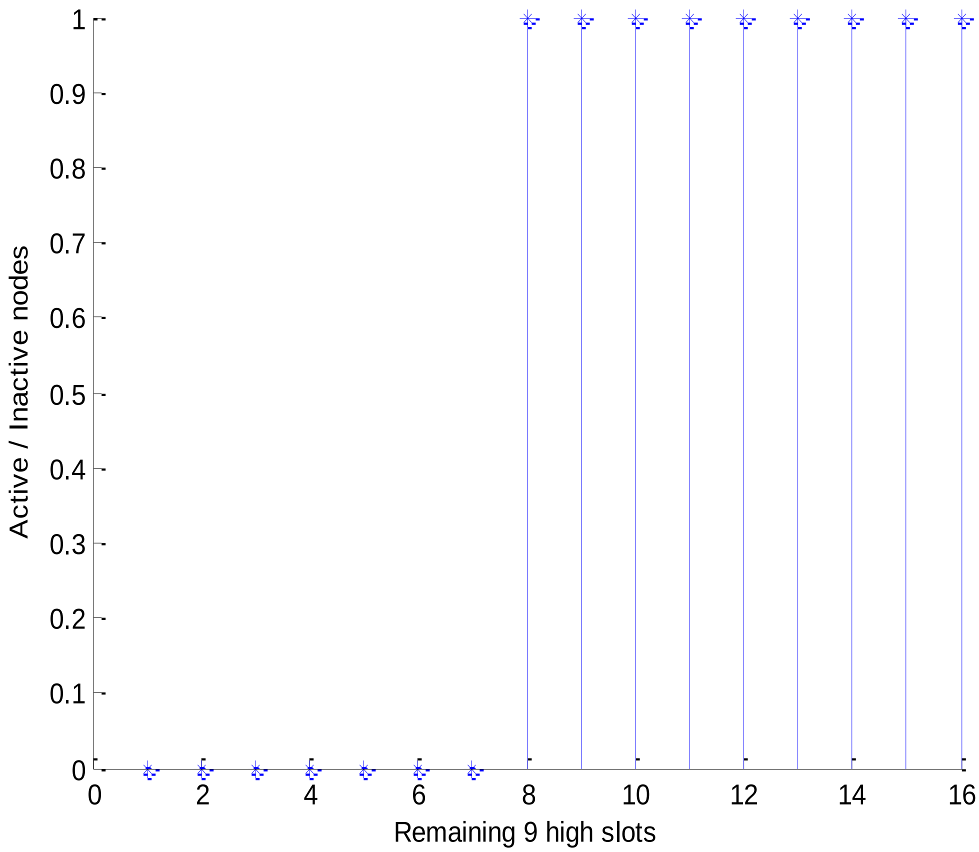


Figure 3-6 Slot allocation for Contention Access Period

In figure 3-7, reservation of 7 nodes to GTS is shown out of 200 nodes in active period while rest of 193 nodes are free to access remaining non-GTSs using CSMA/CA as shown in figure 3-8. Seven GTS's nodes are occupying CFP while remaining 193 are accessing remaining non-GTS using CSMA/CA algorithm of 802.15.4.

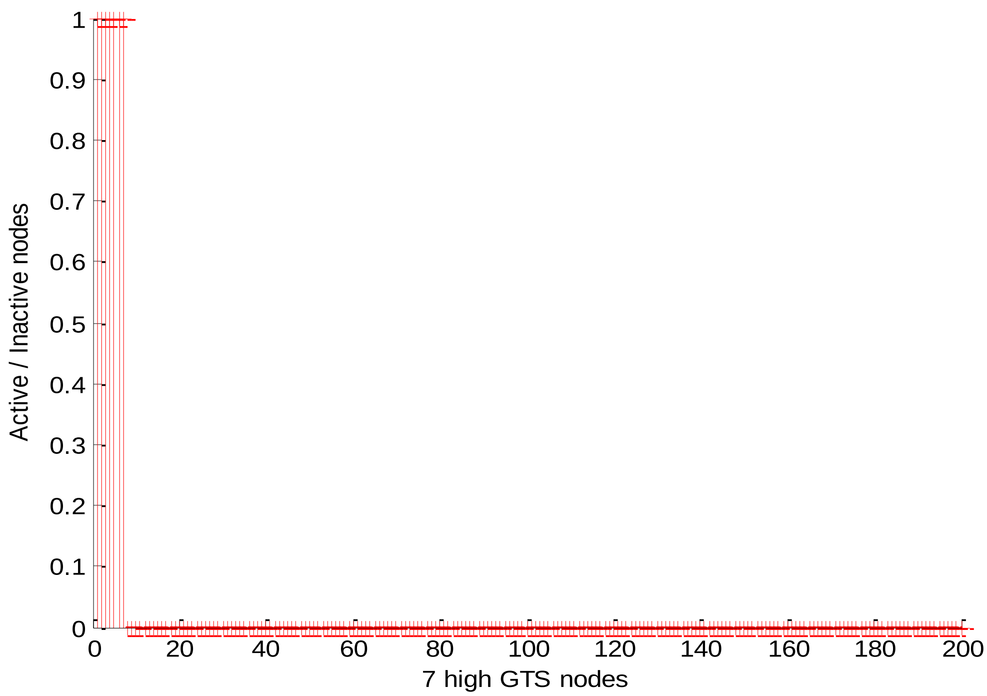


Figure 3-7 Number of GTS nodes high in active period

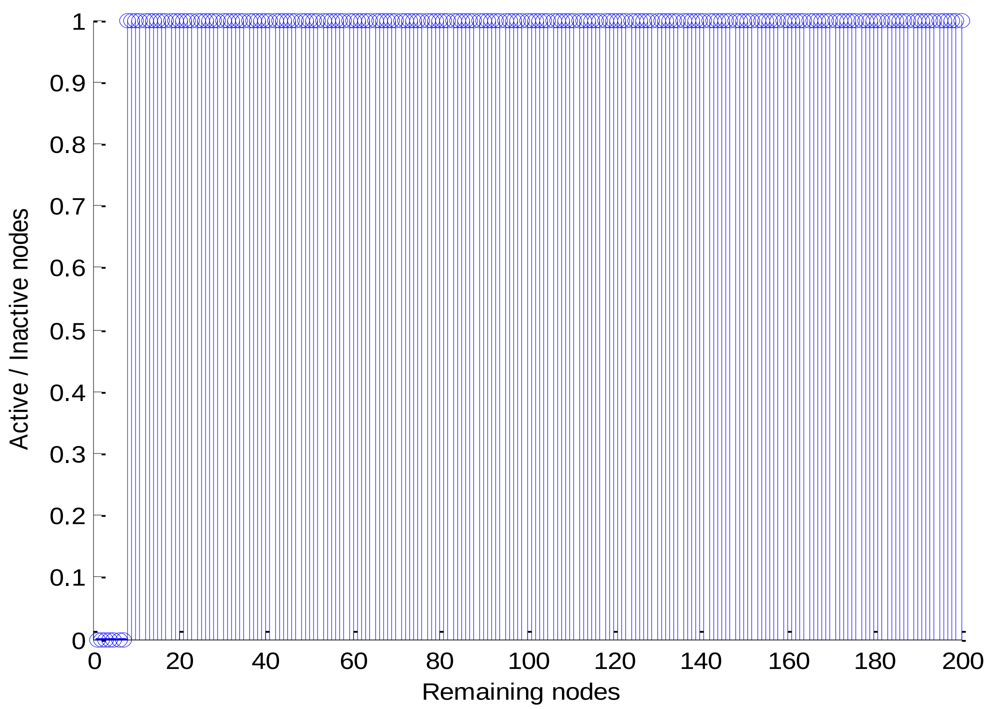


Figure 3-8 Number of non-GTS nodes in CAP

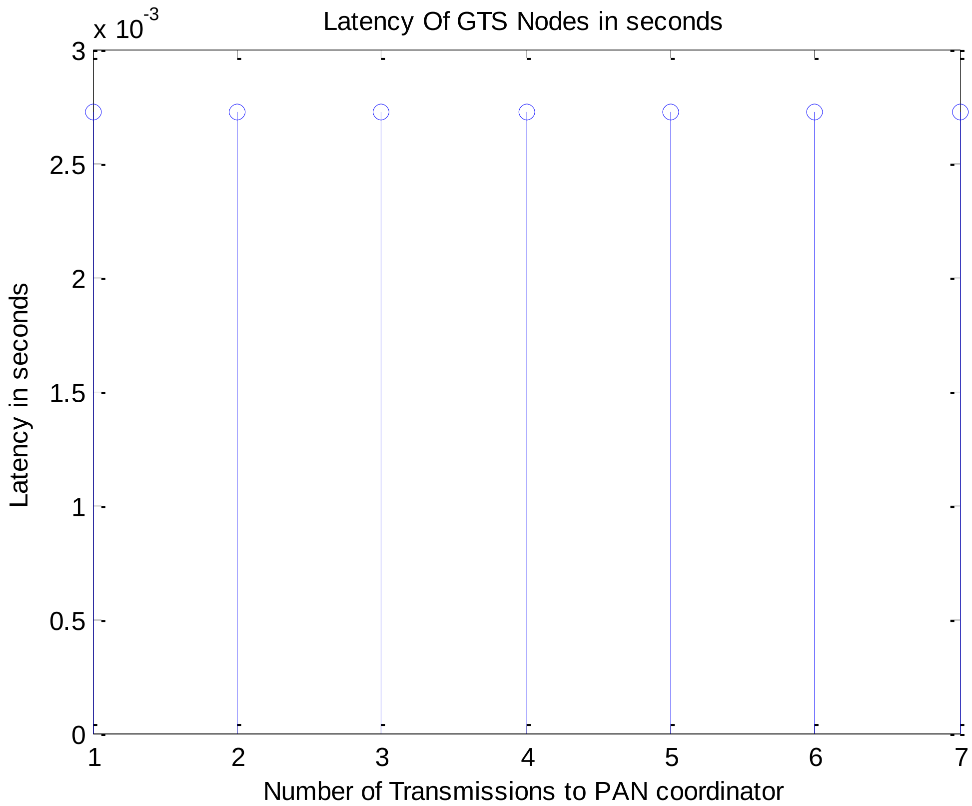


Figure 3-9 Latency of GTS

In figure 3-9, it is evaluated that equiprobable GTS nodes accessing their assigned slots encounters minimum latency of value 2.72 ms each. No queueing delay is here as the nodes have to access their assigned slot. It takes a single transmission of superframe on each round so packet size is not added to previous one. These nodes have to be placed near most critical equipment area.

Data rate (d) is set to be 250 kbps. Packet size is 55 bytes. Latency is calculated as

Latency= ((K/d))+0.00096 ………………….(1)

Where K=Packet size

d=data rate

Slot duration= (15.36 ms/16) = 0.00096 seconds

The latency of overall network evaluated at each transmission is calculated as

Latency of overall network=Average (Latency) ……………………. (2)

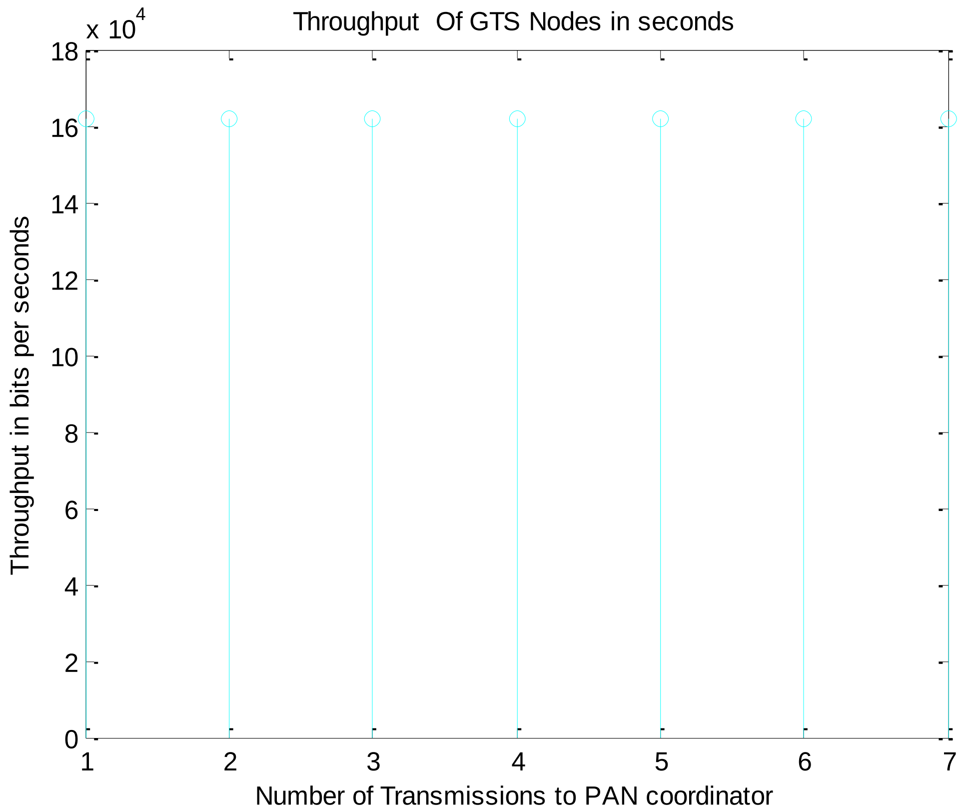


Figure 3-10 Throughput of GTS nodes

While for same assigned nodes, throughput is optimized of value 161.764 for each node as shown in figure 3-10. Transmission/reception of data is performed in their specific assigned slot, that's why, the total is not adding to previous one. Queueing delay is throughout null here as nodes are accessing their assigned slots. Packet size is independent of previous packet size.

Taking formula (2) for overall latency, throughput is calculated as

Throughput= (K)/(Latency of overall network) ……………………………………(3)

Now, calculating for the rest of 193 non-GTS nodes, the latency and throughput are computed as follows:

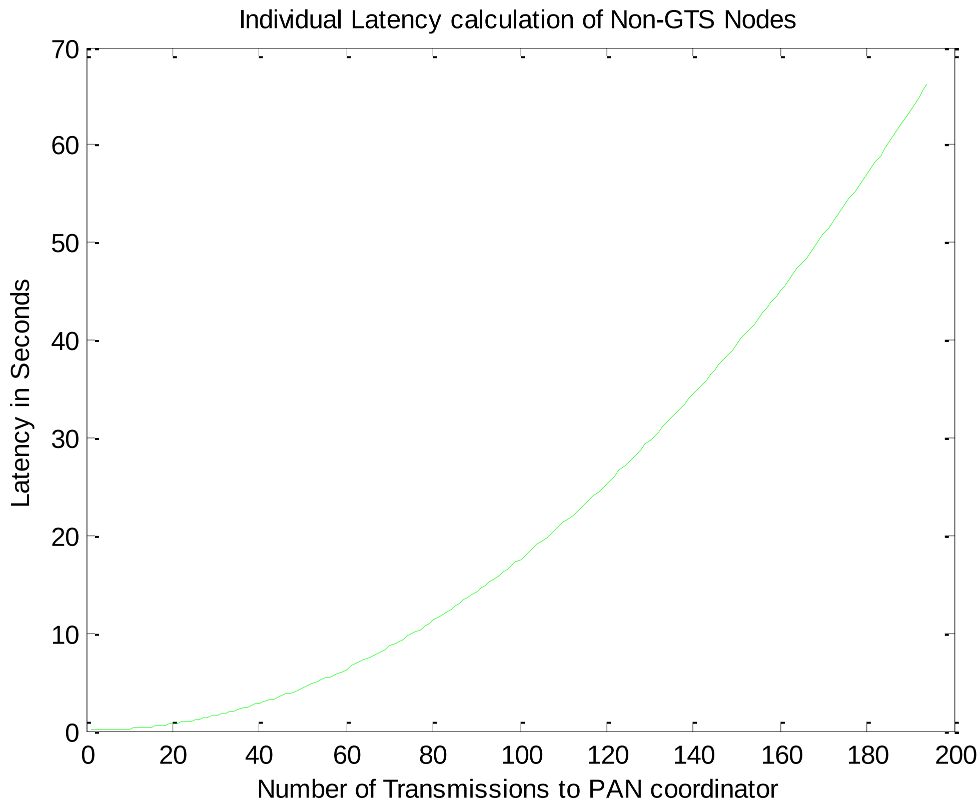


Figure 3-11 Latency between each two consecutive nodes

In figure 3-11, latency calculation with remaining non-GTS nodes is performed. Nodes are competing using CSMA/CA. Packet collisions/losses and retransmissions occur here. Packet size is 55 bytes. Data packet size and queueing delay is updated at each iteration because nodes have to compete to access those CAP slots. It is calculated as follows:

The queueing delay for transmission of first packet is 0 (q=0); Second one has to wait till the first one is completely transmitted with data rate d=250 kbps i.e. (55*8)/ d seconds. Delay for third packet becomes 2*55*8/d as it gets to send after first 2 are sent and so on. Latency is calculated as

Latency= ((K/d)*q) +0.00096 …………………. (4)

Where K=Packet size

d=data rate

Slot duration= (15.36 ms/16) = 0.00096 seconds

q and K are updated at each iteration as mentioned in pseudocode and shown in figures.

In figure 3-12, the latency of overall network evaluated at each transmission is calculated as

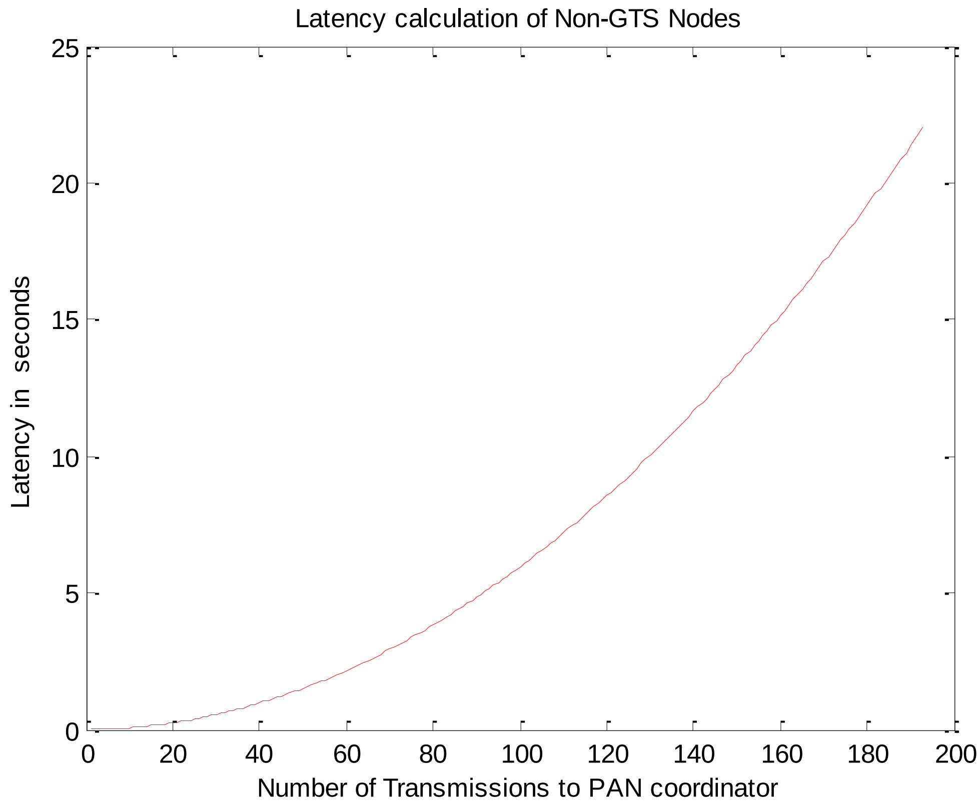


Figure 3-12 Latency calculation with non-GTS nodes

Latency of overall network=Average (Latency) …………………….... (5)

This shows the average of latency encountered by nodes due to interference. It achieved a high value of latency, not appropriate for industrial environment. A need aroused to find an optimal solution to obtain low latency and optimal throughput.

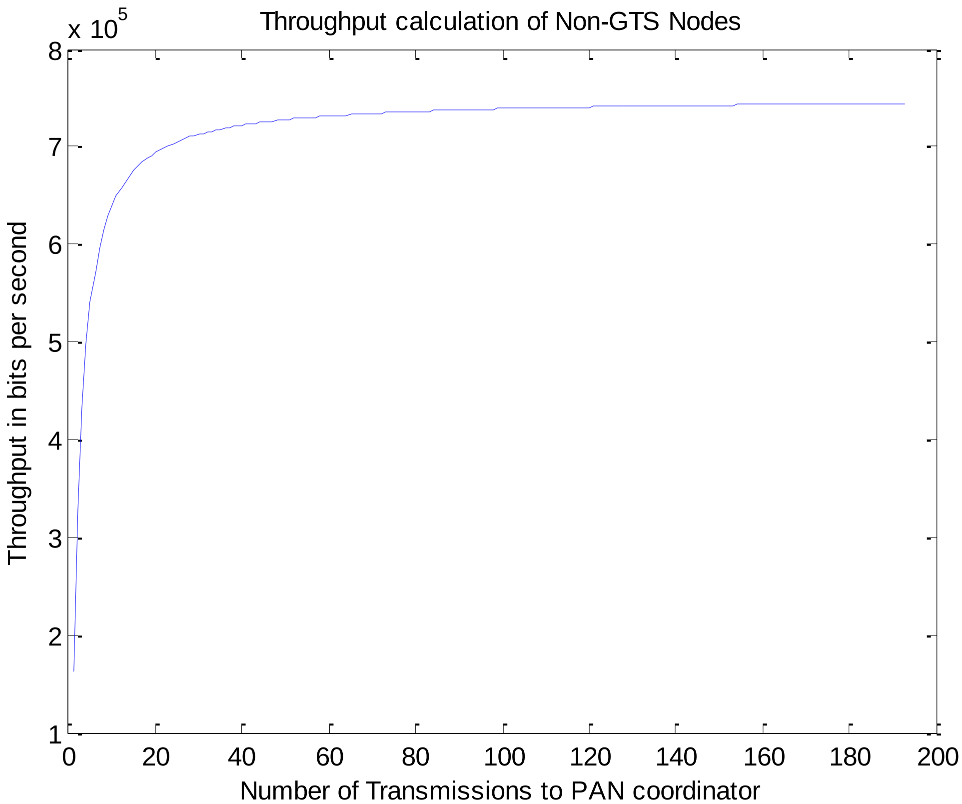


Figure 3-13 Throughput of non-GTS nodes

Throughput is calculated as

Throughput= (K*q)/ (Latency of overall network) ……………………………………(6)

In figure 3-13, Packet size at each iteration is incremented. It offers an optimized value of throughput of value 744.2 kbps at the data rate of 250 kbps. Results summary is shown in table 3-1.

Number of nodes / ***Performance Parameters***	***Node #1***	***Node#2***	**……………**	***200th Node***
Individual latency between nodes	2.72 ms	8 ms	…………….	66.24 seconds
Overall latency	2.72 ms	5.36 ms	…………….	22.02 seconds
Throughput	161.8 kbps	328.4 kbps	…………….	744.2 kbps

Table 3-1 Summary of GTS evaluation

3.8 CONCLUSION

Nodes transmitting in their respective GTSs took an optimum amount of latency to transmit. Devices don't need to wait like they have to wait and compete for slots during CAP. Also it ensures reliability and zero collisions. Throughput obtained is optimized at data rate of 250 kbps.

Using GTS mechanism reduces load on network a bit but this is not the case with non-GTS nodes.193 remaining nodes are competing for 9 slots available which caused latency of higher value than latency of GTS nodes. It is not sufficient for industrial requirement as latency of 22.02 seconds for complete round trip of non-GTS is still not appropriate. To overcome this issue, an efficient technique combining network coding and data aggregation titled NCAMAC (Network Coded-Aggregated MAC) protocol is proposed in chapter 4.

CHAPTER 4

NETWORK CODED-AGGREGATED MAC (NCAMAC) PROTOCOL FOR IWSN

Network is based on nodes. Nodes possess abilities like calculation, communication, incorporation or authentication. Nodes are battery powered and greater amount of energy is consumed in transmission/reception of information rather than processing. Energy cost needed to transmit one bit via radio is equivalent to thousands of instructions to be executed. Therefore, many researchers worked out on methods to find an optimal solution for power conservation. Aggregation is one of these techniques along with other techniques such as data compression, routing protocols, synchronization, scheduling etc. Network coding is a procedure to mix packets at coordinator nodes to reduce number of communications. These two techniques are combined in this chapter to attain low latency goal.

In this chapter, first, the description and literature review of aggregation and network coding is presented. Next, the performance is evaluated in comparison with Wireless HART.

4.1 AGGREGATION

Data aggregation is a smart method of data assembling in distributed system architectures. Sensor nodes utilizes battery , so it would be beneficial to find a solution to increase network lifetime by reducing data in size and removing redundant information. Figure 4-1 represents block diagram of data aggregation process.

Depending on data type, it is divided into temporal, spatial and semantic aggregation. Former two types are explained later in section. Semantic aggregation is defined as type of aggregation in which user is interested in certain conditions.

An author has exploited spatial correlation techniques and adaptation of work on bits to bytes. Sensors are mostly employed in environment monitoring in grid pattern and they observe a round area, so it is most likely that two sensors next to each other sense the same data. To reduce redundancy in data and to save power, it is proposed to exploit spatial correlation and devise a technique, they named as Data Aggregation exploiting Spatial Correlation (DASC). In this technique, reference value is hold at node and the received value is subtracted from the value. This will decrease the number of bits to be transmitted. Secondly, the bit aggregation technique (BAT) combines the bits from all the data in bytes to reduce the data. The unique decoder code is used to separate and decode data. Simulations showed that it reduces transmissions using DASC to 33% while combination with BAT reduces to 55%. On physical WSN, DASC simulation results showed 47% reduction and with BAT, it is reduced to 55%. Energy consumed to implement is less compared with gained energy[15].

WSN devices need not as much of power for processing than communicating data. It is ideal to do network processing within the network and reduce packet size. The primary objective of these procedures is to collect and aggregate data in packets in an energy efficient manner to increase network lifetime. Sensor nodes are grouped in large-scale sensor network to form clusters. Data aggregation in cluster based environment is used to combine and compress the data belonging to a single cluster with appropriate selection of cluster head. Data transmission occurs in multi-hop manner in WSN where each node sends its data to the node next to it closer to sink. Since closely placed nodes may sense same data, above approach cannot be considered as energy efficient. Certain aggregation algorithms are available such as centralized approach, LEACH (Low Energy Adaptive Clustering Hierarchy), TAG (Tiny Aggregation) etc. Aggregation helped to reduce data transmission [16].

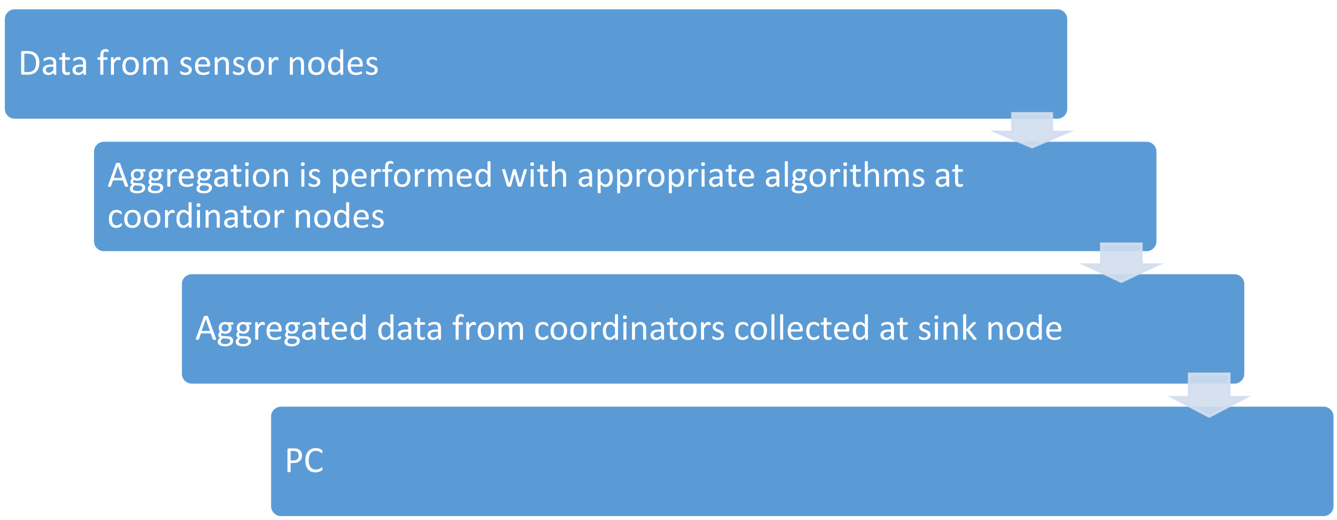


Figure 4-1 Block diagram of data aggregation

IWSN need to gather and optimize data periodically. Redundancy means duplicated data in same vicinity. It is favorable to have a highly redundant data collection to ensure data reliability, less errors to occur, security, accuracy and network lifetime.

It is divided into two types: spatial and temporal. Spatial redundancy refers to sense data based on position of sensor nodes. Temporal redundancy occurs with respect to time with checking of results, used to improve accuracy of readings and to tolerate temporary errors.

In [17], an algorithm OCABTR (Optimal Clustering Algorithm based on Target Recognition) is presented. The authors developed scheme on the concept of genetic algorithm to divide and collect together the neighboring nodes sensing similar data into one cluster and suppressing similar information. Communication cost due to cluster heads is reduced, enhanced network lifetime and higher throughput. They formed cluster first and then find cluster head after that, by considering residual energy and distances. Intra-cluster transmissions is reducing the whole energy cost of clusters considering special environment conditions. The process is divided into rounds which begin with a setup phase and steadystate phase. In setup phase, clusters are brought in ordered manner and in later phase, data transfer from node to cluster head and forwarded to BS.

Improving data aggregation results will decrease the energy consumed for cluster head for distant transmissions.

In [18], a Support Vector Machine (SVM) based Data Redundancy Elimination concept (SDRE: SVM based Data Redundancy Elimination for Data Aggregation in WSN) is proposed. A SVM is a concept of statistics and computer science related to supervised machine learning techniques for pattern recognition and data analysis. In proposed method, first an aggregation tree of appropriate network size is built. After that, SVM is applied to remove redundant information. The Locality Sensitive Hashing (LSH) is used to decrease redundant data and reduces wrong data received due to similarity. The LSH codes are further forwarded to aggregation supervisor node. Supervisor selects one node among nodes to send real data.

This approach reduces redundancy and reduces transmission of false data to improve performance such as delay, energy, packet drops and overheads, works a way better for different network sizes and fluctuating data rate. The supervisor eliminates outliers and does not accept data sent from other nodes.

In [19], authors proposed an optimal aggregator selection problem to reduce the data assemblage cost. Based on the Wireless HART standard, for IWSN, this problem has been sorted out using multi-objective network locality problem. Brute Force-Method is used for small scale networks. An approximate method OAGS is used for large scale networks to obtain the optimal result using the idea of independent set in graph theory. It did not only reduce collection cost but also provided a sensible programming algorithm. Simulation results indicated that the data assemblage cost is 30% lower than that of the data collection with arbitrarily placing aggregators. Moreover, the information accumulation cost was likewise affected by two elements: the number of aggregators and the area of the gateway. Yet, the last effects on aggregation cost delicately when the system size is substantial.

Limitation exists as it is proposed for a relatively small scale network and the algorithm is centralized.

In [20], authors calculated the influence of data aggregation and sink command communications on the performance of an 802.15.4 based wireless sensor network taking on a polling based data gathering procedure using the Contiki COOJA simulator, and also authenticating some of the results with the use of a testbed utilizing sky motes. Experiment was carried out for fixed sized network with 8 user devices with different values of the offered load, approximating network throughput and packet loss for all values of the offered load. Nodes arranged in a column communicates among themselves with less packet losses and high values of average throughput for offered load. Three techniques were discussed.

In first technique, user nodes generate and send data to sink.

In second technique, sink broadcasts a poll message to neighboring nodes and these nodes responds with data immediately as they receive message before sending to its neighbors. In this way, poll message circulates across the column.

In technique 3, it is same as 2 except that the poll message is sent to one of neighboring nodes and waits until it receives information from all the nodes on that side of network before sending the poll to other neighbor to receive the data from rest of nodes on other side of network.

It is concluded that technique 3 with data aggregation in a multi hop fashion to reduce transmission ranges and to minimize interference levels results close to other two techniques and with modified technique 3, it performs close to others for throughput, comes out to be the best selection for requirements of network.

Limitation of proposed design is, if the offered load is increased beyond certain point, congestion degrades modified technique 3 and adding sink commands also degrades a little due to added number of messages to be sent.

In [21], author proposed an enhancement based on the basic rule if the whole energy expended during this method can be reduced. Data funneling algorithm and ZELDA algorithm is used. Node density did not affect drastically the energy cost for setup in ZELDA. Energy dissipated during setup and discovery stays constant.

Superior energy efficiency can be achieved as compared to data funneling algorithm. Kalman filtering techniques are proposed for WSN.

In [22], an ant-colony based optimization based on in-network data aggregation in WSN is presented. An ant-colony algorithm is distributed in nature and exploring search space to optimize settings for an efficient data aggregation. In-network data aggregation reduces traffic in congestive networks by eliminating redundant data.

Authors refine heuristic functions and aggregation node selection procedure to maximize energy efficiency and increase network lifetime. They proposed some algorithms and discussed their effects on performance for hop count delay and network lifetime.

4.2 NETWORK CODING

Network coding was first conceived for wired networks to solve bottleneck issue and to increase network throughput. Broadcast nature of wireless links and diversity of links can best be exploited for network coding. It is classified as intersession network coding and intra-session network coding. In intersession network coding, packets from different sources are mixed to solve congestion issue. In intra-session network coding, diverse links are exploited and packets are mixed from same sources.

Explaining intersession network coding in detail, it is explained that broadcast nature is a source of interference and creates unwanted duplicates of data of same packet, but, if an intermediate node can code those packets, this nature becomes an opportunity. Intermediate node can simply XOR the packets and use further processes to decode those packets [23].

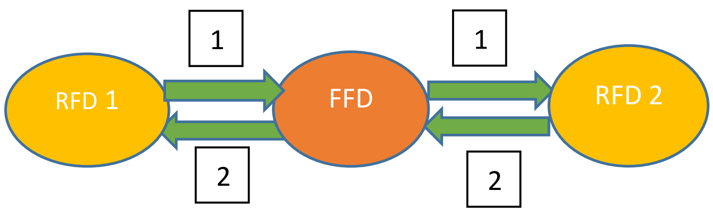


Figure 4-2 Communication without network coding

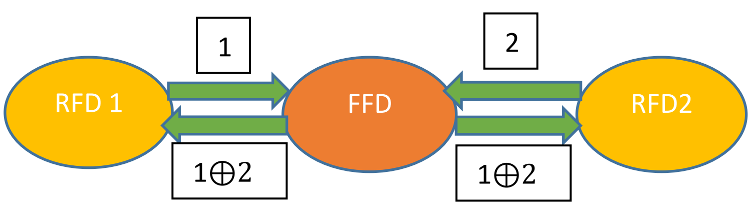


Figure 4-3 Communication using network coding

Figure 4-2 represents a block diagram for transmission of data without using network coding. Arrows show flow of transmissions. It is required four transmissions to exchange packets between these two nodes. First RFD’s packet is labelled as 1 and second RFD’s packet is labelled as 2.In figure 4-3, it is shown with simple XOR binary coding. FFD will perform XOR operation on both packets received from these sources and send them back to RFD1 and RFD2, where they XOR with their own packets to retrieve each other’s packet. Thus,in turn, reduces number of transmissions to three[23].

Explaining intra-session network coding, considering the reliability factor, it is first recommended to use feedback messages to provide reliability but this process consumes bandwidth without network coding as can be explained by an example.

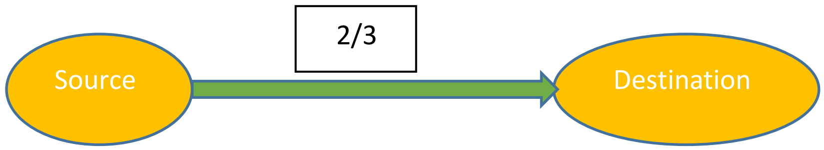


Figure 4-4 Intra-session network coding

Two packets p1 and p2 are generated from source and it is intended to transmit it to destination node with reliability factor 2/3 as shown in figure 4-4, in case, where source node generated p1+p2, p1+2p2 and 2p1+p2. As for optimum consideration of network coding, destination node receives two of three coded data packets and retrieves p1 and p2 using Random Linear (RL) network coding. If we have used the above scheme without network coding, we have to employ a feedback mechanism and each packet needs to send twice. Thus, it can be concluded that network coding provides communication with fewer transmissions [23].

Certain limitations apply to wireless sensor network when it comes to network coding. WSNs have limited memory and it is not possible to store data in them as some of the proposed approaches required overheard data from neighbors to be cached. Let's take a look at few approaches [23].

COPE is conceived to increase throughput. Unicast traffics used to be dynamic and bursty flows. COPE is an intersession technique and it is based on three procedures: opportunistic listening, opportunistic routing and learning neighbors state [23] . Due to short size of WSN memory, COPE cannot be applied and another factor is too much broadcasting, which consumes power, making COPE inappropriate for WSN.

Centralized approach is considered as a cross-layer methodology. Far away communication results in reduced interference whereas close paths increase coding opportunities. Again, overhearing makes it inappropriate for WSN [23].

Network Coding Aware Queue Management Scheme at Intermediate Nodes (NCAQM) is an intersession technique and stores coded packets and drops packets based on congestion information and network coding. MAC or TCP are preserved, making it a practical approach. It is inappropriate for WSN because it is not common in WSNs to have bursty flows [23].

CLONE approach is an intersession technique and is loss aware network coding process. Intermediate nodes in CLONE uses redundant data to increase and ensure delivery of data packets by achieving a given threshold at next hop. It is not ideal for WSN due to its computational complexity [23].

Flow based approach is an intersession technique and considers flow only, not considering individual packets. Overhearing is optimized and capacity region is described using linear equations [23].

MORE is an intra-session technique and opportunistic routing using random linear network coding for unicast and multicast applications. Opportunistic routing allows any node that overhears the transmission and closer to the destination node, to forward the packet. Due to energy consumption, it is not suitable for WSN [23].

CCACK is an intra-session technique where nodes uses collective coded acknowledgements that allows nodes to acknowledge the coded received packets to the upstream nodes utilizing a single compressed feedback message with almost zero cost. It is not suitable for WSN [23].

MIXIT uses arbitrariness for network coding and a dynamic programming algorithm for solving coordinator problem. MIXIT may be applicable in WSNs to deliver data to sink nodes. Data from different sensor nodes can be coded together to improve throughput [23].

CODEB is an intersession broadcasting technique. Network coding is combined with deterministic forwarding and it is shown that network coding helped in reducing number of transmissions. Because of overhead, it is inappropriate for WSN [23].

Directional antenna attached with node makes the node capable of dividing the omni directional area into different sectors and turn a subset on for a transmission. It can be used for WSN but not realistic as the links are not reliable [23].

Deadline aware method is weight based approach, weights and deadline of packets are proportional to each other. A greedy algorithm is used to find maximal clique using a weighted graph. This can be used in WSN due to simplicity and low computational complexity based on XOR [23].

One hop algorithm is conceived for broadcast applications. First, it finds the destination with greater number of lost packets, to a different coding set. This approach can be applied for software updates of sensor node in single hop WSN [23].

Relay aided algorithm is used for broadcast applications based on assumption that links are lossy. Transmissions occur from base station to relay and from relay to users (destination) channel. It works better than to communicate from base station to user directly. It works in three phases:

1: Packets are transmitted from base station to relay and user node. A feedback message from relay is sent to base station. .
2: User node sends feedback to inform the base station and the relay node about received data packets by the user nodes. BS (Base Station) uses network coding to increase efficiency.
3: Relay node performs retransmission. .

It is suitable for transmission from BS to sensor nodes [23].

For multihop broadcast, an author used adaptive network coding where they have taken into consideration linear network coding to decrease traffic in WSNs resulting in an increase in lifetime of the sensors.

In duty code approach, network coding is combined with duty cycle. Network coding increases lifetime by using broadcast nature and overhearing, while duty cycle reduces idle listening which reduces overhearing. Nodes turn part of the system off to save energy [23].

In [24], authors proposed a protocol titled XOR-CoW. It has been evaluated by using a communication, theoretic, delay-limited-capacity structure and then comparing it to different realizations of previously available protocols without network coding. Network coding, along with cooperative technique, is used in XOR-CoW to achieve QoS requirements same as wired field bus systems to attain high throughput and low latency. It is stated in paper that as the network size increases, XOR-CoW benefits in attaining lowest SNR to attain the required latency. SNR attained is better than original occupy CoW algorithm. A case is considered for industrial printing application where 30 nodes were used in the control loop, overall throughput of 4.8 Mb/s, 20MHz of bandwidth and cycle time under 2 ms is achieved, the protocol can strongly attain a probability of error better than 10−9 with a negligible SNR less than 2 dB with rayleigh fading. Relays simultaneously broadcast downlink and uplink packets by XORing them. In the Occupy CoW structure, node that is potentially capable of helping inaccessible nodes attempts to serve whereas, in the innovative XOR-CoW structure, only those nodes having proper links to the nodes, that wants to communicate, serve and guarantee effective use of resources in the network. It also decreases noise. For network size of nodes ($n \geq 25$), SNR penalty of ≈ 3 dB is achieved. Like Occupy CoW protocol, XOR-CoW does not depend on seamless information too, of intense fading and attains maximum reliability by counting on the independence of link failures.

In [25], authors claimed that their paper (published in year 2012) offer the first idea to implement a two-way relay architecture established on the idea of Physical-Layer Network Coding (PNC). Till that time, only a basic version of PNC, Analog Network Coding (ANC), has been effectively carried out but drawback is that relay node amplifies noise along with signal. They examined a PNC implementation in the frequency domain, they called FPNC, to confront these challenges on software radio platform. PNC can be applied in a system with two nodes and one relay node. Without PNC, four transmissions are required but with PNC, it is reduced to two and this will also help in increasing throughput. In first slot, both nodes transmit to relay node simultaneously and in second slot, after processing and mapping their data on network coded packet, it is broadcasted back to two nodes. It is OFDM (Orthogonal FDM) PNC system. They conducted experiment over 802.11g with central frequency 2.412 GHz for time synchronous FPNC (PNC implementation in frequency domain) and time asynchronous FPNC. XOR mapping is done in frequency domain. FPNC, while compared with PNC in time domain, reveals a benefit that FPNC can work with the different arrival times of the signals from two end nodes in a regular way. They derived that if the simultaneously received signals in FPNC have an extreme delay less than the duration of the OFDM Cyclic Prefix (CP), then applying Discrete Fourier Transform(DFT) , the frequency-domain signals on the different subcarriers are independent from each other. In frequency domain, the signals are synchronized. Next, XOR mapping can be used on different subcarrier signals separately in a separate manner. Advantage of FPNC is showed by experimental results that performance degradation in FPNC is not caused by time-domain symbol asynchrony.

In [26], a physical layer network coding (PNC) technique, based on exploiting additive nature of simultaneously arriving EM waves rather than working on bit streams to support communication among nodes, is presented. This produces higher network capacity in wireless networks. Interference can be exploited to increase throughput. Relay node had to process the information and destination node should be able to extract required information. Half-duplex transmissions are considered so transmission and reception occurs in different time slots and based on decode and send approach. A frame-based communication is used where time slot is the time required for the transmission of one fixed-size frame. Each node is embedded with an omni-directional antenna. They considered a case with two nodes, and one relay node, forwarding their packets to each other. Without network coding, they need four slots to communicate. With straight-forward network coding with XOR operation, slots reduced to three. Now with introduced PNC, they assumed for all nodes, the QPSK modulation and also assumed carrier-phase and symbol level synchronization. Power control helps frames, from sending nodes to reach relay node, with same amplitude and phase. For reliable extraction of information, they introduced the concept of PNC mapping for modulation/demodulation of signals. For the same bit error rate (BER) performance, frame exchange in 802.11 needs four slots, straight forward network coding requires three slots and PNC requires two slots for three node network. The overall system throughput increases using PNC by a factor of 100% and 50 % relative to traditional transmission scheduling and straightforward network coding, respectively. Throughput obtained by PNC in a linear multi-hop network is that of the theoretical upper-bound throughput". Packet errors can be reduced using PNC at 802.11.

In [27], according to best of author's knowledge, they proposed a novel approach for collection protocol relying on network coding titled SenseCode. Their approach is to include redundant information to increase reliability but packet loss also occurred. It enables a new form of multipath communication, where each node broadcasts data through all available routes, without having to explicitly determine these routes and without having to maintain multiple routing configurations. They also took memory and processing limitation of sensor networks into consideration and utilized simple , distributed algorithms to achieve improved reliability at low cost. It was implemented in TinyOS and evaluated on TOSSIM. By experimental results, it is concluded that improved robustness is obtained without additional control information and slight modifications in existing protocols. SenseCode provides a substantial improvement of reliability as compared to available effective approaches.

In [28], An author proposed an Orthogonal Physical Layer Network coding (OPNC) with the distinguishing feature used to separate information of two users at relay with no interference. Conventional Link-layer Network Coding (LNC) has less throughput than conventional Physical Layer Network Coding (PNC) but with PNC, interference occurs at relay node as the information is not easily distinguishable. OPNC is proposed to resolve this issue. It is concluded that OPNC achieves 3 dB better BER than conventional PNC. Complexity of OPNC is same or lower than conventional PNC because OPNC performs hard decisions at receiver and conventional PNC performs difficult computations using minimum distance rule.

Taking into consideration the latency requirement of industry that is mentioned in [6], factory automation, conveyors etc. typically necessitates a huge number of sensors/actuators monitoring a system. These applications have very low requirements for latency (transmission of data in 5-50 milliseconds and low round trip of network).

A combination of network coding and data aggregation is presented here to improve performance as shown in figure 4-5.

4.3 BLOCK DIAGRAM

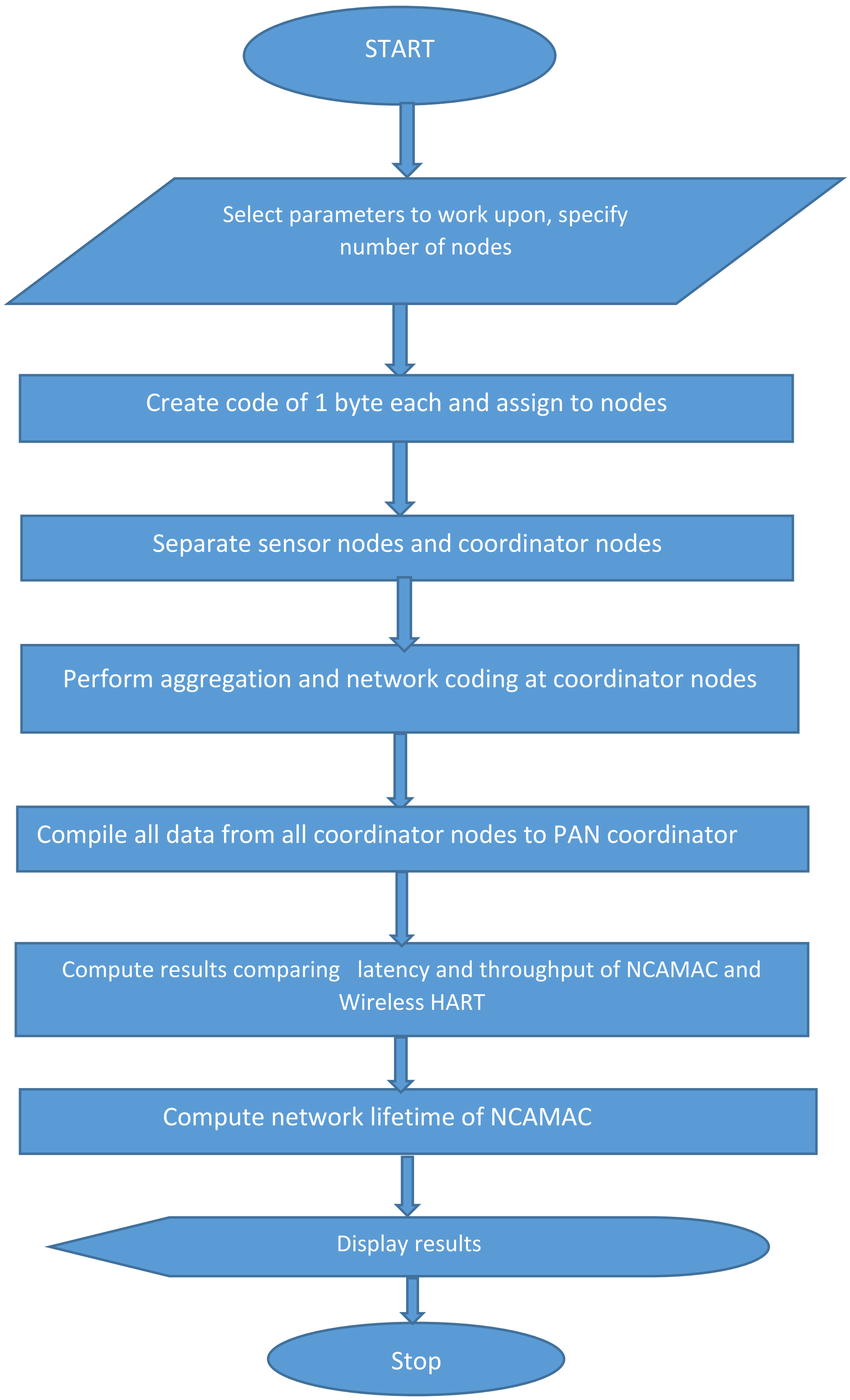


Figure 4-5 Block Diagram of NCAMAC

4.4 PSEUDOCODE FOR NCAMAC

```
Set nn        // Number of nodes
Set R          //Data rate
Initialize queueing delay to zero
loop 1
compute binary code for each node
endloop1
loop 2
Initialize node counter selecting three sensor nodes and one next to it as a coordinator node
Get generated code from list to each node
Generate frame from data collected from three nodes
Increment node counter
if node counter≥specified value
break
endif
Compute Coded packets and retrieve them using XOR coding
Remove redundant data
Accumulate in a single packet
Increment counter till reached final value
Store in a compiler
Make a logical decision on temperature values
end loop2
Display compiled result
Compute S1  // network coded packet size in bits
loop 3         // Latency and Throughput
Compute latency
Compute throughput
Increment counter
Increment queueing delay
endloop3
```

Display latency

Display throughput

// Calculation for network lifetime

Compute field dimensions,probability to become cluster head,packet length and some other parameters

Compute do

Generate a random sensor network

Initialize count for cluster head

loop4

for maximum rounds

Compute operation for epoch

endfor

Initialize count for bits transmitted to cluster heads and to base stations per round

Initialize dead nodes to zero

loop5

if dead node==true

Increment dead node

endif

if dead node==nn

break end if

endloop5

Compute statistics

Compute first node died

loop 6

Select cluster head

Compute distance,distance broad,energy dissipated

Increment packets to base station

Store packets in each round

end loop6

loop7

Compute election of associated cluster head for normal nodes

Compute energy dissipated by associated cluster head

Compute energy dissipated

endloop7

end loop4

Display network lifetime

4.5 RESULTS

The simulation setup is constructed using MATLAB 2013a.The setup is composed of a network of 200 nodes with clustering where each cluster is formed using star topology. It is based on assumption that packet error rate is zero as coded packets are used. As mentioned in [30], with coded data packets, no or fewer collision occurs in the network.

Latency is the major performance parameter of any system, specifically speaking for industrial environment, it's very important. That's why, we have selected the goal of this thesis to devise a methodology to achieve low latency among nodes with low round trip time and providing optimal throughput. Here it is explained and evaluated in detail.

Latency in a system may cause equipment damage and put lives at risk if not properly monitored in a timely manner. Latency requirements vary from application to application. Some applications require the system to respond in milliseconds, some requires seconds while other applications require monitoring at interval of minutes or even hours. For industrial application, it requires as mentioned in [6], it has very low requirements of latency (transmission of data in 5-50 milliseconds and low round trip of network.). That's why, the system adopted should counter the delay issue at first place as there is no room for making mistakes in monitoring those valued equipment.
Several state of the art protocols are proposed up till now and few of them are already addressed in chapter 1. They are providing promising solutions to industrial environment but some of them are providing these solutions at the cost of complexity. Complex routing algorithms make system to introduce unnecessary latency. Also redundancy helps in attaining reliability but again, unnecessary transmissions will incur more power consumption and introduce latency.

Wireless HART, as discussed in chapter 1, is a state of art protocol that can support 30k devices, real time but inherently complex as it supports mesh. It can also work with star topology but graph routing makes it complex, as mentioned in [30], latency got increased due to graph routing ,multi-channel, channel blacklisting to name a few. Proactive routing algorithms are used and it needs setup and scheduling time. Separate transmissions from different sources causes delay.

Graph routing bring high reliability but causes long delays and energy consumption. WHART also got some extra overheads problems and limitations in industrial networks. Also, if network manager fails, it takes down the whole network. Although a backup router is allowed but at a time, only one can be activated as discussed in chapter 1. Research illustrates that routing in complex network topology is subject to data packet loss but network coding can be used to overcome the limitation to secure the data via encryption and also avoids collision by minimizing the network congestion. Slot size is equal to 10 ms regardless of data size. More source node generating more packets requires more slots to transmit fragmented packet of each node.

Network Parameters	**Value**
Number of Nodes	200
Number of coordinator nodes(FFDs)	67
Number of source nodes(RFDs)	133
Data rate	250 kbps
Packet size	32 bytes
Super frame duration	15.36 ms
Slot duration	0.96 ms
Simulation time	20 seconds

Table 4-1 NCAMAC parameters

Network Parameters	**Value**
Number of nodes	200
Data rate	250 kbps
Packet size	55 byte
Slot duration	10 ms

Table 4-2 WirelessHART parameters

Table 4-1 and 4-2 summarizes network parameters of NCAMAC & WirelessHART respectively.Now working with these parameters, comparison of WirelessHART and NCAMAC is given as follows:

4.5.1 LATENCY AND THROUGHPUT RESULTS OF 802.15.4 & NCAMAC

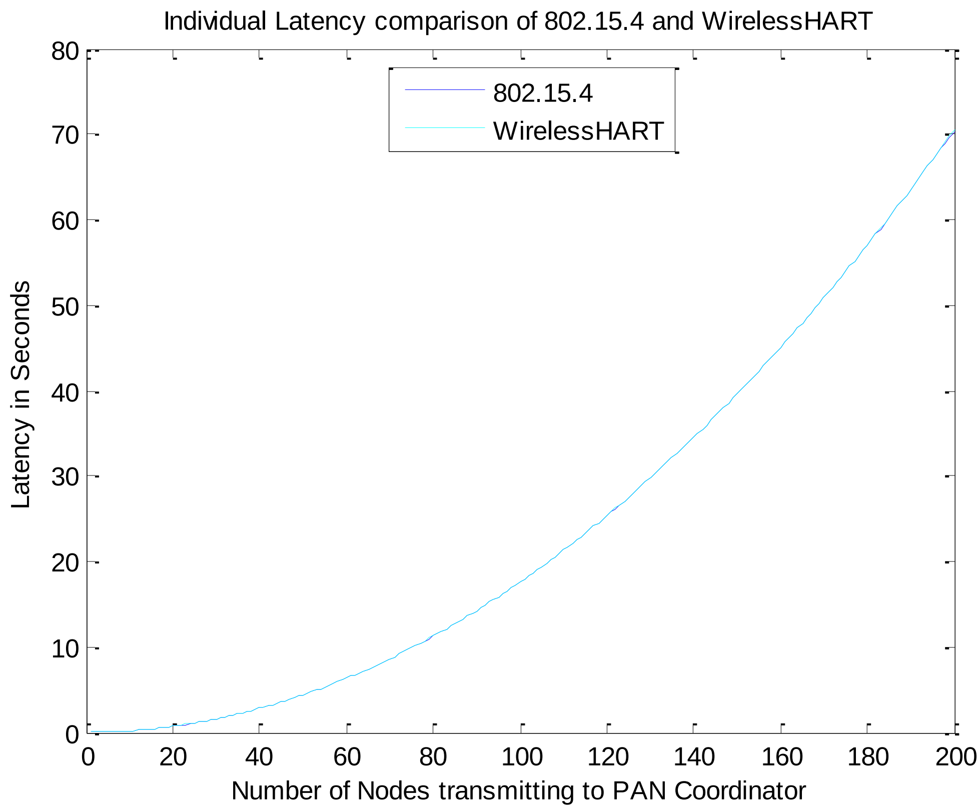


Figure 4-6 802.15.4 and WHART individual latency comparison

First, the general comparison for 802.15.4 and WirelessHART is given. Sensors are RFDs while coordinators are FFDs. All of the computations (aggregation and network coding) is performed at coordinator. With no coordinator in between, complete iteration for 200 nodes need to be computed as shown in figure 4-6. Latency is being calculated around 70 seconds using formula (4) given in chapter 3.

Latency= ((K/d)*q) +0.00096

Where K=Packet size

d=data rate

Slot duration= (15.36 ms/16) = 0.00096 seconds

802.15.4 encounters interferences and unbounded delays due to CSMA/CA algorithm for accessing slots during Contention Access Period(CAP). WirelessHART is 802.15.4 based protocol so, it produces almost same results.

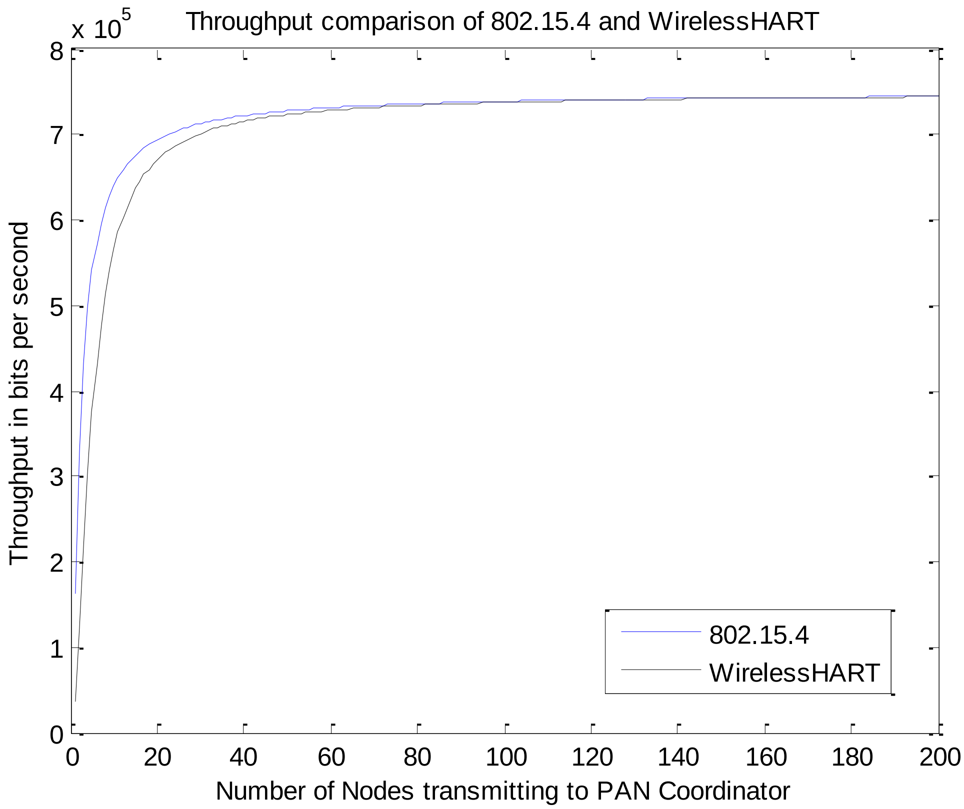


Figure 4-7 802.15.4 and WHART throughput comparison

Throughput offered by both protocols is optimized and is almost same i.e .around 721 kbps at data rate of 250 kbps as shown in figure 4-7. Packet size is incremented at each transmission. Calculation is done using formula (6) from chapter 3 and taking latency of overall network from result of figure 4-8.

Throughput= (K*q)/ (Latency of overall network)

802.15.4 is conceived for limited battery life and optimized throughput. With this maximum throughput achieved, it is needed to find an optimal solution to enhance network lifetime.

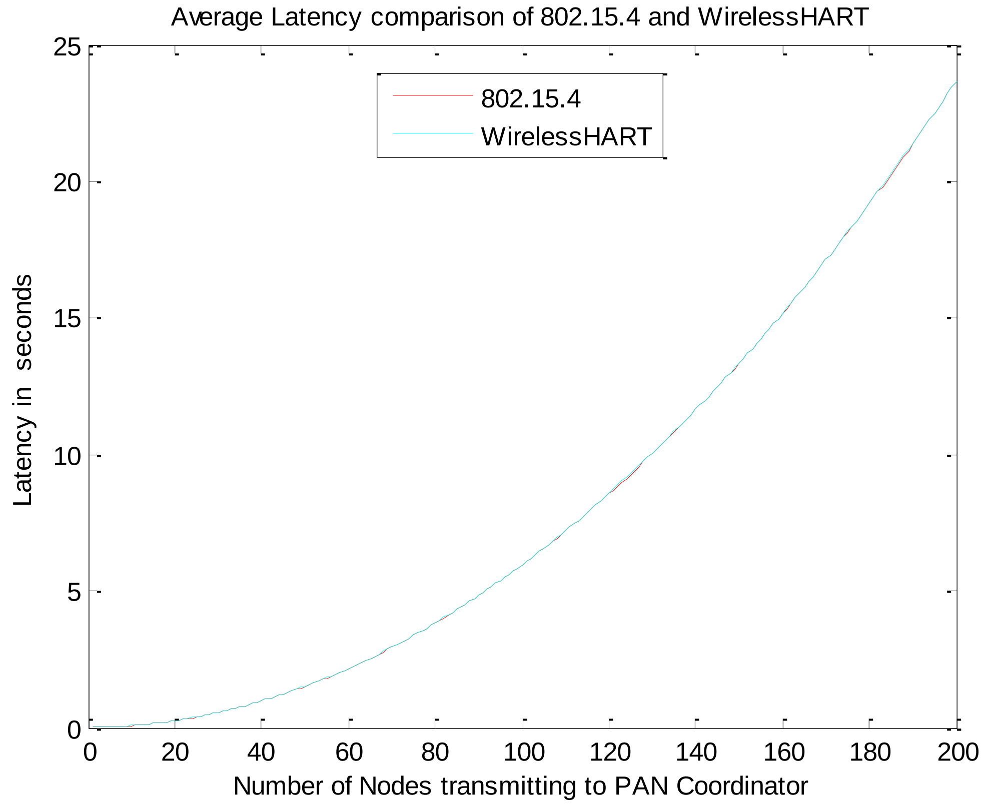


Figure 4-8 802.15.4 and WHART average latency comparison

With no coordinator in between, average latency is around 23 seconds , calculating using formula(5) from chapter 3, for complete round as shown in figure 4-8. 802.15.4 is slightly lower at some points than WirelessHART due to large slot size of WHART.

Latency of overall network=Average (Latency)

WHART supports proactive routing taking more time for setup and scheduling of network. Transmission from different nodes separately causes to increase the latency of WHART. NCAMAC works on star topology with 802.15.4 super frame structure of 16 slots .

Now, for the case where coordinator in between is aggregating the data received from sensor nodes, the number of iterations are being reduced to 133 .Evaluating this, we get the following results:

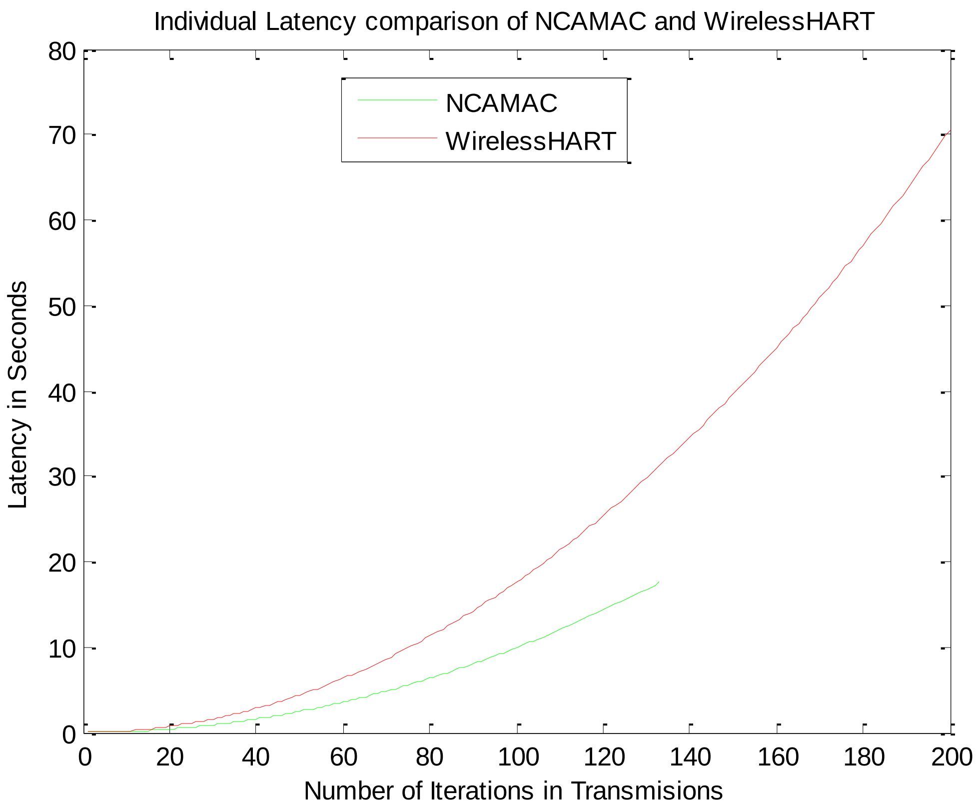


Figure 4-9 Impact of reduction of iterations on NCAMAC latency

Latency is being calculated around 17 seconds reduced from previous case as shown in figure 4-9. Number of packets are incremented at each iteration whereas aggregation and network coding combined to reduce packet size by removing redundant data and reduced number of transmissions with reduced packet size. Rest of the detailed explanation is given in explanation of figure 4-11.

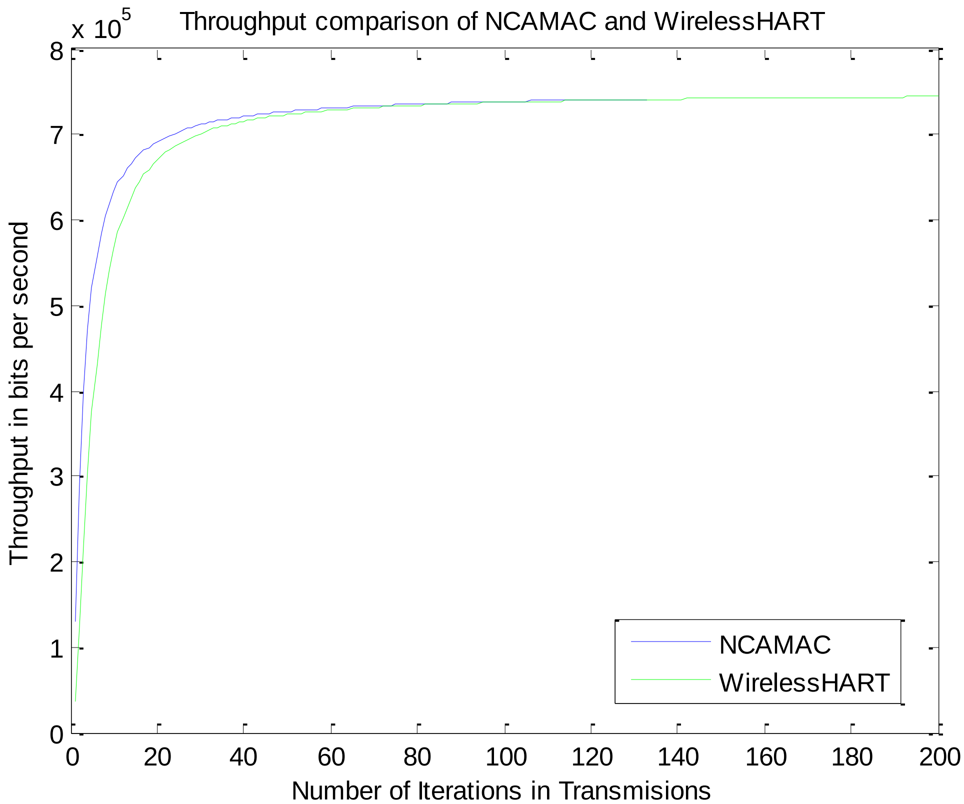


Figure 4-10 Impact of reduction of iterations on NCAMAC throughput

Industrial application requires an optimized throughput for monitoring promptly. WHART,having large slot size with greater number of bytes should generate a higher throughput than NCAMAC but due to collisions, retransmissions and packet losses, it generates almost same or slightly lower throughput as NCAMAC as shown in figure 4-10. NCAMAC uses coded packets. Initially, with no collisions, it provided a higher throughput for small scale networks but due to few collisions for large scale network, it is providing an optimized throughput with less transmissions.

Throughput is calculated as shown in figure 4-10 using formula (9).

In figure 4-10, packet size at each iteration is incremented. It offers an optimized value of throughput of value 721 kbps at the data rate of 250 kbps.

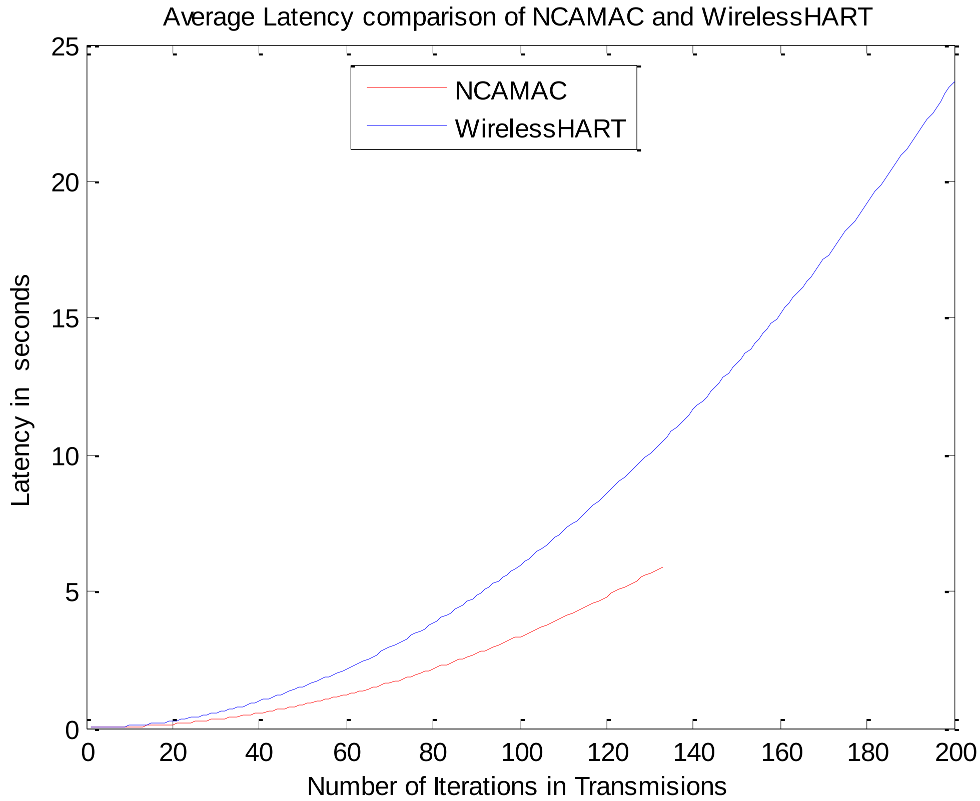


Figure 4-11 Impact of reduction of Iterations on NCAMAC average latency

Latency results of both protocols are presented. Latency of NCAMAC is found to be much lower than WirelessHART. The major reason is complex routing algorithm of WHART i.e. graph and source coding. Generation of graph and source coding, making tables, updating those tables at each node and allocation of channel and slot for communication introduces delay in system. Proactive routing requires additional time for network setup and scheduling. WHART works on TDMA introduces large delays with fixed slot size of 10 ms, irrespective of data size. More slots are required to transmit fragmented packet of each source and more data packets are generated. Transmission of data from different sources separately contributes in latency.

Whereas, for NCAMAC, optimized clusters ,using star topology with simple routing ,are formed with three sensor nodes and one coordinator node .Each node has its own ID and data packets are coded so no or fewer collisions occur. Data packet size got reduced using aggregation and network coding and communication occurs with less transmissions. This contributes in decreasing latency of overall system to level of required industrial level as shown in figure 4-11. Data packets and queueing delay is updated at each iteration in both protocols but reduced packet size,short duration slot(0.96 ms) and less number of transmissions of NCAMAC offers low latency as compared to WirelessHART.

Using parameters given in table 4-1 and 4-2 ,simulation is performed as follows:

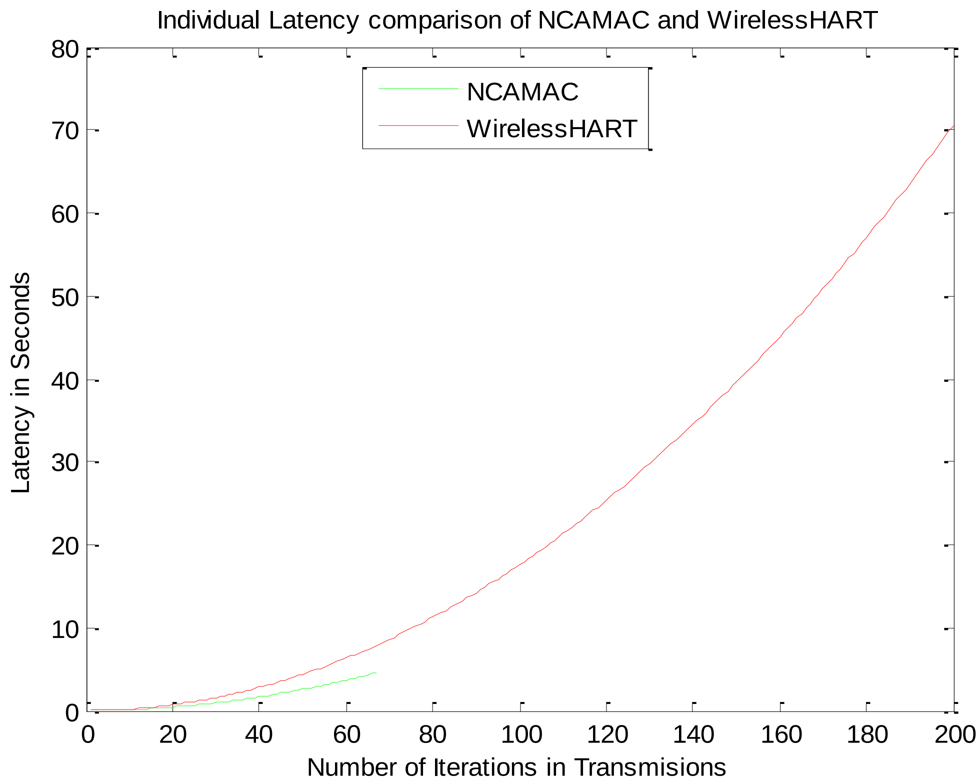


Figure 4-12 Individual latency comparison of WirelessHART and NCAMAC coordinators

In figure 4-12, with reduced number of transmissions using network coding and data aggregation and small packet size, the latency between two coordinator nodes is calculated as

$$\text{Latency} = ((K/d)*q) + 0.00096 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (7)$$

Where K=Packet size

d=data rate

Slot duration= (15.36 ms/16) = 0.00096 seconds

q and K are updated at each iteration as mentioned in pseudocode and shown in figures. The queueing delay for first packet is 0(q=0); Second one has to wait till the first one is completely transmitted with data rate(d) of 250 kbps i.e (K*8)/ d seconds. Delay for third packet becomes (2*k*8)/d as it gets to send after first 2 are sent and so on. Latency is calculated as around 5 seconds. Rest of the explanation is given in explanation of figure 4-13.

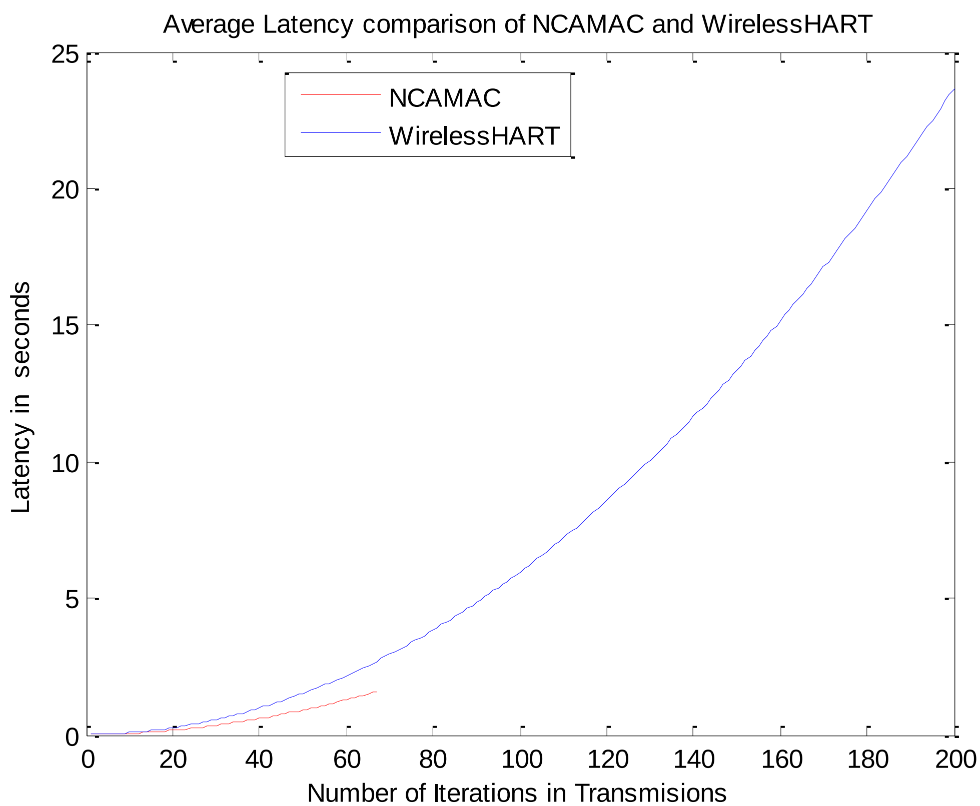


Figure 4-13 Average latency comparison of WirelessHART and NCAMAC coordinators

The overall average latency is calculated as shown in figure 4-13 using

Latency of overall network=Average (Latency) ……………………. (8)

Latency of network is calculated as 1.592 seconds.

Latency experienced by coordinators is calculated. Sensors are RFDs while coordinators are FFDs. All of the computation/processing is performed at coordinator. Three sensor devices send their data to coordinator making cluster that are organized in star topology . After data aggregation and network coding, packet size got reduced and number of transmissions become less, resulting in low value of latency as shown in figure 4-13. All coordinators send their data to PAN coordinator.

WirelessHART offers a high latency due to complex routing algorithm i.e graph routing which requires making tables and updating those table causing delay in communication. Network setup and scheduling time in proactive routing also causes delays. It works on TDMA with slot size of

10 ms, regardless of data size , contributing in high latency of system. Also, transmission of data from different sources separately causes to increase latency.

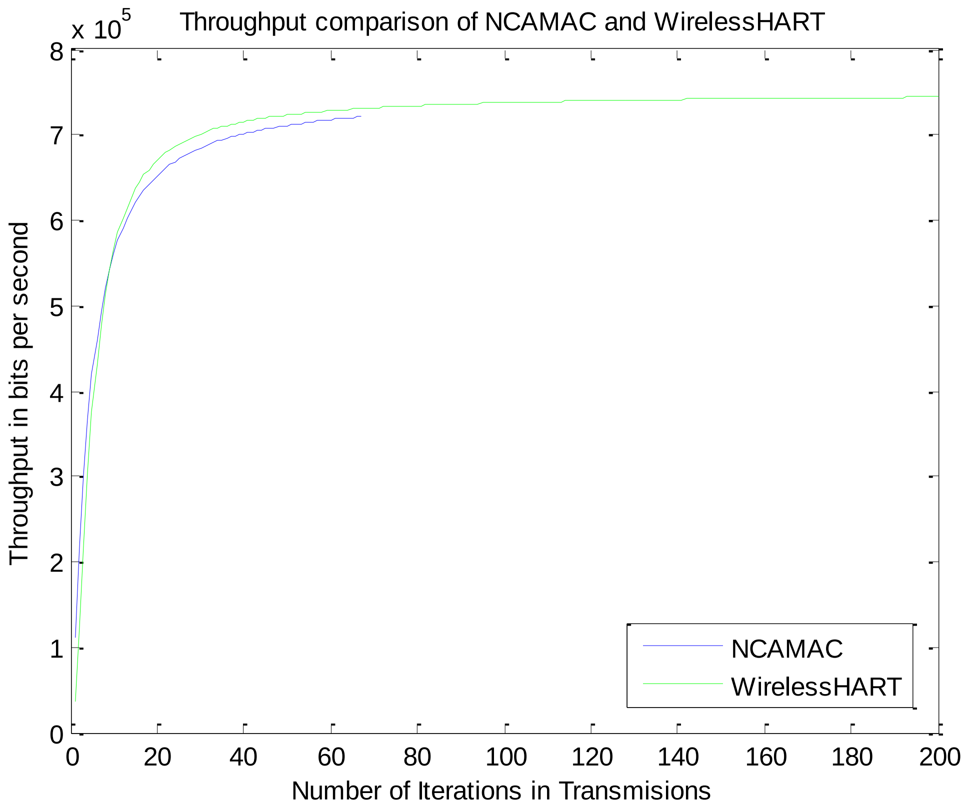


Figure 4-14 Throughput comparison of WirelessHART and NCAMAC coordinators

Throughput is calculated as shown in figure 4-14 as

Throughput= (K*q)/(Latency of overall network) ……………………………………(9)

In figure 4-14, Packet size at each iteration is incremented. It offers an optimized value of throughput of value 721 kbps at the data rate of 250 kbps.

To communicate promptly, throughput need to be optimized. WHART, having large slot size with greater number of bytes should generate a higher throughput than NCAMAC but due to collisions, retransmissions and packet losses, it generates almost same or slightly lower throughput as NCAMAC as shown in figure 4-14. NCAMAC uses coded packets. Initially, with no collisions, it provided a higher throughput for small scale networks but due to few collisions for large scale network, it is providing an optimized throughput with less transmissions. Coordinators collects data from three sensor nodes and after data aggregation and network coding,they send them to PAN coordinator with reduced size. Coordinator helped sensor devices to communicate their data with fewer transmissions resulting in low latency.

4.5.2 NETWORK LIFETIME OF NCAMAC

It is the amount of time during which a network is completely in working state. Another definition is, it is the time at which the first node dies. It is also possible to use a definition that some nodes are working and some are died[32].

For calculation of network lifetime, an author's code[29] is used with few changes.

Parameters	**Values**
Number of nodes	*200*
Data aggregation energy	$5 * 10^{-9}$ joules
Initial energy	0.5 joules
Etx	$50*10^{-9}$ joules
Erx	$50*10^{-9}$ joules
Efs	$10*10^{-12}$ joules
Emp	$0.0013*10^{-12}$ JOULES
Probability of cluster head	0.0597

Table 4-3 Network lifetime's simulation parameters

Using network coordinators reduces number of transmissions from 200 to 133. Using network parameters given in table 4-3 with 133 transmissions, network lifetime is evaluated as follows:

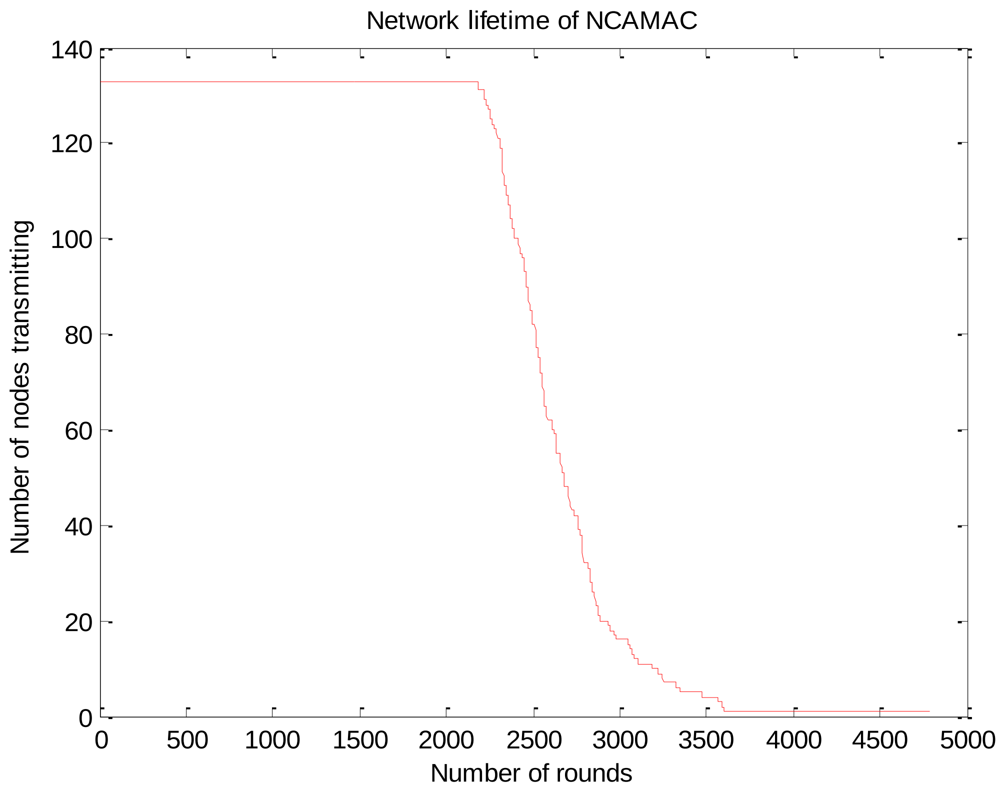


Figure 4-15 NCAMAC network lifetime

Sensor nodes are battery powered and for an industrial network, the nodes should provide an efficient network lifetime. Most of the energy is consumed in transmissions, causes the nodes to run out of battery. Additionally, collisions and retransmissions causes to loss power. Complex routing schemes lead to packet losses due to collisions. For NCAMAC, we have used network coding and data aggregation to reduce packet size and decrease number of transmissions. Since packets are coded, no or fewer collisions occur.

Simple routing scheme with star topology and cluster construction with three sensor nodes and one coordinator node for each cluster helped to reduce losses .Reduced packet size and very low rate of retransmissions saves energy and enhances network lifetime as shown in figure 4-15.

In figure 4-15, it is clear that first node died around 2400th round. Distance between consecutive nodes is calculated as 3.15 m.

It is an optimized value achieved beneficial for industrial environment. The coordinators have a reduced data packet containing data of its RFDs (sensor nodes) processed at coordinators using network coding and data aggregation. Each node has its own ID, so no or fewer collisions occur. These coordinators are transmitting data to PAN coordinator.

Summary of latency and throughput results are given as under:

- Latency results for Wireless HART and 802.15.4(without using network coding and data aggregation) are compared. Due to collisions and retransmissions and some other causes as discussed, they are producing average latency of high value around 23 seconds.

- Throughput is found to be of optimal and high value as 802.15.4 is conceived for maximum throughput applications. Value is around 721 kbps.

- Latency results of NCAMAC sensor nodes are presented using network coding and data aggregation. Reduced packet size and reduced number of transmissions helped to attain low latency goal and provided an average latency of around 5 seconds.

- With reduced packet size and less transmissions, throughput achieved with NCAMAC is almost equal to Wireless HART i.e. around 721 kbps.

- Evaluating latency of coordinators separately, it is found be around 1.592 seconds.

- Throughput of coordinators, calculated, is same as around 721 kbps.

4.6 CONCLUSION

In this chapter, a complete overview of data aggregation and network coding techniques is presented. Also review from papers is included on both topics. The goal of this chapter is to devise a methodology to attain low latency and optimized throughput with optimized network lifetime.

To achieve this, a combination of data aggregation and network coding techniques is used and a novel algorithm is produced titled NCAMAC. Data aggregation technique removed redundant data and network coding technique helped to reduce number of transmissions. Optimized clusters are formed using star topology with three sensor nodes as RFDs while a coordinator node processing the data as FFD. Coordinator node is responsible for data aggregation, network coding, synchronization and relaying data to PAN coordinator. NCAMAC is compared with state of the art Wireless HART protocol.

Results have shown that NCAMAC produces far better results than Wireless HART. Latency obtained using NCAMAC is much lower than WirelessHART .This is due to complex routing scheme, channel blacklisting, HART specific field devices of Wireless HART that contributes in high value of latency whereas NCAMAC is based on star topology with optimized cluster size.NCAMAC is based on simple algorithm with XOR coding. Reduced number of transmissions in NCAMAC helped to attain low latency.

CHAPTER 5

LOW LATENCY MAC (LLMAC) PROTOCOL FOR INDUSTRIAL WIRELESS SENSOR NETWORK

5.1 BACKGROUND

To counter latency issues, we first evaluated generally the performance of 802.15.4 GTS mechanism as described in chapter 3 but it did not provide sufficient improvement. To improve the performance, a novel protocol NCAMAC is proposed in chapter 4 in which it is evaluated how the coordinators can be used in transmission with network coding and data aggregation techniques to attain low latency.

To further improve the results, a novel protocol, Low Latency MAC (LLMAC) protocol is proposed using NCAMAC along with GTS mechanism of 802.15.4 to achieve minimum latency and optimized throughput. Packet size got reduced by using data aggregation (DA) merging packets from 3 nodes and send them to coordinator node to remove redundant bits. Network coding (NC) is used which further supports for less number of transmissions. GTS feature reserved 7 slots for seven devices in a super frame of 16 slots and rest of 9 slots are free for other non-GTS nodes with each slot size equals to 0.96 ms . NCAMAC is applied on those free non-GTSs. Figure 5-1 represents a block diagram of LLMAC process.

Rest of the details are included in forthcoming sections.

5.2 BLOCK DIAGRAM

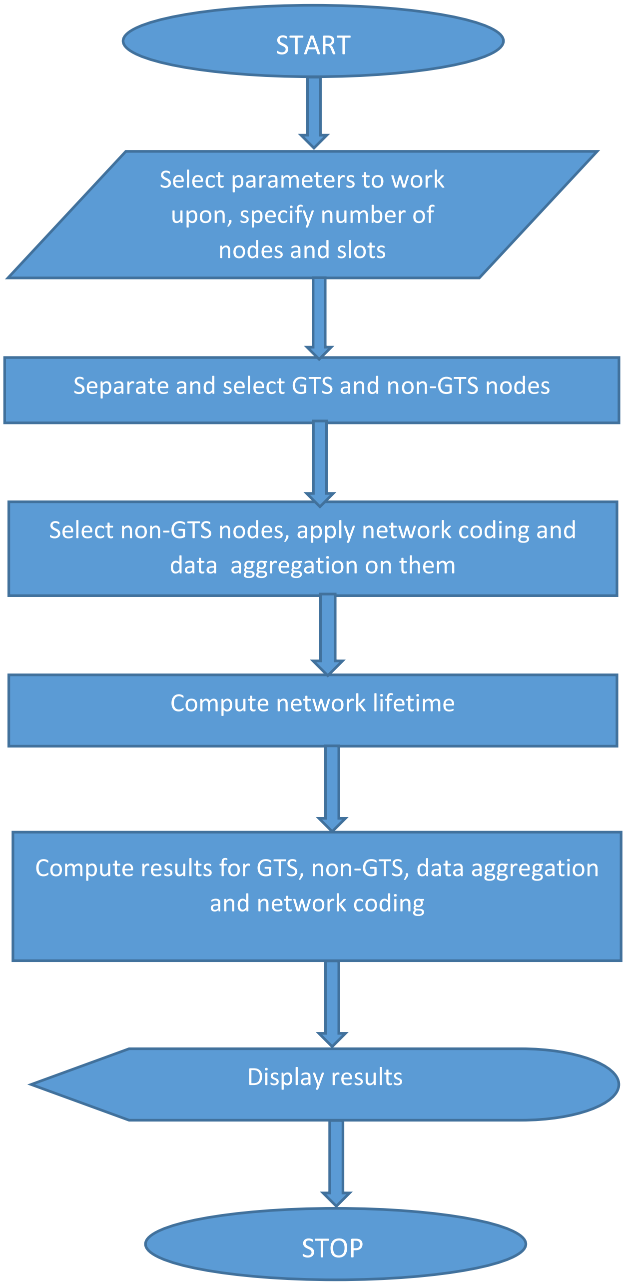


Figure 5-1 Block diagram of LLMAC

5.3 PSEUDOCODE OF LLMAC

loop1

set k   // k=Number of iterations for assigning GTS slots

set nn   // nn= Number of nodes

set ns   //ns=Number of slots

if nn>k

Increment nn

else nn≤ k

Generate GTS nodes

Compute remaining nodes

endif

if ns>k

Increment ns

else ns≤k

Generate GTS slots

Compute remaining slots

endif

end loop1

set R   //Data rate

set S   //packet size in bits

Initialize queueing delay to zero

loop 2

Compute binary code for each node

endloop2

loop 3

Initialize node counter selecting three sensor nodes and one next to it as a coordinator node

Get generated code from list to each node

Generate frame from data collected from three nodes

Increment node counter

if node counter≥specified value

break

endif

Compute coded packets and retrieve them using XOR coding

Remove redundant data

Accumulate in a single packet

Increment counter till reached final value

Store in a compiler

Make logical decision on temperature values

end loop3

Display compiled result

Compute S1 // Network coded packet size in bits

// Calculation for network lifetime

Compute field dimensions,probability to become cluster head,packet length and some other parameters

Compute do

Generate a random sensor network

Initialize count for cluster head

loop4

for maximum rounds

Compute operation for epoch

endfor

Initialize count for bits transmitted to cluster heads and to base stations per round

Initialize dead nodes to zero

loop5

if dead node==true

increment dead node

endif

if dead node==nn

break end if

endloop5

```
Compute statistics
Compute first node died
loop 6
Select cluster head
Compute distance,distance broad,energy dissipated
Increment packets to base station
Store packets in each round
end loop6
loop7
Compute election of associated cluster head for normal nodes
Compute energy dissipated by associated cluster head
Compute energy dissipated
endloop7
end loop4
//Calculation for network lifetime ended here
Display network lifetime
loop8                    // latency and throughput for GTS
Set q
Compute S1               //packet size in bits
Compute probability
Compute individual latency
for q<=specified value
Compute overall latency
Compute throughput
Increment S1
Increment q
if  q>specified value
break
endfor
endloop8
```

```
Display individual latency,overall latency and throughput
loop9                    // latency and throughput for non-GTS nodes
Set q
Compute S2               //packet size in bits
Compute probability
Compute individual latency
for q<=specified value
Compute overall latency
Compute throughput
Increment S2
Increment q
if  q>Specified value
break
endfor
endloop9
Display individual latency,overall latency and throughput
loop10                   // Latency and throughput for network coding,data aggregation and GTS
Set q
Compute  S3              //Network coded packet size in bits
Compute probability
Compute individual latency
for q<=specified value
Compute overall latency
Compute throughput
Increment S3
Increment q
if  q>specified value
break
endfor
endloop10
```

Display individual latency,overall latency and throughput

Results of above pseudocode are given as under:

5.4 SIMULATION AND RESULTS

Now, to realize proposed protocol NCAMAC with already available protocol 802.15.4 , a novel protocol titled Low Latency MAC (LLMAC) protocol for Industrial Wireless Sensor Network(IWSN) is proposed which merges NCAMAC with GTS mechanism of 802.15.4. Simulation setup is same as proposed in chapter 4 with 200 nodes. It is carried out in three phases. Details of experiment and results are described below:

5.4.1 802.15.4 & WIRELESS HART COMPARISON

In the first part of simulation, no GTS, aggregation and network coding is considered . 200 nodes are transmitting to PAN coordinator with no coordinators assigned to nodes.

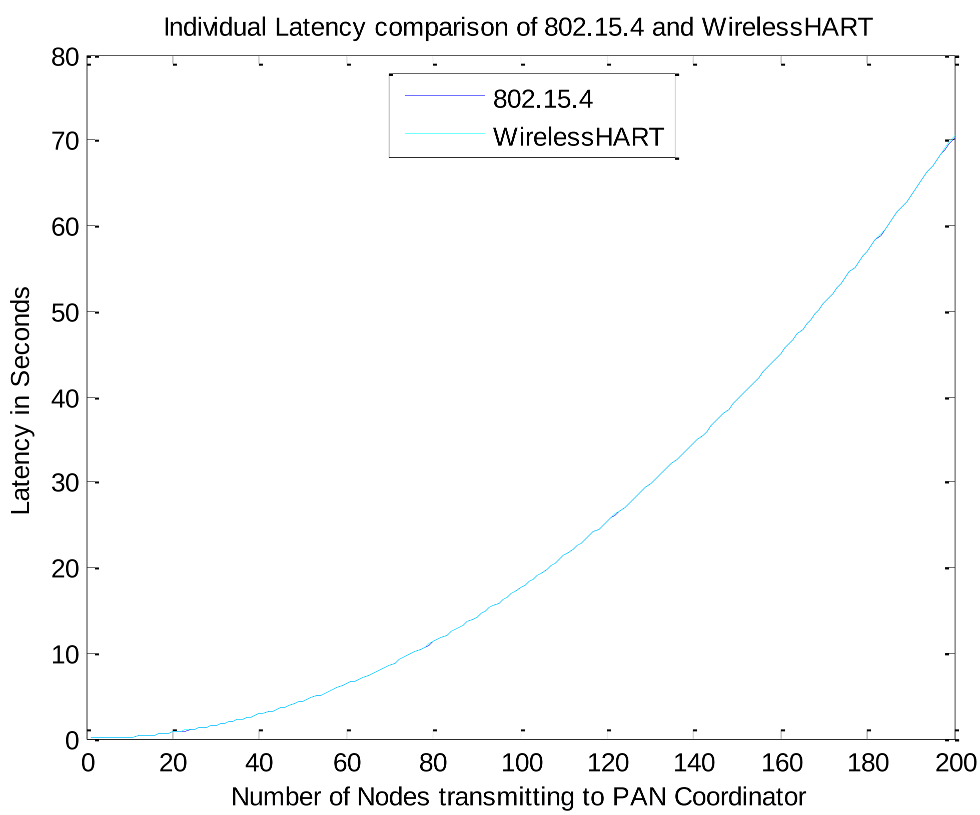


Figure 5-2 Individual latency comparison of WirelessHART and 802.15.4 with no NC and DA

Calculations are same using the same formulae (7),(8) and (9) given in chapter 4. Packet size and delay are incremented at each iteration. All nodes are delivering the data to PAN coordinator by hopping around all nodes. Latency is calculated around 70 seconds as shown in figure 5-2.

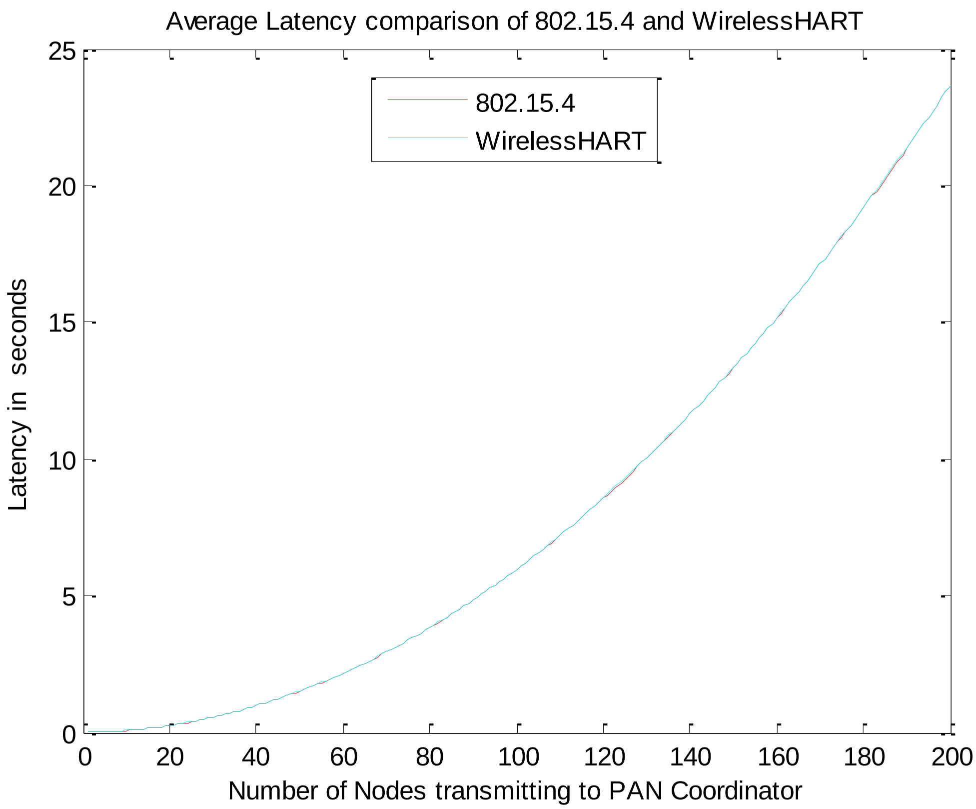


Figure 5-3 Average latency comparison of WirelessHART and 802.15.4 with no NC and DA

Average latency of 802.15.4 is slightly lower than WirelessHART as shown in figure 5-3. Unbounded delays occur due to CSMA/CA. Packet collisions/losses also requires retransmissions which is increasing latency of system. With no coordinator in between and no enhancements, all the nodes are randomly attempting to access 16 slots which increases collision rates. WHART is 802.15.4 based protocol, that’s why, producing almost same result as 802.15.4.

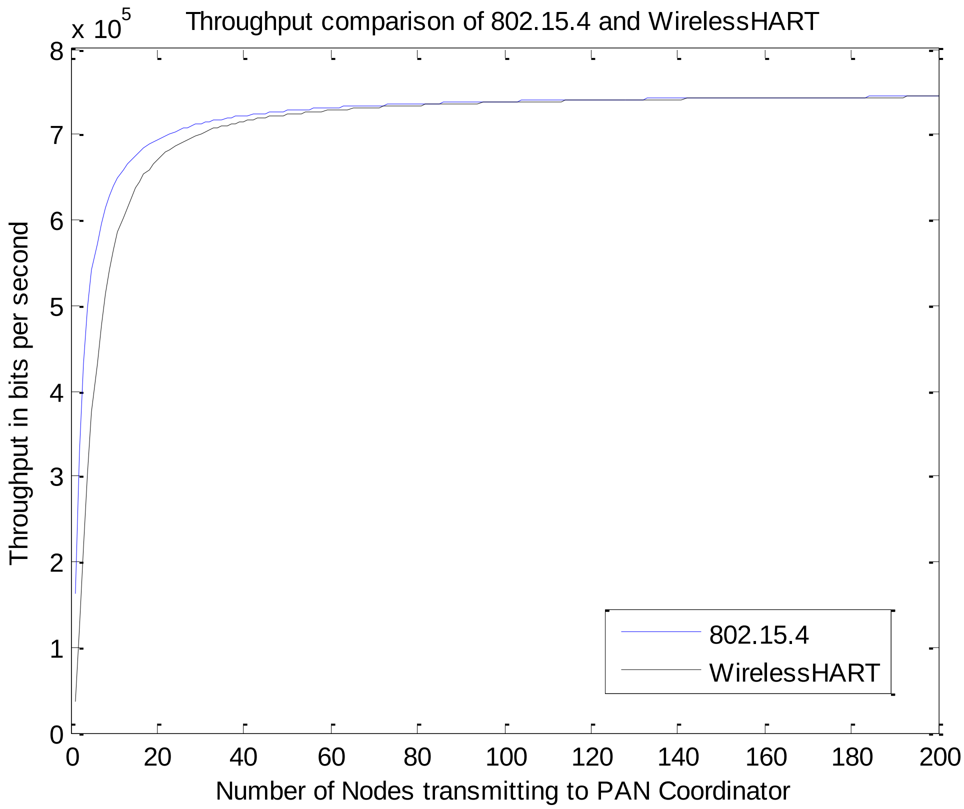


Figure 5-4 Throughput comparison of WirelessHART and 802.15.4 with no NC and DA

Throughput of 802.15.4 is slightly higher than WirelessHART for small scale networks as shown in figure 5-4 but as the network size grows, both protocols produce same throughput. This is due to large slot size of WirelessHART irrespective of data size.

802.15.4 is conceived for maximum throughput at data rate of 250 kbps.As we can see, it offers an optimized throughput with given packet size.

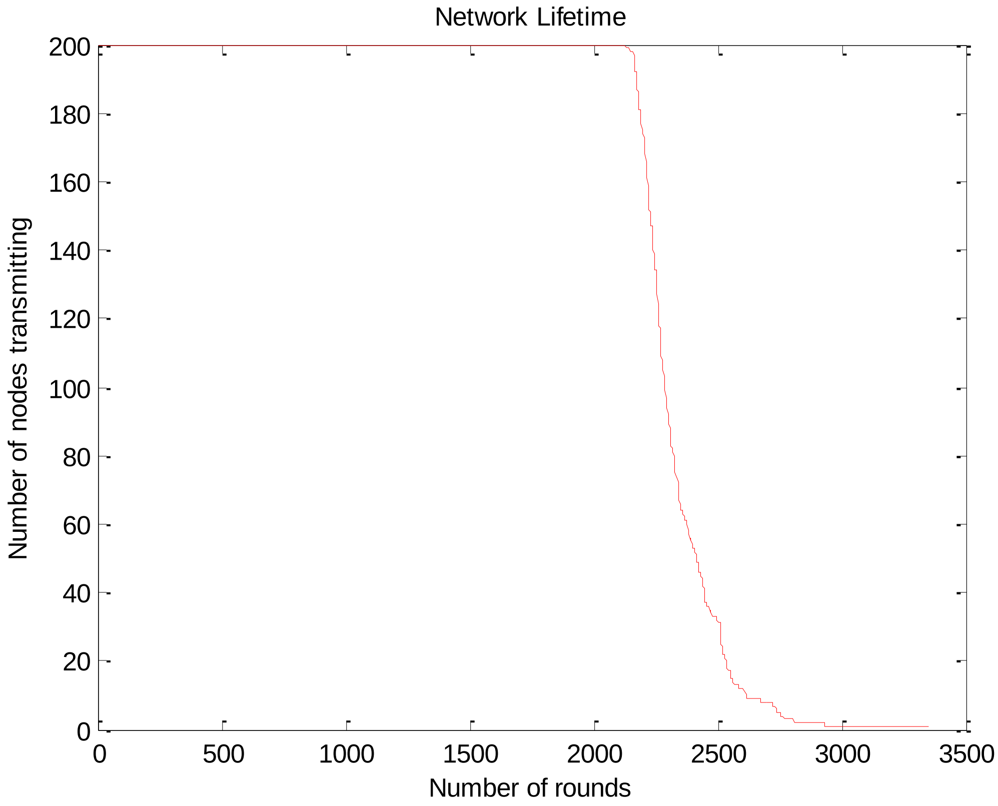


Figure 5-5 Network lifetime of 802.15.4 with no NC and DA

Battery life of sensor node is limited, so it is required to devise a solution to enhance network lifetime. Calculation of network lifetime results in that, as shown in figure 5-5, first node ran out of battery around 2100th round. To further improve it, a novel protocol is proposed using GTS, aggregation and network coding titled, Low Latency MAC (LLMAC) protocol for Industrial Wireless Sensor Network (IWSN).

Now applying GTS, aggregation and network coding mechanisms on a network of 200 nodes, we get the following results:

5.4.2 LLMAC EVALUATION

Number of sensor nodes transmitting are being reduced to 128 by applying GTS, aggregation and network coding. GTS mechanism reserves seven slots for seven nodes to transmit data free of contention in their respective slots. Contention Access period is of 9 slots and 193 nodes are competing to access those slots. Out of those 193 nodes, 128 are RFDs (transmit only, sensor nodes) while 65 nodes acts as coordinator nodes (FFDs) to process and transmit data to PAN coordinator. Network parameters regarding energy to calculate network lifetime are same as given in chapter 4. Coordinators performs aggregation and network coding. This section will evaluate the effect of using aforementioned techniques to attain low latency and an optimized throughput.

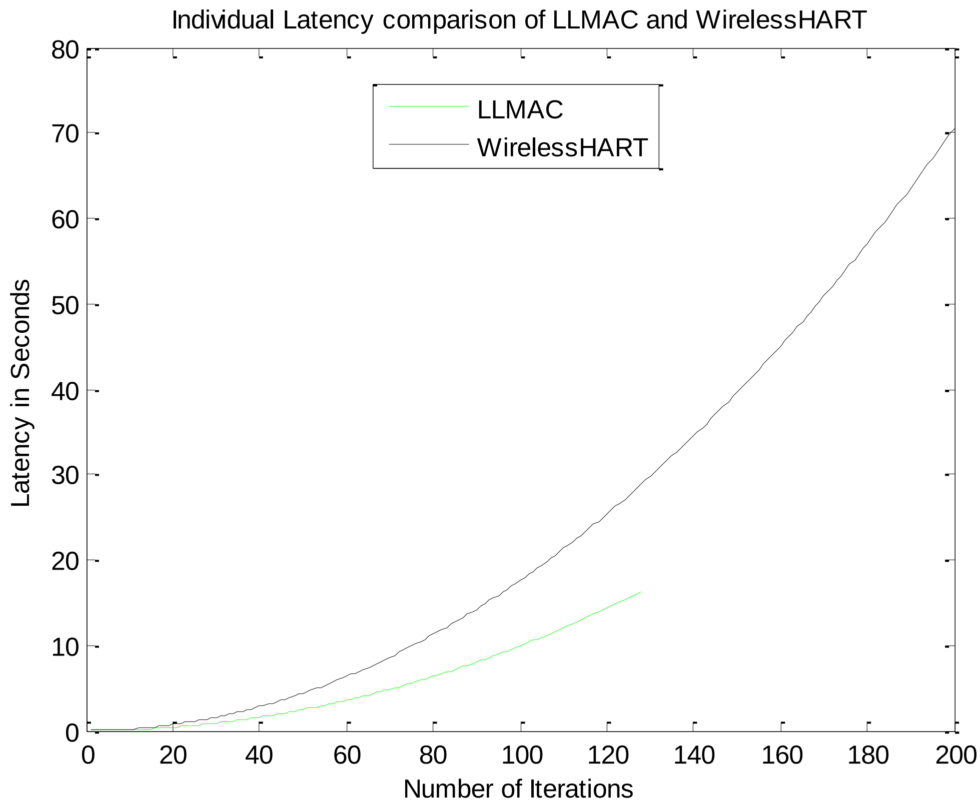


Figure 5-6 Impact of reduction of iterations on LLMAC latency

Latency of LLMAC is too lower than WirelessHART by employing network coordinator as number of iterations for LLMAC becomes less as compared to WHART as shown in figure 5-6. Packet size and number of transmissions are also reduced by using network coding and aggregation. The average latency of LLMAC is too low as compared to WirelessHART as shown in figure 5-7. Routing technique of WirelessHART is complex and LLMAC follows simple star topology based cluster architecture. Each cluster is formed by three sensor nodes and one coordinator node. Each cluster works independent of other clusters in network. All coordinators responds to PAN coordinator. Coordinators are responsible for synchronization.

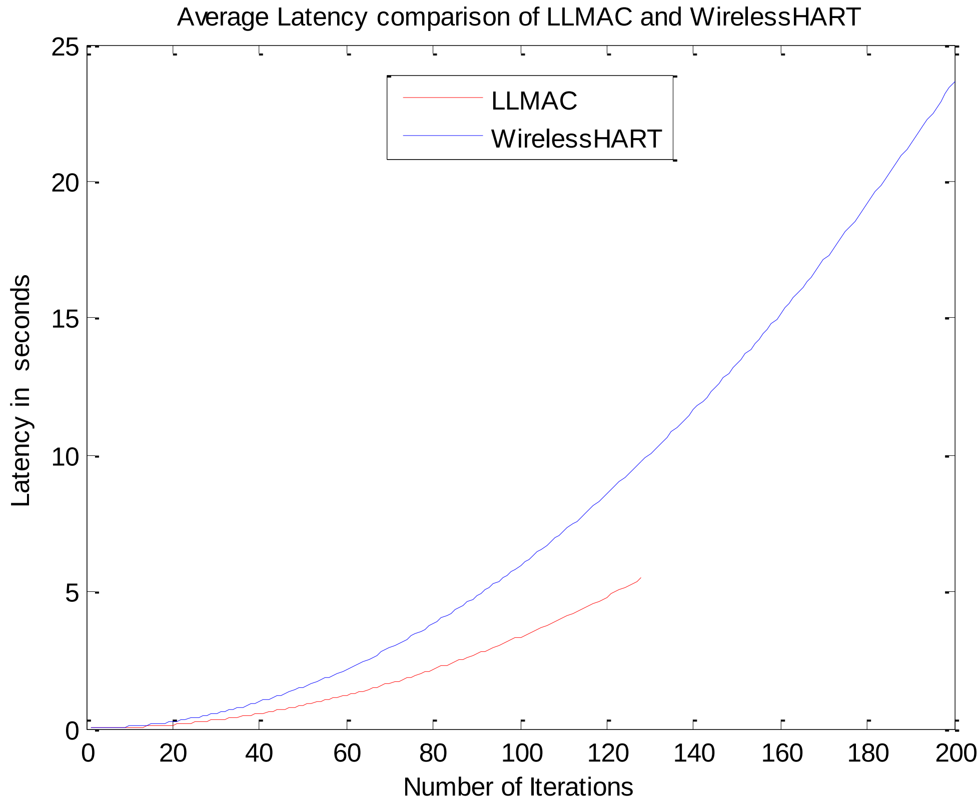


Figure 5-7 Impact of reduction of iterations on LLMAC average latency

Latency results of both protocols are presented. Latency of LLMAC is found to be much lower than WirelessHART. The major reason for high latency of WHART is complex routing algorithm of WHART i.e. graph and source coding. Generation of graph and source coding, making tables, updating those tables at each node and allocation of channel and slot for communication introduces delay in system. Proactive routing requires additional time for network setup and scheduling. WHART works on TDMA introduces large delays with fixed slot size of 10 ms, regardless of data size. More slots are required to transmit fragmented packet of each source and more data packets are generated. Transmission of data from different sources separately contributes in latency.

Whereas, for LLMAC, seven slots are reserved for GTS and seven nodes will communicate in those dedicated slots. Packet size and queueing delay is not updated for GTS. They are communicating with low latency and optimized throughput. Now, we are left with 193 nodes to compete and they will be competing for 9 slots. Optimized clusters are formed with those non-GTS nodes ,using star topology with simple routing with cluster of three sensor nodes and one coordinator node. Each node has its own ID and data packets are coded so no or fewer collisions occur. Data packet size got reduced using aggregation and network coding and communication occurs with less transmissions. This contributes in decreasing latency of overall system to level of required industrial level as shown in figure 5-7. Data packets and queueing delay is updated at each iteration in both protocols but reduced packet size, short duration slot (0.96 ms) and less number of transmissions of LLMAC offers low latency as compared to WirelessHART.

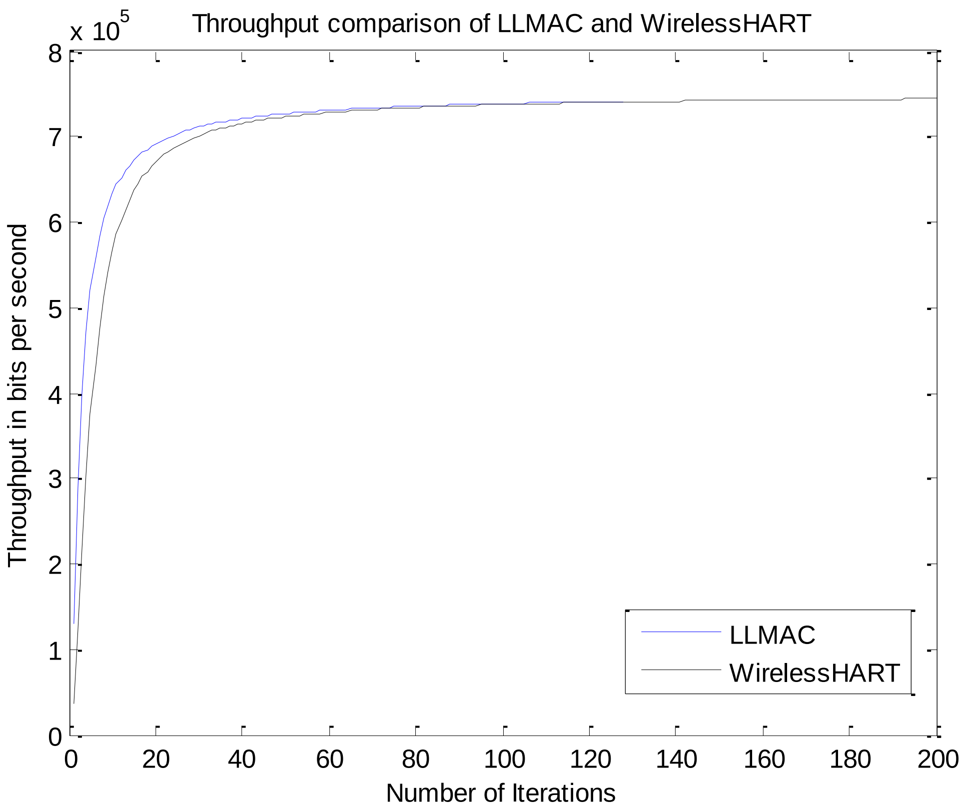


Figure 5-8 Impact of reduction of iterations on LLMAC throughput

Industrial application requires an optimized throughput for monitoring promptly. WHART, having large slot size with greater number of bytes should generate a higher throughput than LLMAC but due to collisions, retransmissions and packet losses, it generates almost same throughput as LLMAC as shown figure 5-8 . LLMAC uses coded packets. Initially, with no collisions, it provided a higher throughput for small scale networks but due to few collisions for large scale network, it is providing an optimized throughput with less transmissions. Latency of overall network is taken from result of figure 5-7.

Throughput is calculated as shown in figure 5-8 as

Throughput= (K*q)/(Latency of overall network)

k=packet size

q=queueing delay

In figure 5-8, packet size at each iteration is incremented. It offers an optimized value of throughput at the data rate of 250 kbps.

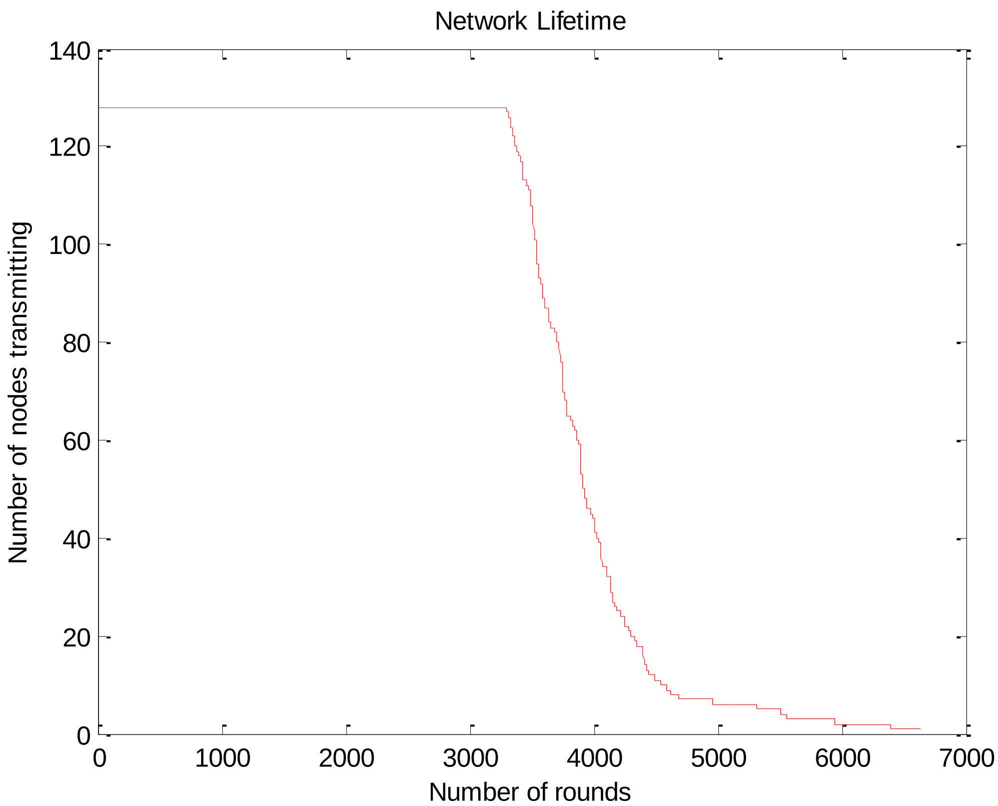


Figure 5-9 Network lifetime of sensor nodes

Sensor nodes are battery powered and for an industrial network, the nodes should provide an efficient network lifetime. Most of the energy is consumed in transmissions, causes the nodes to run out of battery. Additionally, collisions and retransmissions causes to harm energy efficiency. Complex routing schemes lead to packet losses due to collisions. For LLMAC, we have used network coding and data aggregation to reduce packet size and decrease number of transmissions. Since packets are coded, no or fewer collisions occur. Further, GTS are used that helped to attain zero collisions for seven nodes.

Seven nodes are reserved for GTS and they are directly communicating to PAN coordinator. For rest of 193 nodes, 128 are sensor nodes and 65 coordinator nodes. Optimized clusters are formed by using three sensor nodes and one coordinator node each. Coordinators are communicating with PAN coordinator. Simple routing scheme with star topology and cluster construction helped to reduce losses .Reduced packet size and very low rate of retransmissions saves energy and enhances network lifetime as shown in figure. 5-9. First node died at 3293th round.

5.4.3 LLMAC'S COORDINATORS PERFORMANCE

Sensors are RFDs, responsible for simplex transmission. Coordinators in LLMAC are responsible for synchronization , processing and communication. Evaluating the latency of coordinators seperately, we get the following results:

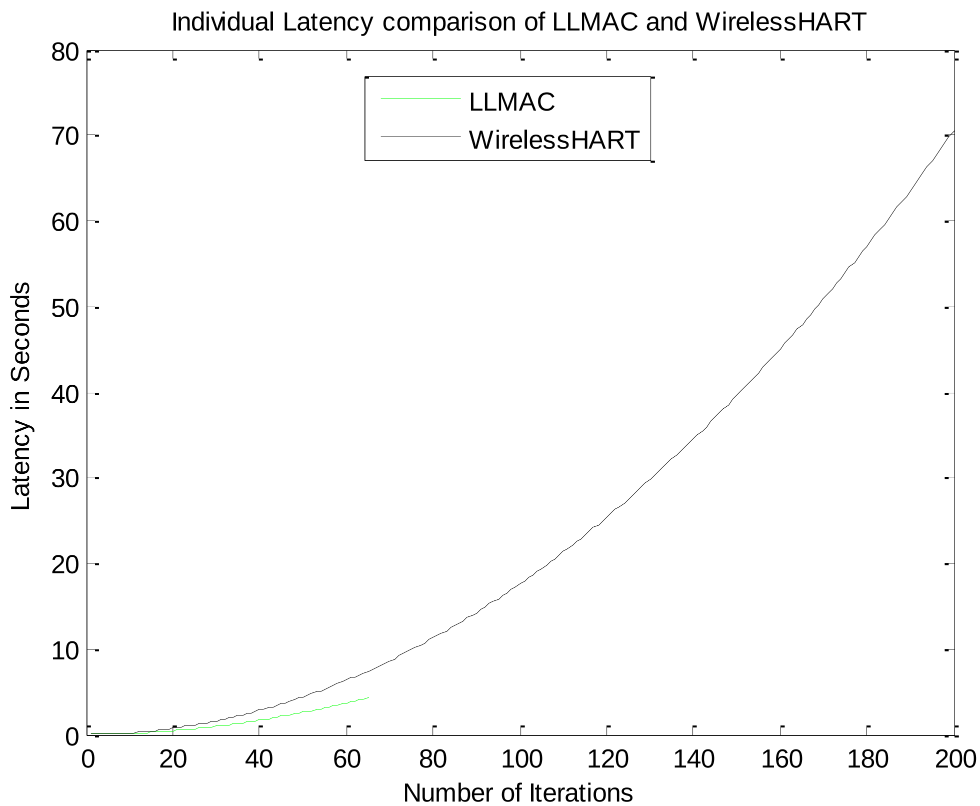


Figure 5-10 Impact of reduction of iterations on LLMAC coordinator's latency

7 slots are reserved for 7 nodes of high priority in a vicinity. Rest of 193 nodes are competing on remaining 9 slots of super frame, out of which 128 are sensor nodes and 65 coordinator nodes. Each of three sensors are transmitting to their respective coordinators. Same formulae 7, 8, 9 and table 4-1 and 4-2 for simulation parameters from chapter 4 are used for latency and throughput calculation. Probability for coordinators is taken as 0.0308 and for sensors it is taken as 0.0677. As shown in figure 5-10, number of iterations and packet size at coordinators got reduced due to network coding and data aggregation. The average latency of coordinators is still low as compared to WirelessHART as shown in figure 5-11.

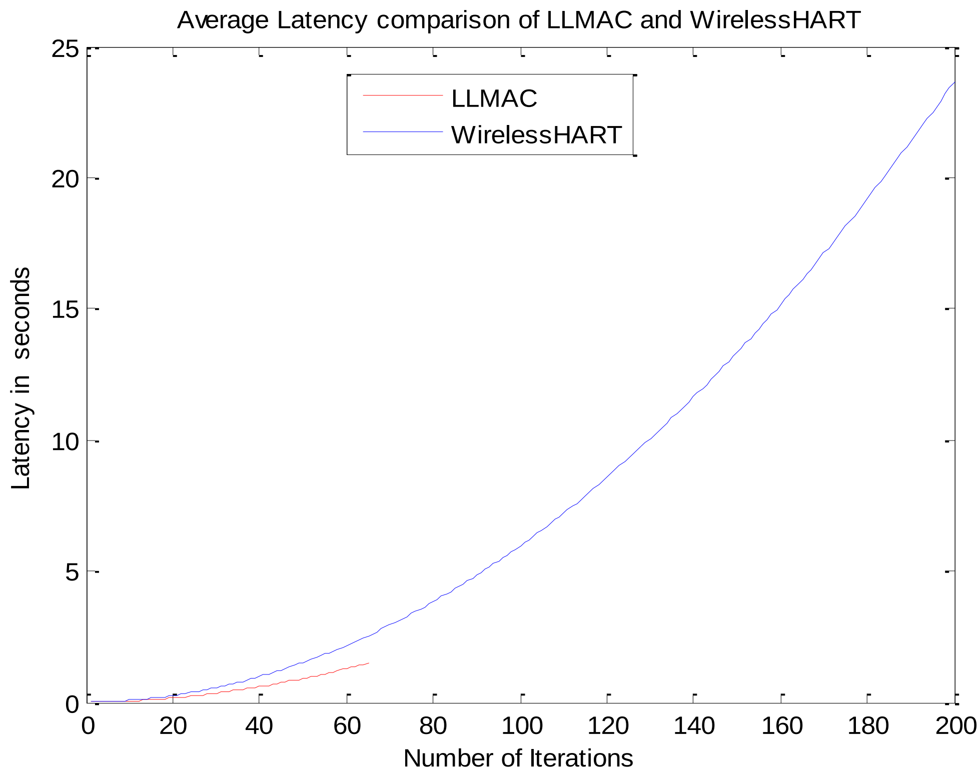


Figure 5-11 Impact of reduction of iterations on LLMAC coordinator's average latency

WHART offers high latency due to its complex routing algorithm. For graph and source routing in WHART, generation of graph and source coding, making tables, updating those tables at each node and allocation of channel and slot for communication introduces delay in system. Proactive routing requires additional time for network setup and scheduling. WHART works on TDMA introduces large delays with fixed slot size of 10 ms, regardless of data size. More slots are required to transmit fragmented packet of each source. Transmission of data from different sources separately contributes in latency.

Average latency of LLMAC coordinators (1.502 seconds) excluding GTS nodes is lower than NCAMAC coordinators (1.592 seconds) Because LLMAC works on GTS mechanism along with network coding and data aggregation. The overall latency of LLMAC coordinators with reduced packet size and including latency of GTS nodes results in 1.50472 seconds for single round which is providing an ideal solution for industrial environment better than NCAMAC.

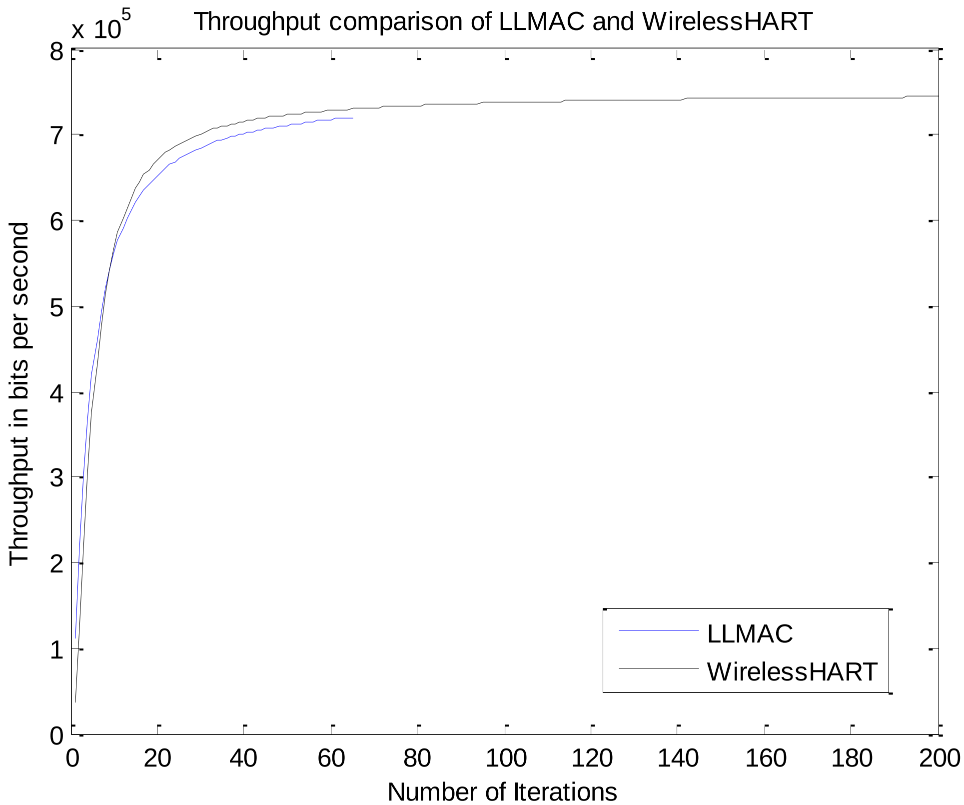


Figure 5-12 Impact of reduction of iterations on LLMAC coordinator's throughput

As shown in figure 5-12, throughput of LLMAC is slightly lower because packet size is reduced and the less number of bytes are transmitting from coordinator after data aggregation and network coding at coordinator.

WHART, having large slot size with greater number of bytes, should generate a very high throughput as compared to LLMAC but due to collisions, retransmissions and packet losses, it generates almost same throughput as LLMAC as shown in figure 5-12.

LLMAC uses coded packets and GTS mechanism for seven slots, reducing latency of network. Initially, with no collisions, it provided a higher throughput for small scale networks but due to few collisions for large scale network, it is providing an optimized throughput with less transmissions.

Summary of latency and throughput results are given as under:

- Latency results for Wireless HART and 802.15.4(without using network coding and data aggregation) are compared. Due to collisions and retransmissions and some other causes as discussed, they are producing average latency of high value around 23 seconds.

- Throughput is found to be of optimal and high value as 802.15.4 is conceived for maximum throughput applications. Value is around 721 kbps.

- Latency results of LLMAC sensor nodes are presented using GTS, network coding and data aggregation. Reservation of slots, reduced packet size and reduced number of transmissions helped to attain low latency goal and provided an average latency less than 5 seconds.

- With reduced packet size and less transmissions, throughput achieved with LLMAC is almost equal to Wireless HART i.e. around 721 kbps.

- Evaluating latency of coordinators separately, it is found be around 1.50472 seconds. This is slightly better than NCAMAC due to GTS mechanism.

- Throughput of coordinators, calculated, is same as around 721 kbps.

5.5 CONCLUSION

In this chapter, a novel protocol titled LLMAC (Low Latency MAC) for Industrial Wireless Sensor Network(IWSN) is proposed. It is based on 802.15.4 GTS mechanism combined with NCAMAC which is already discussed in chapter 4.

NCAMAC is working well to attain low latency and to further improve its performance and realize it on 802.15.4, a combination of GTS, aggregation and network coding is proposed. LLMAC further reduced latency as compared to NCAMAC. Seven nodes are communicating in their seven respective slots in super frame of 16 slots. Rest of the nodes (193) are competing on 9 slots as per procedure discussed in chapter 5. LLMAC is based on star topology with three RFDs (sensor nodes) and one FFD (coordinator node). Seven GTS nodes are operating independently, and communicating with PAN coordinator only, with low latency and zero network congestion as nodes are communicating in their respective slots.

Latency of LLMAC is further reduced by 5.799% using GTS mechanism whereas maintained an optimized throughput and network lifetime.

CHAPTER 6

CONCLUSION AND FUTURE ENHANCEMENT

In this thesis, Low Latency MAC (LLMAC) for IWSN, protocol is proposed for industrial applications to minimize hazards caused by latency. A comparative study of state of the art IWSN protocols is also presented. Moreover, the details for selection of 802.15.4 protocol and importance of proposed network in achieving low latency is also provided in the thesis. It can be concluded from the thesis that these state of the art protocols produces promising solutions to wireless networking problems, however, they introduce complexity and in turn introduces latency issues at the cost of reliability within the network.

First, the GTS mechanism is evaluated and its network latency and throughput is calculated. The simulation environment selected is MATLAB 2013a. Network is composed of 200 nodes with network parameters as described in chapter 3. It has been shown that equiprobable GTS nodes assigned to their respective slots causes an equal minimum value of latency and optimized throughput for all GTS nodes. Rest of the 9 slots in a super frame of 16 slots are free to access by remaining 193 nodes. These GTS nodes are independent of each other and only respond to PAN coordinator. PAN coordinator is responsible for synchronization.

Second, a novel approach, Network Coded-Aggregated MAC (NCAMAC) is proposed in chapter 4. It combines data aggregation and network coding to attain low latency in network. Redundant data is removed and XOR coding is being used to code packets. These coded packets, bearing ID of their respective nodes, are sent to coordinator where they are processed by using aggregation and network coding mechanism that reduces number of transmissions and packet size. These coordinators are responsible for synchronization and send data to PAN coordinator. Sensors are RFDs (transmit only) while coordinators are FFDs (transmission, process, reception). Using NCAMAC, the latency is achieved of desirable range for industrial automation as mentioned in [6] i.e. transmission of data in 5-50 milliseconds and low round trip of network.

To realize NCAMAC in real world and to further reduce latency, NCAMAC is merged with GTS mechanism of 802.15.4. The main protocol, Low Latency MAC(LLMAC) for IWSN using data aggregation, GTS and network coding constructed on star topology with cluster based structure is proposed. This approach provides low latency mechanisms by exploiting slots reservation of GTS mechanism and data aggregation combined with network coding techniques to reduce packet size and number of transmissions with star topology, making it less complex. Simulation setup is taken same as NCAMAC with an addition of GTS mechanism taking almost same network parameters. It maintains an optimal throughput while reduces latency further by 5.799%.

In future, it can be further extended by increasing number of small clusters to further make it scalable. Another enhancement could be to devise a method to select shortest path in distributed approach for proposed architecture. Backup routers with replaceable batteries can also be implemented to enhance network lifetime further. One can also make it work with other 802.15.4 based protocols to provide collaboration among protocols.

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