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Enhancement of The IEEE 802.15.4 Standard By Energy Efficient Cluster Scheduling

Enhancement of The IEEE 802.15.4 Standard By Energy Efficient Cluster Scheduling

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A thesis submitted to the University of Huddersfield
in partial fulfilment of the requirements for
the degree of Doctor of Philosophy

School of Computing and Engineering
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AUGUST 2015

Abstract

The IEEE 802.15.4 network is gaining popularity due to its wide range of application in Industries and day to day life. Energy Conservation in IEEE 802.15.4 nodes is always a concern for the designers as the life time of a network depends mainly on minimizing the energy consumption in the nodes. In ZigBee cluster-tree network, the existing literature does not provide combined solution for co-channel interference and power efficient scheduling. In addition, the technique that prevents network collision has not been provided. Delay and reliability issues are not addressed in the QoS-aware routing. Congestion is one of the major challenges in IEEE 802.15.4 Network. This network also has issues in admitting real time flows.

The aim of the present research is to overcome the issues mentioned above by designing Energy Efficient Cluster Scheduling and Interference Mitigation, QoS Aware Inter-Cluster Routing Protocol and Adaptive Data Rate Control for Clustered Architecture for IEEE 802.15.4 Networks. To overcome the issue of Energy efficiency and network collision energy efficient cluster scheduling and interference mitigation for IEEE 802.15.4 Network is proposed. It uses a time division cluster scheduling technique that offers energy efficiency in the cluster-tree network. In addition, an interference mitigation technique is demonstrated which detects and mitigates the channel interference based on packet-error detection and repeated channel-handoff command transmission.

For the issues of delay and reliability in cluster network, QoS aware inter-cluster routing protocol for IEEE 802.15.4 Networks is proposed. It consists of some modules like reliability module, packet classifier, hello protocol module, routing service module. Using the Packet classifier, the packets are classified into the data and

hello packets. The data packets are classified based on the priority. Neighbour table is constructed to maintain the information of neighbour nodes reliabilities by Hello protocol module. Moreover, routing table is built using the routing service module. The delay in the route is controlled by delay metrics, which is a sum of queuing delay and transmission delay.

For the issues of congestion and admit real-time flows an Adaptive data rate control for clustered architecture in IEEE 802.15.4 Networks is proposed. A network device is designed to regulate its data rate adaptively using the feedback message i.e. Congestion Notification Field (CNF) in beacon frame received from the receiver side. The network device controls or changes its data rate based on CNF value. Along with this scalability is considered by modifying encoding parameters using Particle Swarm Optimization (PSO) to balance the target output rate for supporting high data rate.

Simulation results show that the proposed techniques significantly reduce the energy consumption by 17% and the network collision, enhance the performance, mitigate the effect of congestion, and admit real-time flows.

ACKNOWLEDGEMENTS

At the outset I wish to thank Allah, the Almighty for His blessings bestowed upon me with the strength to complete this thesis.

I would like to convey my sincere thanks to my grateful supervisor, Dr. Martin Sibley his precious guidance and supervision that enabled me to complete this thesis. Without his guidance and dedication this work would not have seen the light. Also I would like to thank my co-supervisors Dr Peter Mather for his kind coordination and guidance while carrying out my research.

I thank to all the staff at the Research Studies, University of Huddersfield for their cooperation and helpfulness in academic matters.

Also I am especially thankful to my family for their endless prayers and moral support. I dedicate this thesis to them. I am also grateful to Dr. Syed Abdul Sattar for his support throughout my career.

Last, but not the least, great thanks to all who had been involved directly and indirectly throughout the making of this thesis. I really appreciate it.
Thank you.

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List of Acronyms

Abbreviations	Description
ACCS	Adaptive Contention Control Strategy
ADRC	Adaptive Data Rate Control
AGA	Adaptive GTS Allocation
ALEC	Adaptive Low-Energy Clustering
AODV	Ad hoc On-demand Distance Vector
ANOVA	Analysis of Variance
BFS	Breadth-First Search
BI	Beacon Interval
BIAS	Bluetooth Interference Aware Scheduling
BO	Beacon order
BS	Base Station
CAP	Contention Access period
CBR	Constant Bit Rate
CDMA	Code Division Multiple Access
CDSWS	Coverage-Guaranteed Sleep/Wake Scheduling
CFP	Contention free period
CH	Cluster Head
CMT	Cluster Mesh Tree
CNF	Congestion Notification Field
CP	Communication Period
CP	Most critical data packets (CP)
CSMA-CA	Carrier Sense Multiple Access-Collision Avoidance
CW	Contention Window
DDTC	Differential Dynamic Traffic Control
DP	Delay-driven data packets

DSA	Distributed Slot Assignment
DSSS	Direct Sequence Spread Spectrum
EDF	Earliest Deadline First
EECS	Energy Efficient Cluster Scheduling and Interference Mitigation
ERA	Energy-aware routing algorithm
EXP	Exponential
FCFS	First Come First Served
FDMA	Frequency Division Multiple Access
FFD	Full Function Device
GSA	GST Scheduling Algorithm
GTS	Guaranteed Time Slot
HART	Highway Addressable Remote Transducer
HTP	Hidden Terminal Problem
ID packet	High Power Detection packet
Implicit-EDF	Implicit-Earliest Deadline First
IP	Internet Protocol
LEACH	Low-Energy Adaptive Clustering Hierarchy
LR-WPAN	Low-Rate Wireless Personal Area Network
MAC	Media Access Control
MBS	Backoff scheme
MIA	Minimum Interference Algorithm
MCT	Multi-Channel Transmission
NCS	IEEE 802.15.4 Networked Control System
ND packet	Normal Power Detection packet
NS	Network Simulator
OP	Ordinary data packets

PAN	Personal Area Network
PARM	Power Aware Real-Time Message Scheduling
Ph-PDU	Physical protocol data unit
PHY	Physical Layer
PSO	Particle Swarm Optimization
PSOADRC	PSO based Adaptive Data Rate Control technique
QAICR	QoS Aware Inter-Cluster Routing
QoS	Quality of Service
QP	Quantizer Parameter
QPRR	QoS-aware Peering Routing
RCPS-TC	Resource Constrained Project Scheduling with Temporal Constraints
RC-VBR	Rate Control Variable-Bit-Rate
RF	Radio Frequency
RFD	Reduced Function Device
RID	Radio Interference Detection
ROI	Region of Interest
R_{option}	Reliability option
RP	Reliability-driven data packets
RSP	Reliability sensitive packet
SCT	Single Channel Transmission
SDS	Superframe Duration Scheduling
SO	Superframe order
SSMTT	Sleep Scheduling algorithm for Multiple Target Tracking
ST	Single-Channel Transmission
TCP	Transport Control Paradigm
TDBS	Time Division-Based Scheduling

TDCS	Time Division Cluster Scheduling
TDMA	Time Division Multiple Access
TES	Transform-Expand-Sample
TMCP	Tree-based Multichannel Protocol
UDP	User Datagram protocol
VBR	Variable Bit Rate
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Networks
ZC	ZigBee Coordinator
ZCT	ZigBee Cluster Tree
ZED	ZigBee End Devices
ZR	ZigBee Router

List of Notations

Notations	Description
T_{BI}	Cluster period
BI	Beacon interval
T_{SF}	Superframe duration
O_{BI}	Beacon order
O_{SF}	Superframe order
CNT_S	Channel-sensing counter
Hyp_0	Hypothesis related to absence of interference signal
Hyp_1	hypothesis related to presence of interference signal
i	Sample index
RX(i)	Received signal
IR(i)	Impulse response of channel
S(i)	Signal transmitted from the interference source
$\tau(i)$	Additive Gaussian noise
E_{th}	Energy threshold
λ	Test statistics
a	Number of samples taken for the test
λ_j^{tx} and λ_j^{rx}	Number of allocated time slots need to be estimated for all flows towards transmitter and receiver side
T_{GTS1} and T_{GTS2}	Period of GTS for entire data transmission for transmitter and receiver
c1 and c2	Duration of a slot for transmitter and receiver
R_j	Router
C_j	Cluster
N_i	Node
T_{SR}	Shortest required period
CS_{td}	Cluster Scheduling period
CD	Coordinator
σ	Channel
I_m	Interference existence message
T_{MM}	Time duration among two successive MCT
T_M	Duration of MCT
Th	Threshold
N_E	Number of packet transmission errors in superframe
N_{MCT}	Number of interference existence message
N_b	Beacon loss counter
E_{tx} and E_{idle}	Power consumed by transmitter during dynamic mode and idle mode
E_c	Average energy consumed by the cluster
N_{e2e}	Number of end to end devices
E_{e2e}	Energy consumed by end to end devices
Nr_j	Number of packets received at each destination j
Ns_i	Number of packets sent from each source i
Tr_{ij}	Received time of j_{th} packet of node i
Ts_{ij}	Sending time of packet j for node i
n	Total number of packets sent

t	Unit time
ρ	Average weighing factor
χ_i	Average probability of successful transmission after 4 seconds
$R_{link(I,j)}$	Link reliability
$R_{path(I,Dst)}$	Path reliability between node and destination node
ID_{Dst}	Destination ID
L_{Dst} and L_j	Destination location and neighbour node j location
ID_j	Neighbour node j ID
$R_{E(I,j)}$	Residual energy
T	Total energy
T_c	Total energy consumed
P_i	Geographic location
$\hat{d}(i)$	Delay in route
η	Constant smoothing factor
NH_E	Energy aware next hop
NH_R	Reliable next hop
n	Number of nodes
r	Arrival rate per unit time
D_i	Transmission data rate
P	Prediction frame
B	Bidirectional frame
I	Intra frame
TR	Target rate
n	Number of frames
fr	Frame rate
a	Frame width
y	Height
MF	Motion factor
P_i	Current position of a particle travelling at velocity V_i
L_{bp}	Local memory space
G_{bp}	Global memory space

CHAPTER-1

INTRODUCTION

1.1 IEEE 802.15.4 Zigbee Network

The rapid growing popularity of the wireless communication has necessitated a new standard featuring low complexity, low power consumption etc. IEEE 802.15.4 standard for the low-rate wireless personal area network (LR-WPAN) is having low complexity, ultra-low power consumption, and low data rate wireless connectivity in the fixed, inexpensive, portable, and moving devices which has no devices to operate (Kim et al., 2007). It is formed by the WPAN working group that specifies the physical layer and the Medium Access Control (MAC) layer protocol for the low-rate (LR-WPANs) (Zeng et al., 2011).

IEEE 802.15.4 network has three logical devices. They are coordinator, PAN coordinator and end devices. PAN coordinator is one of the nodes that is used to initiate the network and acts as a primary controller of the network. It can operate as a gateway to other networks. Each network has one PAN coordinator. The PAN coordinator may transmit beacons and can communicate directly with any device in range. Full function device (FFD) can act as PAN coordinator whereas reduced function devices (RFD) can communicate only with the FFD and acts as the end devices.

The FFD device that supports the data routing functionality, including acting as an intermediate device to link different components of the network and forwarding message between remote devices across multihop paths. A router can communicate with other routers and end devices. The RFD device that contains just enough functionality to communicate with its parent node: a Coordinator or the PAN Coordinator. An end device does not have the capability to relay data messages to other end devices (Mohanty, Sanatan, 2010).

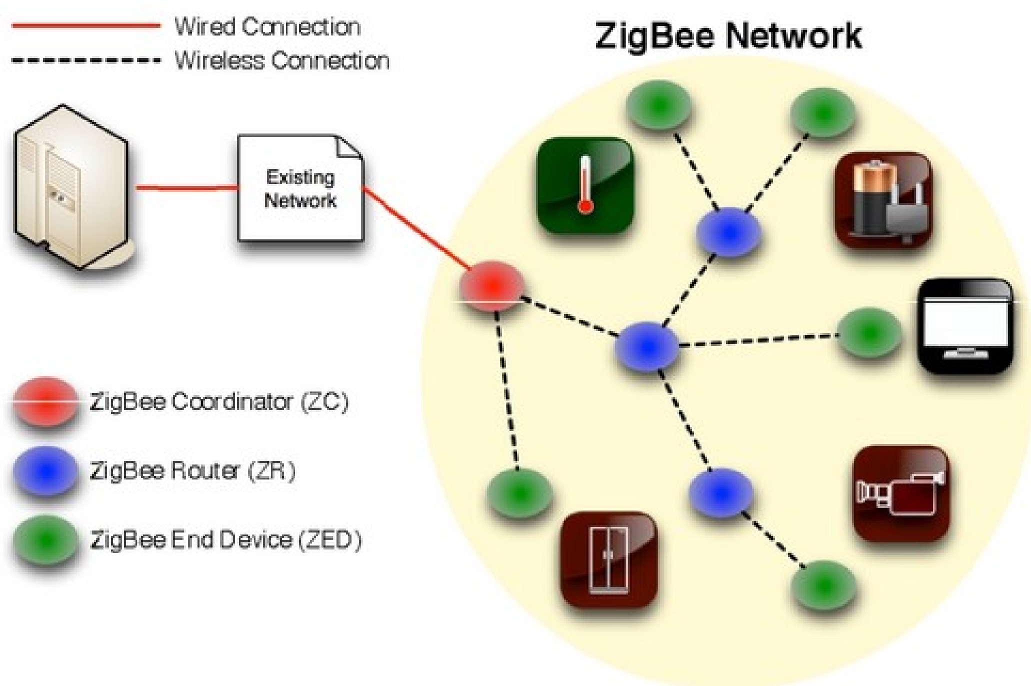

Fig 1.1 IEEE 802.15.4/ ZigBee Network Architecture

The IEEE 802.15.4 MAC has features like low-duty cycle operation and self-organization for WPANs. Hence, this standard is more attractive for providing multimedia services over the networked sensors (Suh et al., 2008). IEEE 802.15.4 devices are used in industry, health and environment monitoring, home automation, security, asset tracking, emergency and disaster monitoring (Cuomo et al., 2007).

In IEEE 802.15.4 networks, each layer should perform certain part of the standard and deliver services to the upper layers. The interfaces between the layers define the logical links in this standard. LR-WPAN device has at least one PHY (that contains a RF transceiver along with its low-level control mechanism and MAC sub layer). It offers access to the physical channel for all kinds of transfer.

Figure 1.2 illustrates the blocks in the standard in a graphical representation, which are discussed in more detail below.

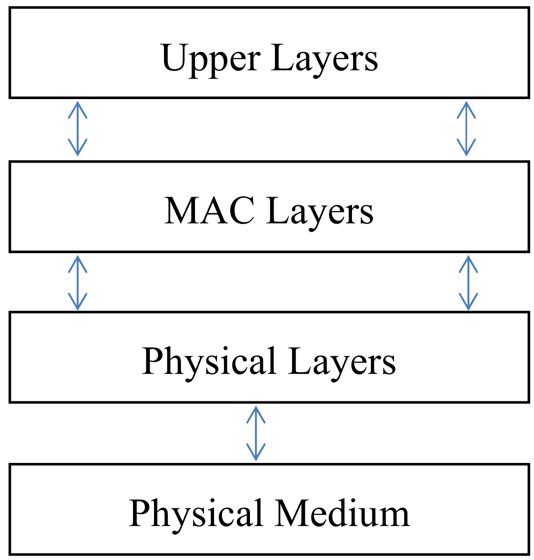

Figure 1.2 LR-WPAN Device Architecture

The upper layers comprise a network layer and application layer. Network layer offers network configuration, manipulation, and routing, whereas application layer offers the envisioned device's function. Physical Layer (PHY) offers data service and management service for the transmission and reception of PHY protocol data units through radio channel. Activation and deactivation of the radio transceiver, channel selection, clear channel assessment, transmission and reception of receiving packets through the physical medium, and precision ranging are the functions of PHY (Chen et al., 2010).

1.1.1 Characteristics

Some of the key characteristics of the IEEE 802.15.4 are given below:

- IEEE 802.15.4 network has high data rates of 250, 40 and 20 Kbps.
- IEEE 802.15.4 network has two addressing modes, namely, 16-bit short and 64-bit IEEE addressing.
- This network employs Carrier Sense Multiple Access Collision-Avoidance (CSMA-CA) channel access.
- Automatic network is initialized by the network coordinator.
- IEEE 802.15.4 network has power management control so that it consumes less power.
- This network uses 10 channels in 915 MHz ISM band, 16 in the 2.4 GHz ISM band, and one in the 868 MHz band.
- This network provides star operation or peer-to-peer operation.
- This network can support low latency devices.
- This network uses fully handshake protocol for transfer reliability (Aditi Sharma et al., 2014).

1.1.2 Applications

The applications of the networks focused mainly are on sensor network and automatic control. Some of them are discussed below (Desai et al., 2013):

- In-home patient monitoring is an intended application of ZigBee network in which wearable devices measure the patient's essential body parameters. When the patient wears it, the device begins to interface with a sensor that collects health-related information periodically. The data is then wirelessly transmitted to the local server. In some cases, the data is first sent to a personal computer inside the patient's home in which initial examination is done. Lastly, the information is sent to the patient's physician through Internet for further processing.

- Structural health of large scale building is another example of a ZigBee application in which several ZigBee enabled wireless sensors, such as accelerometers, are installed in a building. All these sensors can be combined to form a single wireless network for collecting the information that is used to evaluate the building structural health and detect the damage signs.
- Following an earthquake, the data collected by using a Zigbee network could help reduce the cost of inspection.
- ZigBee wireless networking is used in home automation with the typical data rate of 10Kbps.
- Some other possible applications in a residential building are light control, meter reading systems, security, multi-zone heating, irrigation, ventilation, and air-conditioning.
- AlarmGate applications run on an embedded platform, such as the Crossbow stargate, and serve as a communication backbone and application-level gateway between the wireless sensor and IP networks. Owing to their greater resources, these devices perform major aspects system operation related to dynamic privacy, power management, query management, and security.
- Back-end programs perform online analysis of sensor data, feeding back behaviour profiles to aid context-aware power management and privacy. A database provides long-term storage of system configuration, user information, privacy policies, and audit records.

1.1.3 Issues in IEEE 802.15.4 networks

The factors affecting the performance of IEEE 802.15.4 networks are briefly discussed below:

- When the data is transmitted using the CSMA-CA mechanism sometimes it is possible for data to get lost or corrupted as the network grows.
- If channel is busy due to heavy traffic, the data may not get delivered.
- The data rate is significantly reduced in indirect data transmission due to sending the data periodically (Babita and Sanjeev Indora, 2014).
- If two devices most likely choose the same backoff time due to the small CW collision may occur.
- When using broad CW for decreasing collision leads to reduction of network utilization if the network load is light (Tseng et al., 2009).
- If the MAC parameters are not properly selected, performance will be affected in terms of power consumption, reliability and delay (Park et al., 2011).
- If the node has reserved a Guaranteed Time Slot (GTS), it can contend for channel access in the Contention Access (CAP) period which will clearly decrease the usable bandwidth for other devices.
- Scheduling the contention free period (CFP) at the end of the active portion of the superframe gives the normal data a faster channel access than the real-time data, since the real-time data may wait until the end of the CAP to get deterministic channel access (Huang et al., 2008).
- In the applications that utilize these standards, the devices are battery powered. Battery substitution or recharging in short intervals is impractical.

Battery-powered devices will necessitate duty-cycling in order to minimize energy consumption.

- Battery-powered devices spend the large part of their operational life in a sleep mode. However, each device periodically listens to the RF channel in order to find whether a message is still pending or not. Along with the power saving features of the LR-WPAN system, PHY offers a hybrid modulation. This kind of modulation provides simple, non-coherent receiver architectures to reduce power consumption and implementation complexity.

1.2 Clustering in IEEE 802.15.4 Network

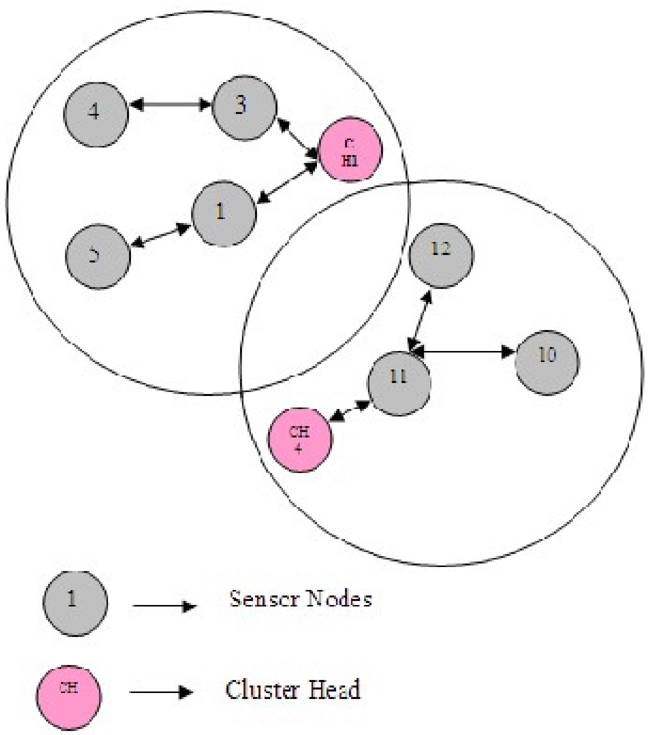

Figure 1.3 Cluster Formation

A cluster is usually built to reduce router power consumption with a Cluster Head (CH). CH is utilized to connect all sensors in the cluster and gather the data. The data is transmitted to the sink through several clusters. A cluster tree is designed by connecting CHs. Nodes that transmit the data to the CH are called leaf nodes. In a cluster tree, the data are transmitted with the help of time division multiple access scheme.

Each cluster necessities a specific time slot during its operation. The time from sensors to the sink is equal to the total time slots of passing clusters. When the passing clusters are more, then the data will be slowly transferred from sensors to the sink. Hence, the transfer delay time in a cluster tree is reduced by decreasing the number of clusters.

Several causes lead to excess clusters. A cluster tree is built from the sink or nodes of random selection. Consequently, a node connects the neighbours and decides whether it can be a CH or not. The benefit of this kind of approach is that nodes can be clustered faster and the drawback is there is no promise to guarantee the number of clusters and the length of the transfer path (Wu Yu et al., 2008).

As a result of which, the number of the clusters will be reduced in the whole network or from sensors to the sink. This may lead to the data transfer delay. One-hop transmission is done in each cluster-operating time slot (Anis et al., 2008). If the nodes perform two-hop transmission in each cluster operating time slot, then the delay time will be reduced. Hence, the concept of bridges has emerged where a bridge acts as a router and works between two CHs in order to transmit and receive the data.

The problems while constructing cluster tree are to allocate CHs, bridges, and leaf nodes, appropriately. Through CH, bridges and leaf nodes can receive and transmit. Thus, they cannot connect to each other directly. In the graph theory, they do not share any common edge. They can act as an independent set. By determining a maximum independent set, we can construct a cluster tree with minimum number of clusters as expected (Tavakoli et al., 2012).

In ZigBee cluster-tree topology, the power-saving mechanisms are accomplished by IEEE 802.15.4 MAC superframe structure. Moreover, a light-weight tree routing protocol is enabled under a distributed address assignment policy that is configured by numerous system parameters. Even though the ZigBee cluster-tree network is effective, the topology often undergoes restricted routing and reduced bandwidth utilization. In a tree structure, any link failure will suspend data delivery and the recovery operation will cause overhead.

1.2.1 Types of Clustering

The following are the two major clustering approaches: distributed approach and centralized approach. In distributed approaches, the decisions for next CH elections are individually made by either cluster members or CH, whereas in centralized algorithms, there is a centralized node for electing new CH nodes. Distributed approaches usually consist of probabilistic methods in which selections of CH nodes are based on evaluation of expressions.

One of the most popular probabilistic schemes is Low-Energy Adaptive Clustering Hierarchy (LEACH). Although distributed algorithms have certain advantages in terms of energy consumption overhead and delay overhead, there is a lack of general knowledge of the entire network by a single node that cannot result in better efficiency during clustering. The presence of more energy resources and processing power makes BS, a good choice for shifting the burden of CH selection and cluster formation phases.

In centralized clustering approaches, selection of future CHs is decided by a node (usually BS). However, these approaches want the periodic communication with BS by sensor nodes to be up-to-date with the essential information regarding the present situation of the network. These approaches impose more energy and more delay overhead on the network. Some centralized methods exist that depend on the LEACH protocol.

1.2.2 Cluster Tree Topology

Cluster-tree topology (Fig. 1.4) is one of the special topology in a mesh network. In this figure, ZR denotes the ZigBee router, ZED denotes the ZigBee End Device and ZC denotes the ZigBee Coordinator

In this topology, there is a routing path between any pair of nodes and a distributed synchronization mechanism that operates in beacon-enabled mode. There is a unique ZC and a ZR in each cluster. Full function device (FFD) can act as a ZR to provide synchronization services to its child nodes, that is, ZEDs or ZRs.

In cluster-tree networks, duty-cycles can be dynamically managed in a per-cluster basis and it is possible to carry out the worst-case network dimensioning, both in terms of worst-case buffer occupation and message end-to-end delays (Koubâa, Anis et al., 2008).

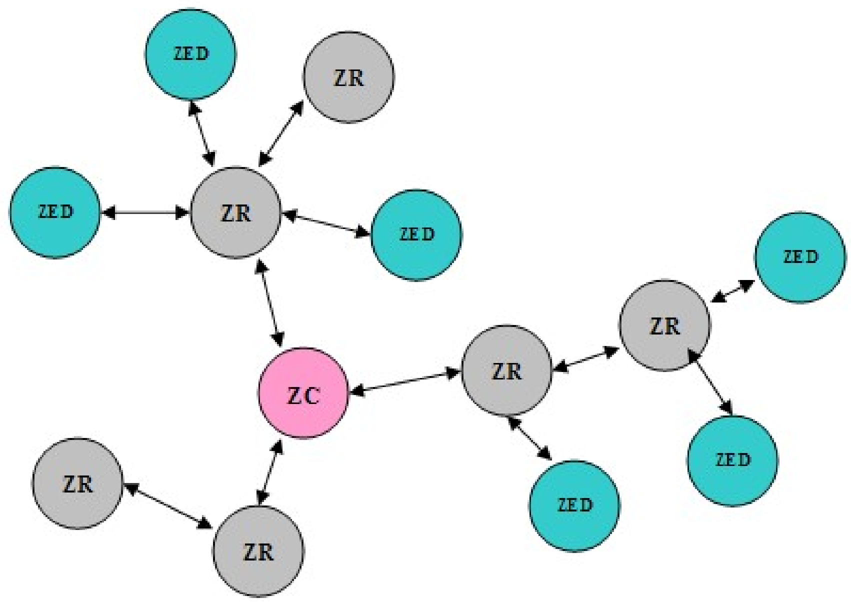

Fig 1.4 Cluster-tree Topology

Even if the ZigBee cluster-tree network is effective, the network topology can be suffered due to the presence of restricted routing and reduced bandwidth utilization. Here, any link failure will interrupt the data delivery and the recovery operation causes a considerable overhead. The ZigBee topology can prevent the usage of several potential routing paths. As a result, a considerable amount of bandwidth cannot be utilized.

In a constructed WSN, the information regarding certain area of interest can need additional investigation. Accordingly, the sampling rate of the sensors deployed in that area will be raised, and more traffic occurs in the network. Since the ZigBee cluster-tree topology did not provide adequate bandwidth for the increased traffic load, the additional information will not be successfully distributed (Chiara et. 2009).

1.3 Problem Identification

In ZigBee cluster-tree network, the existing literature works did not provide combined solution for co-channel interference and power efficient scheduling. In addition, the technique that prevents network collision is not explained. When the network has multiple nodes in MAC layer, the performance will decrease due to collisions. In Quality-of-Service (QoS)-aware routing for IEEE 802.15.4 Networks, issues in delay and reliability domains can occur. IEEE 802.15.4 Network faces difficulties like congestion, and in admitting real time flows in IEEE 802.15.4 Zigbee networks.

When the network has multiple nodes in MAC layer, the performance will decrease due to collisions. Hidden Terminal Problem (HTP) in star network occurs, when multiple out-of-range nodes assume a free channel and starts time-overlapping packet transmissions. This results in packet collision at the receiver node. FFD has full 802.15.4 functionality. All features of this standard provides no mechanisms for coordinated and energy efficient FFD to FFD packet transmission. Hence, FFD need to be kept powered on as communication is consequently realized through CSMA-CA. This situation can reduce the operative lifetime of node.

A good QoS provisioning framework should consider the overheads associated with the operating system and networking protocol stack on a node's ability to send and receive data. When the data is transmitted using CSMA-CA mechanism, there is a possibility for data to get lost or corrupted. When the channel is busy due to heavy traffic, the data may not get delivered. The data rate is significantly reduced in indirect data transmission due to sending the data periodically. Hence, there is requirement of rate control mechanism.

1.4 Objectives

The main objectives of the research are:

- To design an **Energy Efficient Cluster Scheduling and Interference Mitigation for IEEE 802.15.4 Network** for reducing the energy consumption and the network collision.
- To develop **QoS Aware Inter-Cluster Routing Protocol for IEEE 802.15.4 Networks** for providing reliability.
- To design an **Adaptive Data Rate Control for Clustered Architecture in IEEE 802.15.4 Networks** for providing scalability.

1.5 Proposed Contributions

1.5.1 Energy Efficient Cluster Scheduling (EECS) and Interference Mitigation for IEEE 802.15.4 Network

In this chapter, Energy Efficient Cluster Scheduling and Interference Mitigation (EECS) for IEEE 802.15.4 Network have been proposed. In this technique, a time division cluster scheduling technique has been recommended that offers energy efficiency in the cluster-tree network. In addition, an interference mitigation technique has also been demonstrated which detects and mitigates the channel interference based on packet-error detection and repeated channel-handoff command transmission. The proposed technique provides an energy efficient interference detection and avoidance method in order to provide reliability during the data transfer.

The performance of the proposed EECS is compared with Zigbee cluster tree (ZCT) architecture according to the performance metrics such as average end-to-end Delay, average packet delivery ratio, packets received, packets dropped, and energy consumption. By simulation results, it has been shown that the proposed technique reduces the energy consumption and packet drop due to network collision and hence improves the packet delivery ratio and throughput.

1.5.2 QoS Aware Inter-Cluster Routing (QAICR) Protocol for IEEE 802.15.4 Networks

The present research proposes a QoS aware inter cluster routing (QAICR) protocol in the cluster tree network. It consists of modules such as reliability module, packet classifier, hello protocol module, routing service module. The data is transferred from MAC layer to network layer in reliability module, which takes care of transmission of messages and acknowledgements. Packet classifier classifies the data and hello packets. The data packets are classified based on the priority. Hello protocol module constructs neighbour table and maintains information about neighbour nodes reliabilities. Next using the routing service module routing table is built and the data packets are classified into RSP and OP. The delay in the route is controlled using delay metrics, which is a sum of queuing delay and transmission delay.

The proposed QAICR protocol is compared with QoS-aware Peering Routing Protocol (QPRR) according to the performance metrics such as average packet delivery ratio, packets received, packets dropped, and energy consumption.

Simulation result shows that the proposed technique can reduce the drop and energy consumption with the increased delivery ratio and throughput.

1.5.3 Adaptive Data Rate Control for Clustered Architecture in IEEE 802.15.4 Networks

In this work, an adaptive data rate control for clustered architecture has been proposed in IEEE 802.15.4 networks. A data rate control mechanism mitigates the effect of congestion and admits real-time flows in IEEE 802.15.4 Zigbee networks. A network device is developed to regulate its data rate adaptively using the feedback message i.e. Congestion Notification Field in beacon frame received from the receiver side for preventing congestion and packet dropping based on current network buffer status. The network device controls or changes its data rate based on CNF value. Along with this scalability is considered by modifying encoding parameters using Particle Swarm Optimization (PSO) to balance the target output rate for supporting high data rate. For scalability data rate control quantizer parameter is used during encoding to maintain target output rate.

The performance of the PSOADRC protocol is compared with the Adaptive Data Rate Control (ADRC) protocol based on the performance metrics such as average packet delivery ratio, average end-to-end delay, throughput and packet drop. Simulation result shows that the proposed PSOADRC protocol outperforms the ADRC protocol.

1.6 Organization of Thesis

The rest of the thesis has been organized as follows:

Chapter 2 – Literature Review on existing works of IEEE 802.15.4 networks

Chapter 3 – Discussion of the proposed Energy Efficient Cluster Scheduling and Interference Mitigation for IEEE 802.15.4 Network.

Chapter 4 – Discussion of the proposed QoS Aware Inter-Cluster Routing Protocol for IEEE 802.15.4 Networks.

Chapter 5 – Discussion of the proposed Adaptive Data Rate Control for Clustered Architecture in IEEE 802.15.4 Networks.

Chapter 6 – Conclusion and Future Work.

CHAPTER-2

LITERATURE REVIEW

2.1 Inter-Cluster Routing

Conventional routing in IEEE 802.15.4 networks depends on Ad hoc On-demand Distance Vector (AODV) protocol. AODV smoothens the mesh network building for data dissemination (Raghuvanshi and Tiwari, 2010). IEEE 802.15.4 MAC comprises two operational modes, namely, non-beacon-enabled mode and beacon-enabled mode. Energy can be conserved in its beacon-enabled mode using the RF sleep mechanism, though it suffers from lower data throughput. Meanwhile higher data throughput can be achieved in the non-beacon-enabled mode. Hence, this standard seems more attractive for providing multimedia services over the networked sensors, but with significant energy consumption (Feng Chen et al., 2010).

QoS is a measure of the service quality offered by the network to the applications and users. Some typical wireless data networks QoS requirements are throughput, latency, jitter, packet loss and so on (Feng Shu, 2008). A WSN must satisfy four QoS requirements for reliable implementation in industrial environment namely Scalability, Reliability, Timeless, Energy efficiency (Felipe D. M. Oliveira, 2014).

However a good QoS provisioning framework should consider the overheads associated with the operating system and networking protocol stack on a node's ability to send and receive data (Farooq and Kunz, 2012). In mission-critical network servicing a geographic area with risk of people's lives, the quality of service (QoS) for critical packet delivery is of prime importance as any significant transmission delay and packet loss could result in a terrible disaster. However, in traditional ZigBee cluster-tree networks, it is difficult to guarantee QoS for critical packet deliveries because of transmission bottlenecks (Yu-Kai Huang et al., 2012).

2.1.1 Review of Algorithms on Inter-Cluster Routing in IEEE 802.15.4 Network

Novel algorithms have been proposed to construct a cluster tree with near minimum delay (Yu et al. 2008). Specifically, these algorithms can adjust the cluster heads (CHs), bridges, and leaf nodes to obtain the near minimum number of clusters in the cluster tree. At the same time, they can reduce the largest number of the clusters traversed from sensors to the sink. The most important issue in building such a cluster tree is to assign CHs, bridges, and leaf nodes properly. Bridges and leaf nodes have to receive and transmit through CHs. So they cannot connect to each other directly.

In graph theory, they do not share a common edge and can be treated as an independent set. By finding a maximum independent set, a cluster tree can be constructed with the minimum number of clusters as expected. The methods can effectively reduce the total number of clusters up to 40% than previous works. As a result, the average delay time of IEEE 802.15.4 wireless sensor networks can be reduced significantly. However, this cluster tree construction algorithm may increase the time complexity. Moreover, the problem of heterogeneous components in Zigbee networks is not discussed here.

Energy-Efficient Clustering in IEEE 802.15.4 Wireless Sensor Networks has been proposed (Tavakoli et al., 2012). An Adaptive Low-Energy Clustering (ALEC) algorithm is considered operating with IEEE 802.15.4 beacon enabled mode. The energy consumption of message exchanges is associated with ALEC algorithm. It is assumed that individual sensor nodes are battery operated and their transceivers are modelled after the 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver.

The impact of event sensing reliability and number of clusters on the network lifetime are evaluated. According to ALEC, rotating the role of CHs and forming new clusters require message exchanges between nodes and impose power consumption overhead on the network. The results show that energy consumption overhead and delay overhead of ALEC algorithm in worst cases are very low (overhead of power consumption is about 0.06% and overhead of delay is about 0.001 %.).

Implicit-Earliest Deadline First (Implicit-EDF) has been proposed, which assumes that all nodes in each cluster hear each other and that a table containing the characteristics of all the periodic traffic of the cluster has to be transmitted to the nodes in advance (Caccamo and Zhang, 2002). This assumption is uncommon in most of WSN applications.

LEACH, a clustering-based protocol using a randomized rotation and selection of cluster-heads has been proposed to optimize energy consumption (Heinzelman et al., 2000). After the random selection of cluster-heads, the other nodes decide to which cluster they belong, and inform the corresponding cluster-head (using CSMA/CA) of their decision. After the reception of all joint requests, cluster-heads compute a TDMA (Time Division Multiple Access) schedule according to the number of nodes in their cluster. This schedule is broadcast back to the node in the cluster.

Inter-cluster interference is mitigated using different CDMA (Code Division Multiple Access) codes in each cluster.

The clustering and synchronization approach differs from the ZigBee approach in three aspects. First, concerning clustering in ZigBee networks, coordinators are fixed. Second, the synchronization is not made using a TDMA schedule, but by means of periodic beacon frame transmissions, which has the advantage of higher flexibility. Finally, ZigBee does not allow the use of CDMA to avoid inter-cluster interferences, which leads to collisions between beacon and data frames issued in different clusters. In their case, a node that experiences collisions of beacon frames will inevitably lose synchronization. Hence, there is a need to schedule different beacon frames from different coordinators to avoid beacon frame losses that lead to undesirable synchronization problems.

The feasibility of ZigBee multiple cluster (cluster-tree) beacon-enabled networks has been analysed under the assumption of clusters working at full duty cycle (beacon order equals superframe order) (Ha et al., 2005). The authors conclude, with some empirical guidelines, that cluster-tree networks are feasible, but they do not provide any solution to the beacon scheduling problem in order to avoid beacon collision. In fact, they only analyse the probability of failed transmissions of both beacon transmissions and association procedures.

An integrated Inter-piconet scheduling approach that provides QoS assurance of Bluetooth scatternets has been proposed in WPANs (Chen and Lin, 2005). Also they proposed a time slot leasing based scheme to offer extra slave-to-slave QoS communication capability for minimizing the workload of master nodes as well as missing rate of QoS requests. Their proposed cluster-mesh-tree (CMT) QoS routing protocol retains the advantages of the traditional cluster tree structure while providing a backup routing mechanism for constructing optimally effective QoS routing paths. In CMT structure, there are tree-links similar to those of the traditional tree or cluster tree routing paths but with newly added mesh-links that facilitate finding the shortest routing path and decreasing the payload of cluster headers. The constructed CMT can be divided into two parts, a star-based cluster tree and a joined-graph.

2.2 Scheduling in IEEE 802.15.4 Network

In ZigBee sensor networks, scheduling is the process of allocating the active period to every node by means of providing time slots to avoid all feasible collision. The beacon schedule determines packet delivery latency from the end devices to the ZigBee coordinator at the root of the tree. Traditionally, beacon schedules are chosen such that a ZR does not reuse the beacon slots already claimed by its neighbours, or the neighbours of its neighbours. The beacon slots can be reused judiciously, especially when the risk of beacon collision caused by such reuse is low. The advantage of such reuse is that packet delivery latency can be reduced (Li-Hsing Yen, 2012).

As WSN has severe energy constraints, energy-based scheduling is required. Two existing energy-based scheduling algorithms are discussed in the following paragraph.

The sensing activity such as when to activate a node for sensing (active mode) and when to keep it idle (sleep mode) are done by scheduling. The scheduling technique is used to divide all nodes into disjoint subsets and each of which needs to satisfy the coverage constraints (Guofang Nan et al., 2012). Only one disjoint subset is in active state to provide the functionality and the remaining is in the sleeping mode. Once the active disjoint subset runs out of energy and consequently cannot maintain coverage constraints, another disjoint subset will be selected to enter the active mode and provide the functionality continuously (Francesco De Pellegrini et al., 2011).

With the recent improvement in the significance of beacon collision problem, a number of possible solutions have been proposed that can be broadly classified into two categories: proactive and reactive methods.

2.2.1 Types of Scheduling

Some of the scheduling mechanisms are briefly discussed below:

Channel Scheduling**:**

Due to inherent limitations in the network, neither type has provided substantial solutions to the beacon collision problem. A Channel scheduling scheme is mandatory to solve beacon conflict problems. This scheme is an adaptive method with fast recovery that is used to reduce the possibility of beacon collisions by managing the multiple available channels in a hybrid manner (both proactive and reactive methods).

Channel scheduling utilizes multiple channels via dynamic transitions. Personal Area Networks (PANs) present in the same channel can schedule the packets dynamically by overhearing each other. This scheme scans other candidate channels during the idle period. When a device identifies a beacon collision, the coordinator will re-associate with the device through the candidate channel that was confirmed to be clear, whereas the original channels are utilized for other devices during their active period.

A coordinator has both active and inactive periods to form the duty cycles of the devices. If a device notifies its coordinator of a beacon collision in the next active period, then the coordinator commands the device to change its channel during the next inactive period. The coordinator that receives the beacon conflict notification command frame sends a channel switching command frame to the device.

The channel switching command frame comprises a clear channel that the coordinator determines by scanning during the inactive period and a time offset, which is the difference between the original beacon transmission time and the transmission time of the new beacon frame to transmit on the new clean channel. The coordinator switches to new clean channel present in the channel switching command frame on this channel. After receiving the beacon frame that the coordinator transmits on new channel, the device can communicate with the coordinator (Kim et al., 2013).

Power Aware Real-time message scheduling:

To exchange messages between Low Rate Wireless Personal Area Networks (LR-WPAN) devices, a message scheduling algorithm is needed. In particular, periodic real time messages are considered. There are several message scheduling algorithms but since specific parameters in the standard must be considered in order to schedule a message set, it is difficult to use them directly in the LR-WPAN. This problem can be avoided by using a real-time message scheduling algorithm (Yoo et al., 2004).

This scheduling algorithm achieves scheduling by minimizing the energy expenditure of real time wireless networks. It comprises two general components (admission controller and energy consumption controller) and a scheduler. Admission controller performs the function of controlling and maintaining the flow. The packets without any feasible deadline are rejected by the admission controller. Scheduler schedules the accepted packets with the help of earliest deadline first scheduling algorithm. Energy consumption controller is utilized to diminish the node's energy consumption rate by looping the incoming packets. But, Power Aware Real-Time Message Scheduling (PARM) offer energy consumption techniques using several components so that it is not suitable for large scale network and real time multimedia messaging.

Cluster-Tree Based Scheduling:

In cluster-tree WSNs, the flows traverse different clusters on their routing paths from the source nodes to the sink nodes. The clusters may have collisions when they are in the neighbourhood. Thus, the key problem is to find a periodic schedule which specifies when the clusters are active while avoiding possible inter-cluster collisions and meeting all flows' end-to-end deadlines.

The fact that the cluster is active only once during the schedule period leads to so called cyclic behaviour of periodic schedule (i.e. time between the instant when a source sends the message and the instant when the sink receives this message spans over several periods) when there are the flows with opposite direction in a WSN. Since wireless nodes are usually battery-powered, the objective is also to minimize the energy consumption of nodes by maximizing the schedule period (consequently maximizing time when the nodes stay in low-power mode) (Zdenek, and Jurcik, 2010).

Sleep/wakeup scheduling;

In this scheduling algorithm, nodes can send the data efficiently with least energy consumption by switching between sleep mode and active mode. It utilizes the tree-based architecture in order to transmit the data. Further, this algorithm can be characterized in terms of Communication Period (CP), where nodes are either in sleep or awake mode. When node is in active period, it is termed as awake. The switching period between sleep and awake creates more impact on the stage of contention and collision. Contention is lessened significantly by staggered schemes for the nodes which do not depend on message instantly but forward them to routing tree. In simple, node and parent node are communicated only during active period (Gurjit, and Ahuja, 2011).

2.2.2 Review of Algorithms on Scheduling in IEEE 802.15.4 Network

A Time Division Beacon Scheduling (TDBS) mechanism has been proposed for building a ZigBee cluster-tree WSN based on a time division approach (Koubâa et al. 2008). Importantly, the TDBS mechanism can easily be integrated in the IEEE 802.15.4/Zig-Bee protocol stack with only minor add-ons. The worst-case dimensioning of cluster-tree networks can be tackled under this approach. Thus, by engineering cluster-tree networks according to TDBS, it will be possible to experimentally assess and validate the theoretical results obtained.

The beacon frame collision problem is identified and analysed. After that, a beacon frame scheduling mechanism is proposed based on the time division approach to build a synchronized multi-hop cluster-tree WSN. A duty-cycle management methodology is proposed for an efficient utilization of bandwidth resources in the cluster-tree network. Finally, the feasibility of the TDBS mechanism is demonstrated through an experimental test-bed. Results show that this mechanism achieves a milestone towards the use of the ZigBee cluster-tree topology in wireless sensor/actuator networks with energy and timing requirements, filing the existing gap in the IEEE 802.15.4/ZigBee standards. However, the failures in cluster tree topology are not studied. The authors presented the rule for slot reuse but did not detail how to realize it.

A framework is formulated where the risk of slot reuse between any two nodes are analysed (Yen et al. 2012). If the calculated risk is high, the slot reuse is disallowed. Otherwise, slot reuse is allowed. This is essentially the heart of the ZigBee-compatible, distributed, risk-aware, probabilistic beacon scheduling algorithm. Simulation results confirm that the slot reuse rule represented by the core algorithm is better than the slot reuse rules supported by the specification and prior work in the literature, and centralized algorithms with complete topology information offer hardly any advantage over their distributed counterparts that demand only local neighbourhood and parenthood information. A new parent-selection rule is proposed as an augmentation to the core algorithm. Simulation results confirm the benefit of this rule in further reducing message latency.

A novel distributed coverage-guaranteed sleep/wake scheduling algorithm (CDSWS) has been proposed (Nan et al. 2012). In CDSWS, a cluster hierarchy based network framework is considered, and a minimum number of nodes are selected to be active to monitor the area while maintaining better coverage and connectivity in this article. It is assumed that the communication radius of a sensor is equal to or greater than twice of its sensing radius, which has been proved that the coverage of a region implies connectivity of the network. Moreover, a sensor is selected to be in sleep mode based on its sensing radius. If a sensor is in the sleep mode, its whole working area can also be covered by other active nodes, which does not affect whole coverage performance. Thus, any point in the region can be covered by those active nodes and any two active nodes are connected.

In addition, a dynamic node selection mechanism is also adopted in each cluster to maintain network performance. To overcome the deadlock problem in clusters merging, a set of rules are illustrated to avoid existing deadlocks. For each clusterhead, when it sends request to other clusters while receiving other requests simultaneously, obtaining respond from its requesting object or answering other requests is determined by these rules, consequently, merging delay and energy consumption are reduced.

A framework for the synchronization of wake-up schedules has been proposed (Pellegrini et al., 2011), which plays a central role for energy saving in wireless networks, under the joint request to satisfy per node energy and delay constraints. This work left out several interesting directions. In particular, for relatively small numbers, factorization can be done in practice. In turn, the optimal choice of the factor basis and of periods is a key problem to limit the drift of the rendezvous times. However, the wake up problems is not discussed in their research.

Kim et al. (2013) proposed a novel beacon collision avoidance algorithm that utilizes the multiple channels through dynamic transitions. PANs on the same channel can be dynamically scheduled by overhearing each other. This scheme is to scan other candidate channels during the idle period and, then, if a device identifies a beacon collision, the coordinator re-associates with the device via the candidate channel, while the original channels are used for other devices during their active period. A coordinator has Active and Inactive periods which are used to form the duty cycles of the devices. If a device notifies its coordinator of a beacon collision in the next Active period, the coordinator commands the device to change its channel in the next Inactive period. The coordinator that receives the beacon conflict notification command frame sends device a channel switching command frame.

The coordinator switches to new clean channel that is contained in the channel switching command frame on this channel. After receiving the beacon frame that the coordinator transmits on new channel, device can communicate normally with the coordinator. This scheme can shorten the recovery time after a beacon collision occurs by identifying an available channel to switch to by scanning in advance during the inactive period. Simulation results show that this scheme can solve the beacon conflict problem efficiently and rapidly, irrespective of the number of coordinators in the adjacent area.

A real-time message scheduling algorithm has been proposed by (Yoo et al. 2004), which is applied to schedule periodic real-time messages in IEEE 802.15.4 for LR-WPAN. The standard allows Guaranteed Time Slots (GTSs) in the optional use of a superframe structure in a beacon-enabled network to be used to exchange real-time messages. A proper message scheduling algorithm is needed in order to utilize these features of the standard efficiently.

The off-line message scheduling algorithm, which is based on a distance constrained scheduler, generates the standard specific parameters including BO, SO, and GTS information to schedule the given message set. The algorithm is evaluated by simulation and the guaranteed time service using the schedule is implemented and evaluated on CC2420DB, which is a prototyping platform including an IEEE 802.15.4 compliant transceiver of Chipcon AS. However, they did not provide the mathematical analysis, on-line scheduling and scheduling of a periodic real-time messages, and the designing of scheduling algorithms in terms of power-awareness.

An adaptive rate control low bit-rate video transmission over wireless Zigbee networks has been proposed (Zainaldin et al. 2008). ZigBee is a promising protocol stack designed specially to facilitate low cost and low power communication running within a PAN. A generation method of video models enables the study of the performance of video over wireless Zigbee networks without the need for transmitting the real video since both the original and modelled traffic provide similar statistics.

The rate control variable-bit-rate (RC-VBR) algorithm is introduced that outperforms the video transmission over IEEE 802.15.4 using traditional techniques. The quantization parameter is changed adaptively for the different video sources by continuously monitoring the buffer occupancy. The performance metrics are calculated for the original MPEG4 source while all other sources are fed by the TES models. A combination of region-of-interest (ROI) and RCVBR is studied for improved video surveillance by adding more video sources to the network. However, this algorithm is not suitable in case of multiple channels and multiple interfaces over the IEEE 802.15.4 network.

Energy-efficient wakeup scheduling for maximizing lifetime of IEEE 802.15.4 networks has been proposed (Mirza et al., 2005). This technique can intelligently select the operating point of each node in this tradeoff space, such that nodes that would otherwise be energy-critical conserve more energy. The bottlenecks can be efficiently alleviated because of energy-critical nodes, and as a result extend the overall lifetime of the network. This technique intelligently selects the power-save mode of each node to optimize the overall network lifetime, is extendable to asynchronous variants of power-save mode. However, in that approach there are no guarantees on keeping synchronization due to possible beacon frame collisions.

This scheme calculates the optimal settings centrally. Since nodes are idle for extended periods of time, this compensation proves significant and it is shown that the lifetime of an IEEE 802.15.4 network improves up to 65% while ensuring that an end-to-end delay constraint is met. However, this scheme did not consider the distributed version. Hence, it is not suitable for very large and decentralized networks.

An intuitive approach to ZigBee-compatible beacon scheduling is to completely avoid reusing beacon slots (Lopez-Gomez et al., 2008). The ZC allocates an exclusive beacon slot to each ZR upon the ZR's associations with the network. Since all ZRs use exclusive beacon slots, beacon collisions are impossible but the number of ZRs that can be accommodated by the network is limited. The resultant schedule is also not optimal in terms of message latency. Superframe Duration Scheduling (SDS) assumes a configuration with heterogeneous BI/SD settings.

It determines whether the given configuration is schedulable, and provides a collision-free schedule that may span several superframes when the answer is positive. However, SDS still does not consider reusing beacon slots. Spatial reuse of beacon slots is the key to minimizing the latency of data delivery.

Koubâa et al. (2008) proposed i-GAME, an implicit GTS Allocation Mechanism in beacon-enabled IEEE 802.15.4 networks. The allocation is based on implicit GTS allocation requests, taking into account the traffic specifications and the delay requirements of the flows. The i-GAME approach enables the use of one GTS by multiple nodes, still guaranteeing that all their (delay, bandwidth) requirements are satisfied. For that purpose, they have proposed an admission control algorithm that enables to decide whether to accept a new GTS allocation request or not, based not only on the remaining time slots, but also on the traffic specifications of the flows, their delay requirements and the available bandwidth resources. In iGAME the coordinator assigns the requested GTS slots depending on the availability of the bandwidth and following a First Come First Served (FCFS) scheduling policy. Flows are indistinguishable for what concerns data content, and the bandwidth allocation is based on data rate and packet length only. iGAME shares the same GTS among multiple data flows in order to improve the bandwidth utilization. Moreover, the flows are eligible to remain unserved if activated after the saturation of the guaranteed bandwidth.

It is showed that their approach improves the bandwidth utilization as compared to the native explicit allocation mechanism defined in the IEEE 802.15.4 standard. They also presented some practical considerations for the implementation of i-GAME, ensuring backward compatibility with the IEEE 801.5.4 standard with only minor add-ons. Finally, they have resented an experimental evaluation on a real system that validates their theoretical analysis and demonstrates the implementation of i-GAME.

For the problem of finding a collision-free schedule for ZigBee tree networks that minimizes the maximal converge casting latency Pan and Tseng, (2008. proposed two heuristic scheduling algorithms, namely centralized tree-based assignment and distributed slot assignment (DSA). Centralized tree-based assignment requires complete topology information as input and is not much better than DSA. In DSA, each node *u* chooses the slot that gives the lowest latency with respect to *u*'s parent, but at the same time does not collide with the slots occupied by the nodes in *u*'s 2*r*-neighbourhood (*r* is the radio range).

The authors studied how to minimize the latency of broadcasts from the ZC to every end device as well as convergecast latency at the same time. The resultant schedule demands a modification on the original ZigBee superframe structure to allow each ZR to participate in four active periods within a BI, two for cascading convergecast schedules and the other for cascading broadcast ones. This work also considers the same 2*r*- neighbourhood interference model.

A Time Division Cluster Scheduling (TDCS) mechanism has been proposed by Zdenek Hanz´alek et al. (2010). Their proposed scheme is constructed based on the cyclic extension of RCPS/TC (Resource Constrained Project Scheduling with Temporal Constraints). It is a problem for a cluster-tree WSN and it assumes bounded communication errors. It is designed to meet all end-to-end deadlines of a predefined set of time-bounded data flows while minimizing the energy consumption of the nodes by setting the TDCS period as long as possible.

Since each cluster is active only once during the period, the end-to-end delay of a given flow may span over several periods when there are the flows with opposite direction. This scheduling mechanism assists system designers to efficiently configure all required parameters of the IEEE 802.15.4/ZigBee beacon-enabled cluster-tree WSNs in the network design time. However, the method for investigating the adaptive behaviour of scheduling problem is not discussed when new tasks are added to the original schedule. Interference occurred at the channel is not discussed.

The RT-Link protocol has been proposed, which provides a centralized synchronization scheme based on time sync pulses sent by a global clock for indoor and outdoor fixed devices (Rowe et al., 2006). These sync pulses indicate the beginning of each time-slotted cycle and the first frame being sent. This protocol is similar to the IEEE 802.15.4 protocol since it also uses a superframe structure with contention-based and contention-free periods. The authors also proposed a centralized mechanism for dynamic slot re-use and assignment in multi-hop networks, to reduce delays. The use of a global synchronization clock, however, may not be practical for some sensor network applications, especially for synchronization in large-scale networks.

A CoZi has been presented, which is a new packet scheduling mechanism for large scale ZigBee networks (Salhi et al., 2010). CoZi aims at enhancing the reliability of the data delivery and the bandwidth utilization of the network. Their scheduling mechanism entirely based on simple network coding at intermediate nodes to offer better bandwidth utilization and reliable communications with extremely negligible network overhead. Using clever topology inferring from ZigBee signalization messages, this mechanism helps to perform more optimized coding decisions in order to allow a larger range of decoding nodes whether for routed or dissemination based ZigBee sensor networks. CoZi can be included in sleep-awake mechanisms for better energy efficiency.

Their proposed two coding strategies that can be used at each node to maximize the bandwidth utilization of a ZigBee sensor network depending on the nature of its data traffic. To this end, any ZigBee router can perform network coding operations before data transmissions by combining packets using simple XOR operations. The coding decision takes into account that a maximum number of nodes have to be able to decode the outgoing coded packet. However, this technique is not energy efficient and channel interference is not considered.

A novel scheduling algorithm has been proposed for WMSNs (Watfa et al., 2009). Their algorithm divides the frame sent from the cluster-head to the Base Station (BS) into slots and gives a percentage of these slots into each node. The base station (BS) sends a certain query to the cluster-head. Upon receiving query, the cluster head will propagate it to specified nodes and wait for these nodes to sense the medium and come back with needed data. The nodes will respond by sending packets of data to the cluster-head. The job of the cluster head is to schedule these packets coming from different nodes to send them in frames to the BS. One of the advantages of this algorithm is that it is derived for a multi-user network and it is shown to converge to the optimal schedule. Another advantage is that the setting is realistic and thus it is feasible.

V-route has been proposed as an 802.15.4 compliant packet scheduling and routing policy to enable energy-efficiency and high reliability in both single hop and multihop environments (Ruzzelli et al., 2010). V-Route enhances the 802.15.4 with three energy optimization techniques. Experimentations of V-route yielded high data delivery rate and energy reduction ranging from 27.3% to 85.3% against a beaconless 802.15.4. However, they have not considered the throughput metrics and channel interference in the network.

The problem of scheduling a set of packets with minimum energy has been considered (Nair et al., 2002). Designing energy efficient transmission policies for randomly arriving traffic with delay constraints has been studied. The MoveRight algorithm has been proposed, which minimizes energy required to transmit packets in a wireless environment. It is motivated by the observation that in many channel coding schemes it is possible to significantly lower the transmission energy by transmitting packets over a longer period of time. Scheduling combined with adaptive power control schemes could potentially yield interesting results.

The scheduling in Zigbee has been found in the line topology, the time slot can be assigned from the farthest node from the sink. In the ring topology the time slot is also assigned from the farthest node to fill the first half ring (Tseng and Pan, 2006). The next half is filled from the node nearest to the sink and the time slot is chosen from the one that does not conflict with neighbours. In the line and ring topologies the best scheduling can be found. In a breadth-first search (BFS) tree topology centralized and disturbed scheduling can be studied. These two methods can be used for scheduling in a cluster tree.

A new multichannel allocation protocol has been proposed for ZigBee/IEEE 802.15.4 networks (Stéphane Lohier et al., 2011). The main goal is to improve the global throughput which is basically insufficient to satisfy high bandwidth requirements for applications like monitoring or traffic control. The solution is based on the availability of multiple channels on current low-cost, low-energy radio transceivers, such as CC2420, which can be easily tuned dynamically to different frequencies. This possibility can be exploited to increase the number of simultaneous transmissions on adjacent links.

The allocation of the different channels is centralized and distributed by the coordinator thanks to a function designed to compute the channel offset between two successive children routers. In the nodes, the switching process between the transmission and the reception channels is triggered starting from the PHY primitive available on the transceiver. The evaluation shows that the proposed protocol improves the global throughput by a factor between 2 and 5, depending on the scenario, compared to the single-channel solution or a random channel allocation.

GST scheduling algorithm (GSA) has been proposed (Na et al., 2008). They have designed an optimal work-conserving scheduling algorithm for meeting the delay constraints of time-sensitive transactions and show that the proposed algorithm outperforms the existing scheduling model specified in IEEE 802.15.4. They also have proposed an Earliest Deadline First (EDF)-based scheduling algorithm to minimize the total number of unallocated GTSs. GSA tries to smooth out the traffic by distributing the GTSs of a transaction over as many beacon intervals as possible while satisfying its timing constraint. On the other hand, the flows are indistinguishable, so it is not possible to select a subset of packets to be dropped in case of overload.

An adaptive GTS allocation (AGA) scheme for IEEE 802.15.4 has been proposed with the considerations of low-latency and fairness (Huang et al., 2008). The scheme is designed based on the existing IEEE 802.15.4 medium access control protocol without any modification. AGA has been designed to solve the starvation problem providing fairness and low latency to flows. The coordinator computes the GTS schedule for the new beacon interval depending on the bandwidth requests and traffic priority sent by end devices in the previous beacon interval. AGA is not focused on real-time acting on ordinary network metrics like fairness and average latency.

AGA scheme is a two-phase approach. In the classification phase, devices are assigned priorities in a dynamic fashion based on recent GTS usage feedbacks. Devices that need more attention from the coordinator are given higher priorities. In the GTS scheduling phase, GTSs are given to devices in a non-decreasing order of their priorities. A starvation avoidance mechanism is presented to regain service attention for lower-priority devices. A simulation model validated by the developed mathematical analysis is presented to investigate the performance of AGA scheme. The capability is evaluated by a series of experiments and shown that this scheme significantly outperforms the existing IEEE 802.15.4 implementations. However, the larger buffer can introduce the larger latency in the network. Energy efficient scheduling is not discussed for bandwidth utilization.

Jiang et al. (2008) proposed an energy-aware, Sleep Scheduling algorithm for Multiple Target Tracking (SSMTT). SSMTT has been proposed to improve the energy efficiency through a sleep scheduling approach that is conscious of concurrently tracking multiple targets, in contrast to an approach which is not. They introduced a linear target movement model as the foundation for energy efficiency optimization. Based on the movement model, they presented a tracking subarea management mechanism and sleep scheduling for nodes. They introduced an energy saving approach to reduce the transmission energy for alarm broadcasts.

The SSMTT algorithm can describe the target movement, especially its potential moving directions, with a probabilistic model and manage tracking subareas to reduce the number of proactively awakened nodes. They can also leverage the overlapping broadcasts for multiple targets to reduce the energy consumed on proactive wake-up alarm transmission; and schedule the sleep patterns of the subarea member nodes to shorten their active time. The energy saving effort for proactive wake-up alarm transmission is used to cancel the alarm broadcast completely if a zone that is close to the root node is reusable, and reduce the transmission power of the alarm broadcast if a zone that is far from the root node is reusable and all the zones that are closer to the root node than it are not reusable. The experimental evaluation shows that SSMTT can achieve better energy efficiency and suffer less performance loss than single target tracking algorithms.

2.3 Interference Mitigation

IEEE 802.15.4 networks may not work properly in the presence of co-channel interference from other radio systems in the 2.4 GHz ISM band such as IEEE 802.11x wireless local area network (WLAN). The beacon-enabled cluster-tree network can be more susceptible to the interference mainly due to the increase of local interferers. In IEEE 802.15.4 networks, the interference mitigation is of critical importance.

To alleviate the interference problem, ZigBee alliance has proposed an interference avoidance scheme. The coordinator of ZigBee network detects the presence of interference by measuring the packet errors. When the packet error rate exceeds a threshold, it selects a channel for the channel-handoff by scanning all the available channels. Then, it delivers the information on the channel-handoff to the entire network by broadcasting a channel-handoff command through the channel being interfered, which makes it difficult to reliably deliver this command.

Moreover, this centralized mitigation scheme may encounter two major problems. First, it may require considerable amount of signalling overhead since the channel handoff command should be broadcasted to the entire network even when the interference occurs locally. Secondly, it may not be easy to select a single idle channel for large-scale network due to heavy use of the ISM band by other radio systems.

These issues can be alleviated by mitigating the interference in a distributed manner. However, these schemes may not be applicable to the beacon-enabled cluster-tree network. The presence of interference can be detected by means of packet-error detection and/or spectrum sensing in each cluster. When the presence of interference is detected, the coordinator notifies the presence of interference to its end devices (not all the devices of the entire network) by sending channel handoff command in the beacon frame, referred to MT beacon. Then, it changes the operation mode from the normal single-channel transmission (ST) mode to a multichannel transmission (MT) mode.

2.3.1 Review of Algorithms on Interference Mitigation

A Bluetooth Interference Aware Scheduling (BIAS) algorithm (Golmie, et al., 2003) is a dynamic scheduling algorithm to reduce the interference between Bluetooth and IEEE 802.11. It consists of several components, namely, dynamic channel estimation, credit computation, and access priority. Its main algorithm is that a data transmission to a slave experiencing a bad frequency is postponed until a good frequency is found in the hopping pattern.

Since a slave transmission always follows a master transmission, using the same principle, the master avoids receiving data on a bad frequency by avoiding a transmission on a frequency preceding a bad one in the hopping pattern. Thus, it is to guarantee system performance requirements such as QoS while reducing the effect of the interference by WLAN. The performance metrics include the packet loss, the mean access delay, and the channel estimation transient time. BIAS supports QOS and maintains a low access delay for delay-sensitive traffic such as video applications.

In IEEE 802.15.4, a beacon-enabled cluster-tree network to mitigate interference has been presented by Han et al. (2011). This scheme detects the presence of interference using packet-error detection and channel sensing in a cluster wise manner. In the presence of interference, the coordinator fast notifies the presence of interference to its end devices by repeatedly transmitting the channel-handoff command. Interference is avoided using temporary channel hopping via predetermined hopping channels. Finally, it selects the best one among the hopping channels as the final handoff channel. This scheme provides the marked performance improvement over conventional schemes even in the presence of heavy interference. However, they have not given any method for bandwidth utilization and scheduling.

An effective Radio Interference Detection (RID) algorithm to detect interference in a sensor network has been used by Zhou, et al., (2005). Its basic idea is that a transmitter broadcasts a High Power Detection packet (ID packet), and immediately follows it with a Normal Power Detection packet (ND packet). It is called an HD-ND detection sequence. The receiver uses the HD-ND detection sequence to estimate the transmitter‘s interference strength. After the HD-ND detection, each node begins to exchange the detected interference information among its neighbourhood, and then uses this information to figure out all collision cases within the system. The three stages of RID are HD-ND detection, information sharing and interference calculation. Using the RID algorithm, nodes detect interference. However, this algorithm doesn’t consider interference from heterogeneous wireless network system, such as WLAN and Bluetooth.

A particular Topology Control algorithm, the minimum interference algorithm (MIA), has been proposed, which aims to minimize the network interference while maintaining good spanner property (Feng, et al., 2008). Its basic idea is that coordinator detecting interference reduces its own transmission power. If node's transmission power is reduced, an interference that occurs among nodes using the same network protocol can be minimized. Since MIA minimizes network interference, it is optimal and has better performance than other algorithms in that respect. At the same time, compared with Gabriel Graph and *k*-NEIGH algorithms, MIA also has good spanner property. However, this algorithm doesn't consider interference from conventional wireless network system, such as IEEE 802.11.

A hybrid TDMA/FDMA MAC protocol called HYMAC has been proposed in which data gathered by sensor nodes are delivered to a base station (Soroush et al., 2007). The transmissions take place in a fixed-length TDMA cycle divided into several fixed time slots. The base station assigns an appropriate frequency (FDMA) and a specific time slot to each node (TDMA) by running a scheduling algorithm. The communication period in HyMAC is a fixed-length TDMA cycle composed of a number of frames. Each frame is equivalently divided into several fixed time slots where slot duration is the time required to transmit a maximum sized packet. In addition, a fixed number of consecutive slots in each cycle -starting from its beginning- form the scheduled slots while the remaining slots of that cycle are its contention slots.

The base station is responsible to assign an appropriate frequency as well as specific time slot to each node. Such scheduled node will be able to communicate in an energy-efficient collision-free manner turning off its radio when it is not necessary.

All scheduled nodes employ LPL on contention slots during which they randomly select one slot to send a HELLO message to the base station. The simulation results show that HYMAC outperforms MMSN for the number of potential conflicts but these performances are obtained by adding time slots when the number of frequency is insufficient which increases the risk of interferences. Consequently, the MAC layer is specific and not directly compatible with the IEEE 802.15.4 MAC layer or another CSMA/CA MAC layer.

TMCP, a tree-based multichannel protocol has been proposed to assign channels to different subtrees instead of nodes and to avoid interference between nodes of different sub-trees (inter-tree) without the need for time synchronization (Wu et al., 2008. A comparison shows that the performances of TMCP and MMSN are very close. TMCP partitions the whole network into multiple subtrees, allocates different channels to each subtree, and then forwards each data flow only along its corresponding subtree. This scheme can work well with a small number of channels and has a very simple transmission scheme without the need for synchronization at nodes, which makes it suitable for practical WSNs. The main drawback of TMCP protocol, according to the selected context, is the lack of coordination between the tree-based channel assignment scheme and the hierarchical association process already existing in ZigBee networks.

2.4 Rate Control

The process of switching data rates adaptively based on channel conditions, with the intention of selecting the rate that will provide the maximum throughput possible for a given channel condition is called rate control. This mechanism is used to improve the performance of wireless networks, which suffer from fading and interference. The rate selection utilizes the channel quality predictions to decide on the suitable rate. Generally, the threshold selection technique is utilized for rate selection. In this technique, the value of an indicator is matched up to with a threshold value list that denotes the boundaries among the data rates. Data transmission rates can be varied by different modulation schemes and coding techniques practically.

2.4.1 Need for Adaptive Data Rate Control

Rate control refers to the scalability of quality, size and frame rate, respectively in both the spatial and temporal model. Rate control involves modifying the encoding parameters in order to maintain a target output Bit rate by varying Quantizer Parameter (QP) or step size. It is used to transmit a large amount of data in a very short period of time (Samizadeh et al., 2013).

The network device transmits the data by adaptively regulating its data rate using feedback messages received from the receiver that can prevent unnecessary transmissions. Due to small memory size at the coordinator or network interface, packet dropping and congestion may occur which will reduce the network performance, throughput and energy efficiency.

To avoid the dropping of packets and enhancing the channel capacity which is desirable to prevent overflow and underflow at the network interface buffer that is balanced by considering the congestion situation at the sensor nodes and adopting adaptive data rate control to avoid this situation (Yeo et al., 2008). When using data rate control in IEEE 802.15.4 the cost of high data rate video transmission will be lowered (Zainaldin et al., 2008).

2.4.2 Challenges for Rate Control

The issues in rate control techniques are listed below:

- When several devices want to transmit data frames from the network device to the coordinator at the same time, consequently, severe queuing delays occur at network interface buffer which leads to packet dropping.
- Allocating a large buffer size may cause an increase in the queuing delay at the network interface buffer, which could result in TCP Retransmission.
- Due to beacon enabled mode of the fixed superframe structure cannot handle the traffic optimally in varying traffic conditions.
- When using compression scheme for data rate control leads to delay performance which is improper for priority of data.
- Substantial time synchronization is required since each GTS is assigned to a specific device.
- When using the mechanism of an adaptive data rate in the network devices must have to take into account the delivery capability of the coordinator to the network device (Wook Kim and Sun-Shin An, 2010).
- The main purpose of adaptive data rate control should minimize the power consumption while ensuring reliability and delay constraints in the packet transmission.
- If active period is longer than data rate, long idle time will waste large amounts of energy. If the period is too short, many backoff operations and collisions will consume large amounts of energy (Tiberi et al., 2010).

- Abuse of dedicated bandwidth might result in the exclusion of other transmissions.
- Control strategy should minimize the number of transmissions over the network (Khalid El Gholami et al., 2012).

2.4.3 Review of Algorithms on Rate Control

An effective solution has been proposed to Adaptive Scalable Rate Control to MPEG-4 applications over IEEE 802.15.4 (Samizadeh et al. 2013). Their computer simulation results confirm that use of PSO improves the quality of picture whilst reducing data loss and communication delay, when compared to conventional MPEG video transmissions. The Analysis of Variance (ANOVA) test, for the rate of frame rates, determined that there is a significant difference in the means between the three models. The result of the ANOVA test shows that this model in this research has less variation and spread, and no outside value. It can be concluded that the data range is in the target bit rate. Moreover, a nonparametric Kruskal-Wallis test determines that the CBR model has approximately the same variation as the VBR, and this indicates the high data rates in group of pictures for both models.

However, the result for the idea in this research shows that it also has the least variation and spread range of data rates in group of pictures. These results determine that the proposed method is superior to both the VBR and CBR methods. This model achieves an optimum level of quality of picture whilst maintaining the ZigBee target bit rate. The adaptive quantization increases the available bandwidth, which leads to improvement in the quality of picture by reducing the data loss.

The stability of IEEE 802.15.4 networked control systems (NCSs) is addressed (Tiberi et al., 2010). While in recent works fundamental results are developed for networks that are abstracted only in terms of packet loss and time delays, here the constraints imposed by the protocol to the feedback channel and the network energy consumption are explicitly considered. A general analysis for linear systems with parameter uncertainty and external bounded disturbances with control loops closed over IEEE 802.15.4 networks is proposed. To reduce the number of transmissions and thus save energy, a self-triggered control strategy is used. A sufficient stability condition is given as function of both the protocol and control parameters.

A decentralized algorithm to adapt jointly the self-triggered control and the protocol parameters is proposed. It is concluded that stability is not always guaranteed unless protocol parameters are appropriately tuned, and that event-triggered control strategies may be difficult to use with the current version of IEEE 802.15.4. However, the fundamental stability conditions are not analysed. The problem of scheduling the guaranteed time slots, for each combination of number of sensors and controllers, is not considered.

Shih et al. (2010) brought forth two fresh hash channel selection mechanisms for improving performance of IEEE 802.15.4. This hashing mechanism is simulated by using the network simulator NS-2 and the results are compared with those from the original protocol. The throughput is important for measuring the performance of a wireless sensor network. It can be seen that the throughput and utilization of the rehashing mechanism are better than the original. However, the curves reveal that the throughput and utilization rate are lower than original in the beginning. In addition, the results of the simulation show that average delay and drop-off of the rehashing mechanism are better than the original. However, the curves are higher than the original protocol in the beginning.

An adaptive data rate mechanism has been proposed (Indong Yeo et al., 2008). This algorithm first considers the network interface buffer capacity of the receiver (CH or coordinator) and the receiver monitors the network interface buffer state to determine whether it exceeds the threshold or not. If the number of packets in the network interface buffer exceeds the threshold, the coordinator broadcasts a new beacon message with a modified payload field to inform the network devices to control their data rate.

Through this mechanism, the performance can be increased in terms of both the throughput and energy efficiency. These two factors together allow the network lifetime to be extended. Through the performance evaluation, it is confirmed the validity of this mechanism using the NS-2 simulator and demonstrated its superiority over the current scheme. This data rate control mechanism will contribute to the performance enhancement of WPAN.

An adaptive contention control strategy (ACCS) has been recommended to solve the problem of transmission efficiency in IEEE 802.15.4. (Tseng et al., 2009). In the first stage, an MBS is used to detect the traffic load of IEEE 802.15.4 networks and to dynamically adjust the size of the backoff window based on the network load. Once the network load is considered-to be a heavy state by MBS, the second stage of ACCS distributes the tremendous amount of downlink packet transmission to the inactive period. This scheme can be implemented in the IEEE 802.15.4 MAC protocol standard without adding any new message type. An analytic model was developed to evaluate the performance of IEEE 802.15.4 and ACCS, which has been validated against simulation experiments. The simulation results demonstrate that the proposed scheme significantly improves the goodput, the average queuing delay, the average MAC delay, and the energy consumption.

Kim and An (2008) offered Differential Dynamic Traffic Control (DDTC) scheme for dynamic traffic conditions by measuring recent traffic status to determine the appropriate super-frame duration and used two-level queue scheduling for differential service. Coordinator obtained the delivery ratio through the data frame during the active period by measuring period traffic when accessing the channel. After classification of data type as priority type and non-priority type, priority means the device forwards the data to the transmission queue otherwise transferred to the compression queue for compression and waits until waiting time expires. After the expiration, data is compressed as a single packet then this process is repeated for non-priority data in the compression queue and forwards it to the transmission queue.

The simulation shows that DDTC provides a higher delivery ratio and differential service according to data types. DDTC consequently shows better performance in power consumption and priority traffic processing. Instead, an increase in queuing delay of non-priority traffic is inevitable and it is the only defect of DDTC. However, the elaborate and diverse scenarios are not analysed and this scheme is not considered for multihop connections.

A generalized Markov chain is considered significant to model these relations by simple expressions without giving up the accuracy (Park et al., 2011). The presence of limited number of retransmissions, acknowledgments, unsaturated traffic, and packet size is accounted for. The model is then used to derive an adaptive algorithm for minimizing the power consumption while guaranteeing reliability and delay constraints in the packet transmission. The algorithm does not require any modification of the IEEE 802.15.4 standard and can be easily implemented on network nodes.

Markov model of the of the slotted CSMA/CA mechanism of beacon-enabled IEEE 802.15.4 is developed by considering retry limits, ACKs, and unsaturated traffic regime. Based on developed Markov model, adaptive tuning of MAC parameters such as macMinBE, macMaxCSMABackoffs, macMaxFrameRetries are proposed using the physical layer measurement of channel sensing for constraints of reliability and timely communication of the packet delivery while minimizing the total energy consumption. Simulation results show that the analysis is accurate and that the proposed algorithm satisfies reliability and delay constraints, and ensure a longer lifetime of the network under both stationary and transient network conditions.

Summary

Most of the cluster tree construction algorithm may increase the time complexity. Moreover, the problem of heterogeneous components in Zigbee networks and the failures in cluster tree topology have not been studied to overcome the problems. The wake up problems and the mathematical analysis, on-line scheduling and scheduling of a periodic real-time messages, and the designing of scheduling algorithms in terms of power-awareness are not considered..

Energy-efficient wakeup scheduling is not suitable for very large and decentralized networks. RID algorithm did not consider interference from heterogeneous wireless network system, such as WLAN and Bluetooth. The method for investigating the adaptive behaviour of scheduling problem is not considered when new tasks are added to the original schedule. Interference occurred at the channel is not discussed. In Tibari et al. (2010), the fundamental stability conditions have not been analysed. The problem of scheduling the guaranteed time slots, for each combination of number of sensors and controllers, is not taken into account.

2.5 Conclusion

From the analysis of the existing mechanisms, the following conclusions are made:

- Some existing tree protocols did not consider QoS for constructing tree/cluster. None of the schemes use multiple tree construction.
- The existing clustering schemes for Zigbee networks did not use multiple tree topologies.
- A lot of scheduling schemes have been discussed. Some of them are not possible for large-scale network and real time messaging of multimedia content.
- Very few algorithms can be used for scheduling a cluster tree.
- Most of the scheduling schemes did not consider collision avoidance and power saving simultaneously. Also, they are not applicable for multiple cluster tree architecture.
- In ZigBee cluster-tree network, the existing literature works did not provide combined solution for co-channel interference and power efficient scheduling. In addition, the technique that prevents network collision is not explained.

To overcome these issues, effective techniques must be developed. The present research identifies and scrutinizes such problems and recommends workable solution to them through effective techniques. Hence the objectives of the present research can be formulated as:

- To design an Energy Efficient Cluster Scheduling and Interference Mitigation for IEEE 802.15.4 Network.
- To develop QoS Aware Inter-Cluster Routing Protocol for IEEE 802.15.4 Networks.
- To design an Adaptive Data Rate Control for Clustered Architecture in IEEE 802.15.4 Networks.

CHAPTER-3

ENERGY EFFICIENT CLUSTER SCHEDULING AND INTERFERENCE MITIGATION FOR IEEE 802.15.4 NETWORK

3.1 Overview

In this chapter, an Energy Efficient Cluster Scheduling and Interference Mitigation have been proposed for IEEE 802.15.4 Network. The nodes in the network are grouped to form a cluster. Then, a time division cluster scheduling technique is considered that offers energy efficiency in the cluster-tree network. The dynamic mode and beacon interval is calculated to schedule the time division scheduling. The interference in the channel is detected using channel sensing technique. Finally, an interference mitigation technique is used to mitigate the interference based on packet-error detection and repeated channel-handoff command transmission.

3.2 Cluster Tree Topology Model

Cluster tree is also called undirected tree as the wireless links are bidirectional. In this topology, there are two types of nodes, namely routers and end-nodes. The nodes in the network are arranged in the form of clusters. The router that forms the cluster is called cluster head. The data transmission of other end-nodes is handled by cluster head. As the nodes are only connected to the cluster head, multihop communication becomes difficult. Hence, the data is transmitted from one cluster to another until it reaches the sink. Figure 3.1 shows the cluster tree topology.

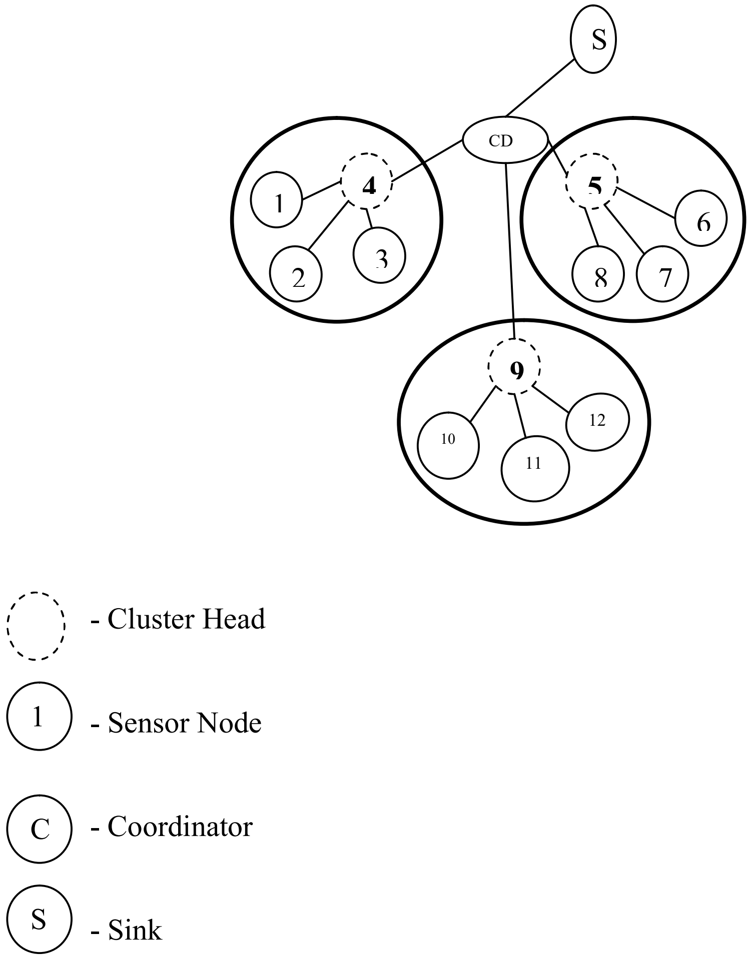

Fig. 3.1 Proposed Cluster Tree Architecture

3.3 Time Division Cluster Scheduling (CS_{td})

3.3.1 Dynamic and Stationary mode

Every cluster period (T_{BI}) corresponding to Beacon Interval (BI) is divided into dynamic and stationary mode (Hanzalek, Zdenek, and Jurcik, 2010).

Dynamic mode: In this mode, the segment is divided into 16 equal sized time slots with respect to the superframe duration (T_{SF}) and the data transmission is permitted.

Stationary mode: In this mode, the node goes to sleep mode for conserving the energy.

The structure of superframe is shown in figure 3.2 where the stationary and dynamic mode is defined.

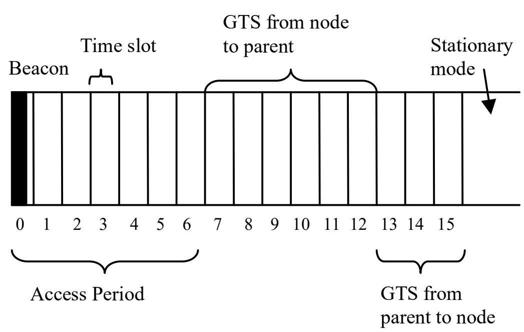

Fig. 3.2 Format of Superframe

Let T_{BS} be the base superframe period, and T_{BI} and T_{SF} are defined using two parameters such as Beacon order (O_{BI}) and Superframe order (O_{SF}), which is shown using following Eq. (3.1) and (3.2), respectively (Hanzalek, Zdenek, and Petr Jurcik, 2010).

$$T_{BI} = T_{BS}.\ 2^{O_{BI}} \tag{3.1}$$

$$T_{SF} = T_{BS}.\ 2^{O_{SF}} \tag{3.2}$$

3.3.2 Channel sensing technique

Let CNT_S be the channel-sensing counter. The channel sensing is performed during stationary period exclusive of dynamic intervals of neighbouring clusters. The interference is detected based on the following hypothesis related to absence (Hyp_0) and presence (Hyp_1) of interference signal that are defined as:

$$Hyp_0: RX(i) = \tau(i) \qquad (3.3)$$

$$Hyp_1: RX(i) = IR(i)\, S(i) + \tau(i) \qquad (3.4)$$

Where i = sample index

RX (i) = received signal

IR (i) = impulse response of channel

S (i) = signal transmitted from the interference source

$\tau(i)$ = additive Gaussian noise

The coordinator decides the existence of channel interference based on the following condition.

$$\eta = \begin{cases} 0; \lambda < E_{th} \\ 1; \lambda \geq E_{th} \end{cases} \qquad (3.5)$$

Where E_{th} = energy threshold

λ = Test statistics

$$\lambda = \frac{1}{a} \sum_{i=1}^{a} \left| RX(i)^2 \right| \qquad (3.6)$$

Where a is the number of samples taken for the test.

3.3.3 Cluster Scheduling Algorithm

The aim of cluster scheduling algorithm is to minimize the energy consumption of the nodes. This is accomplished by maximizing the Cluster Scheduling period (CS_{td}) in relative to beacon interval. Also, it prevents resource requirements such as inter-cluster collision and fulfils temporal requirements such as end-to-end deadlines of all the flows. All the clusters have equal BI, which is defined using O_{BI}. However, it contains various dynamic mode (T_{SF}), which is defined by O_{SF} in order to ensure efficient bandwidth utilization (Hanzalek, Zdenek, and Jurcik, 2010).

Let us assume a cluster tree topology that is described using adjacent matrix X = x_{ij}; the matrix represents a square matrix, which includes the total number of nodes in the network; a collision matrix Y = y_{ij} which represents the total number of clusters within the network. After initialization, the dynamic mode (T_{SF}) is estimated based on the data flow within the given cluster.

For each node N_j within cluster C_i, the number of allocated time slots need to be estimated for all flows towards transmitter (λ_j^{tx}) and receiver (λ_j^{rx}) side using Eq. (7) and (8) respectively.

$$\lambda_j^{tx} = \left\lceil \frac{T_{GTS1}}{c1} \right\rceil \qquad (3.7)$$

$$\lambda_j^{rx} = \left\lceil \frac{T_{GTS2}}{c2} \right\rceil \qquad (3.8)$$

Where T_{GTS1} and T_{GTS2}=period of Guaranteed Time Slot (GTS) for entire data transmission for transmitter and receiver, respectively.

c1 and c2 = Duration of a slot for transmitter and receiver, respectively.

After the estimation of dynamic mode, BI value is iterated from minimum to maximum value. BI_{max} given by max (O_{SF}) is rounded off to the nearest BI value towards T_{SR} among all the flows. Then, BI_{min} given by min (O_{SF}) is rounded off to the nearest BI towards all the clusters T_{SF}. If a optimal CS_{td} is found for given BI, time schedule, then the process will be repeated with new BI.

The steps involved in cluster scheduling are given in Algorithm-1.

Notations

R_j; C_j; N_i: Router; Cluster; Node; O_{SF}: Superframe order; T_{SF}: Clusters dynamic mode; T_{SR}: Shortest required period; GTS: Guaranteed time slot; BI: Beacon Interval; CS_{td}: Cluster Scheduling period.

Algorithm-Time Division Cluster Scheduling

Initialization:

If R_j is the parent router of N_i, then

$x_{ij}= 1;$

Else

$x_{ij}=0;$

End

If C_j is within collision domain of C_i, then

$y_{ij} =1;$

Else

$y_{ij} = 0;$

End

Estimation of dynamic mode

Consider $O_{SF} = 0;$

For each N_j *within* C_i, λ_j^{tx} and λ_j^{rx} *is calculated using Eq. (7) and (8);*

While (Entire allocated GTSs does not fit into given T_{SF}*)*

If $(\sum_j \lambda_j^{tx} + \sum_j \lambda_j^{rx}) \leq 16 - [A_{min}/c]$, *(where* A_{min}*=aMinCAPLength) then*

$O_{SF} = O_{SF} + 1;$

Recalculate length of each GTS;

End

End

End

Estimation of Beacon Interval

BI value is rounded off;

If a optimal CS_{td} *is found for given BI, time schedule then*

$O_{SF} = O_{SF} + 1$;

Iteration is repeated with new BI;

Else

The iteration is repeated until O_{SF} = max (O_{SF}) or till optimal CS_{td} is found;

End

3.4 Mitigation of Interference

In the allotted duty cycle SD, the Coordinator (CD) detects the co-channel interference using packet-error detection and repeated channel-handoff command transmission. By using channel-sensing technique, when the coordinator concludes that the channel σ is interfered, CD repeatedly transmits interference existence message I_m in the beacon frame during dynamic mode of the cluster to its end devices. The number of I_m is given by

$$N_{IM} \leq \left\lfloor \frac{T_{SF} + T_{MM}}{T_M + T_{MM}} \right\rfloor = Th \qquad (3.9)$$

where T_{MM}= time duration among two successive MCT

T_M= duration of MCT

T_h =Threshold

CD swaps the operating mode from normal SCT to MCT. When the end device receives an I_m through channel, it will confirm the presence of interference and change the transmission mode. Without receiving I_m, the end device confirms the presence of interference through beacon-loss counting. The steps involved in the mitigation of interference are given in Algorithm-2.

Notations

N_E: Number of packet transmission errors in superframe; SCT; MCT: Single and multi-channel transmission; N_{MCT}: Number of interference existence message; N_b: Beacon loss counter; CD: Coordinator; σ: Channel; CNT_S: Channel sensing count; I_m: Interference existence message.

Algorithm- Mitigation of Interference

If N_E > Threshold then

CD concludes that σ has interference signal through channel sensing technique;

End

If η= 1 then

CD concludes that interference source exists on σ;

Else

CD increments the CNT_{cs} by 1;

If CNT_{cs} > threshold then

CD concludes that interference source exists on σ;

End

End

CD transmits I_m to end device and swaps the operating mode from normal SCT to MCT;

If the end devices receive I_m then

Change the transmission mode;

Else

N_b is increased by 1;

If N_b = Th then

The existence of interference is acknowledged to σ and mode is switched to MCT;

End

End

It switches back to the normal SCT mode after selecting the best one among the hopping channels.

The energy consumed by CD for the mode change from SCT to MCT is shown using following Eq. (10)

$$E_{CD} = N_{MCT} * E_{tx} * T_M + (N_{MCT}-1)\ E_{idle} * T_{MM} \qquad (3.10)$$

where E_{tx} and E_{idle} are the power consumed by transmitter during dynamic mode and idle mode, respectively.

The average energy consumed by the cluster E_c is shown using following Eq. (3.11)

$$E_c = \frac{1}{1+N_{e2e}}(E_{CD} + N_{e2e}E_{e2e}) \quad (3.11)$$

Where N_{e2e} = number of end to end devices

E_{e2e} = energy consumed by end to end devices

Based on Eq. (3.10) and (3.11), it is confirmed that the energy consumed for the change of transmission mode can be minimized by repeated transmission of channel handoff command.

The overall flowchart of the proposed work is given in figure 3.3.

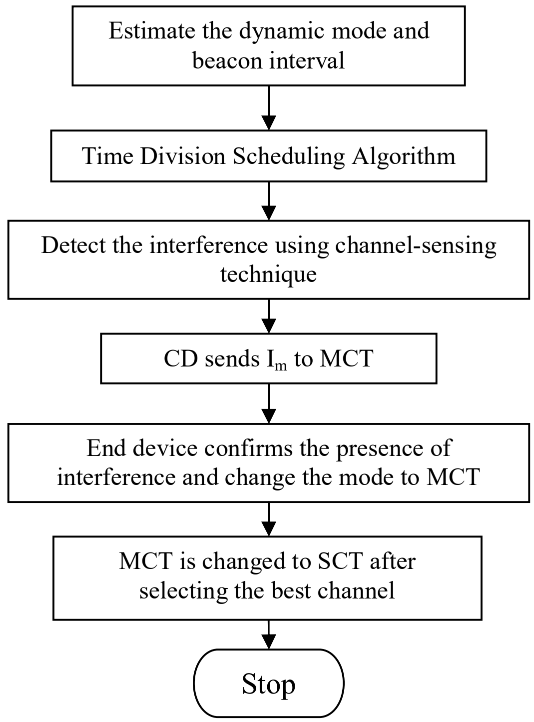

Fig 3.3. Flowchart of EECS

3.5 Simulation Results

3.5.1 Simulation Setup

The performance of the proposed Energy Efficient Cluster based Scheduling (EECS) is evaluated using NS-2 simulation. A network, which is deployed in an area of 50X50 m is considered. IEEE 802.15.4 MAC layer is used for a reliable and single hop communication among the devices, providing access to the physical channel for all types of transmissions and appropriate security mechanisms. The IEEE 802.15.4 specification supports two PHY options based on Direct Sequence Spread Spectrum (DSSS), which allows the use of low-cost digital IC realizations. The PHY adopts the same basic frame structure for low-duty-cycle low-power operation, except that the two PHYs adopt different frequency bands: low-band (868/915 MHz) and high band (2.4 GHz). The PHY layer uses a common frame structure, containing a 32-bit preamble, a frame length. In the simulation scenario, the number of normal nodes is varied as 20,40,60,80 and 100 with a single coordinator node. Since IEEE 802.15.4 networks uses Best Effort traffic and real-time traffic, the Constant Bit rate (CBR) and Exponential traffic are considered for experimentation. The CBR traffic generates constant amount of traffic per second and generally used in non-real-time applications which does not involve bursty data. The exponential traffic follows the Poisson distribution and generates bursty traffic which is suitable for real-time applications like multimedia and voice. Simulation is done for 50 seconds as the cluster tree topology is dense, it takes less time to construct the clusters and transmit the data. In 50 seconds simulation time, the performance can be evaluated and results are stabilized and increasing the simulation time increases the volume of data which is not suitable as Zigbee is a low-rate low-range device.

Table 3.1 summarizes the simulation parameters used.

Number. of Nodes	20,40,60,80 and 100
Area Size	50 X 50m
MAC Protocol	IEEE 802.15.4
Transmission Range	12m
Traffic Source	CBR and Exponential
Packet Size	80 bytes
Antenna	Omni Antenna
Propagation	Two Ray Ground
Simulation time	50 seconds

Table 3.1: Simulation Parameters

3.5.2. Performance Metrics

Since EECS, uses the Zigbee cluster tree (ZCT) architecture of Huang et al. (2012), the performance of EECS is compared with ZCT. The performance is evaluated mainly, according to the following metrics:

Average Packet Delivery Ratio (PDR):

It is the ratio of the number of packets received successfully and the total number of packets transmitted.

It is given by

$$PDR = \sum_{\forall i,j} \left(\frac{N_{r_j}}{N_{s_i}} \right)$$

Where Nr_j is the number of packets received at each destination j and Ns_i is the number of packets sent from each source i.

Average end-to-end delay (E2E)

$$E2E = \sum_{\forall i} \sum_{\forall j} \left(\frac{T_{r_{ij}} - T_{s_{ij}}}{n} \right)$$

Where Tr_{ij} is the packet received time of j_{th} packet of node i and Ts_{ij} is the packet sending time of packet j for node i and n is the total number of packets sent or received at node i.

Energy Consumption:

It is the total amount of energy consumed by the nodes during the data transmission.

$$E = \sum_{\forall j} E_{C_j}$$

Where Ec_j is the energy consumed by the node.

Throughput: It is the number of packets successfully received by the receiver per unit time.

$$Tp = \sum_{\forall j} \left(\frac{N_{r_j}}{t} \right)$$

Where Nr_j is the number of packets received at each destination j and t is the unit time.

3.5.3 Results

The number of nodes is varied as from 20 to 100 and the above metrics are measured for CBR and Exponential traffic. Table 3.2 and 3.3 show the results for both EECS and ZCT techniques for CBR and Exponential traffic, respectively, when the nodes are varied.

Nodes	CBR									
	Delay (seconds)		Delivery Ratio		Packets Dropped		Energy (Joules)		Throughput (Packets)	
	EECS	ZCT	EECS	ZCT	EECS	ZCT	EECS	ZCT	EECS	ZCT
20	9.731332	19.04636	0.036079	0.027043	13565	14501	8.339863	9.202465	547	110
40	10.04246	17.20635	0.053558	0.01583	13104	15022	8.318048	9.849879	612	134
60	10.92569	21.27649	0.106985	0.020221	10868	14078	7.881685	9.85243	622	150
80	11.00836	21.45375	0.116483	0.03958	10755	14068	7.987924	9.92058	766	160
100	11.4675	23.88188	0.150261	0.04187	12885	15081	8.058525	9.858269	762	218

Table 3.2 Results for CBR traffic

Nodes	Exponential									
	Delay (Seconds)		Delivery Ratio		Packets Dropped		Energy (Joules)		Throughput (Packets)	
	EECS	ZCT	EECS	ZCT	EECS	ZCT	EECS	ZCT	EECS	ZCT
20	21.51775	27.57342	0.111094	0.005289	5280	8728	6.048773	9.267985	788	560
40	21.07126	25.02722	0.300117	0.003629	4735	7947	6.341555	9.602281	2313	729
60	18.58486	25.27649	0.338151	0.020221	4479	7637	6.960216	9.85243	2714	950
80	14.99707	23.30084	0.326311	0.109904	4298	7578	7.351205	9.960641	3370	1976
100	14.96332	22.54532	0.599187	0.268716	2525	4310	7.975085	10.04015	4126	2247

Table 3.3 Results for Exponential traffic

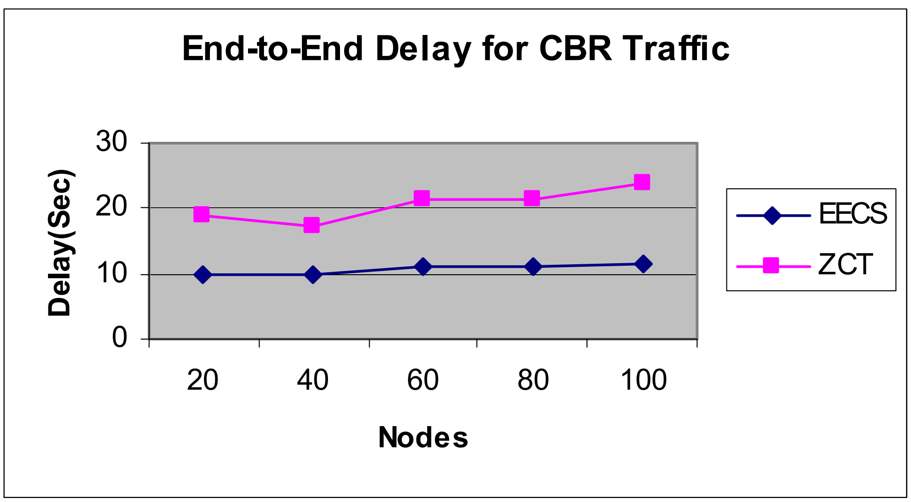

Fig 3.4 (a): Delay for CBR Traffic

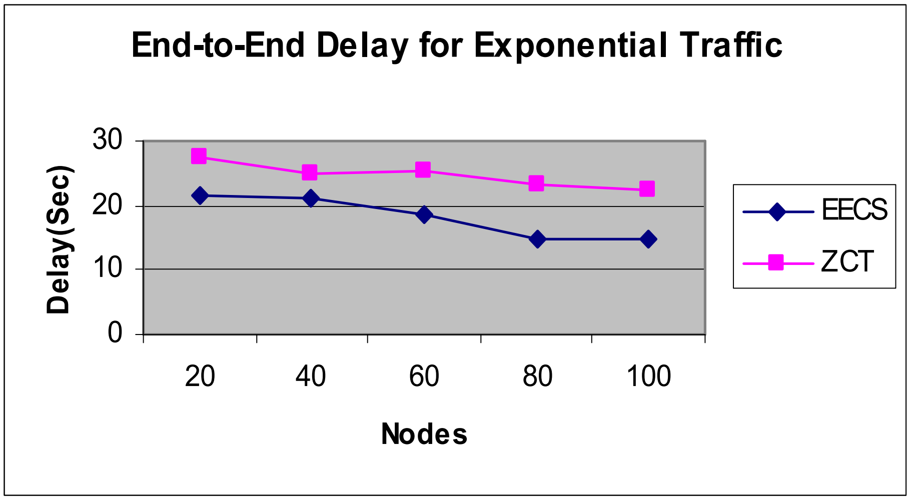

Fig 3.4 (b): Delay for EXP Traffic

Figure 3.4 (a) and (b) show the delay occurred for CBR and Exponential traffic, respectively, by varying the number of nodes.

The delay slightly increases in case of CBR traffic whereas it slightly decreases in case of EXP traffic. In both the traffics, EECS outperforms ZCT in terms of delay by 48% and 26%. This improvement is due to the fact that EECS completely eliminates the interference there by reducing the waiting time.

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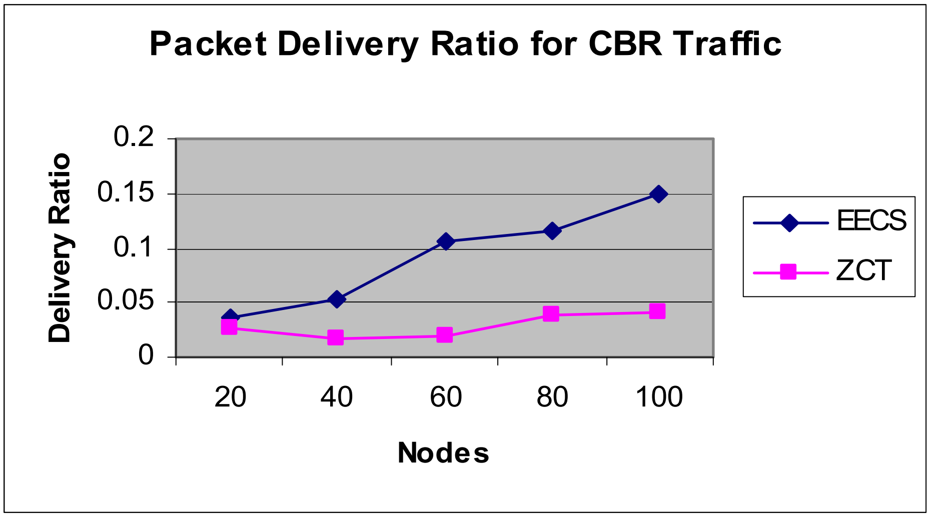

Fig 3.5 (a): Delivery Ratio for CBR Traffic

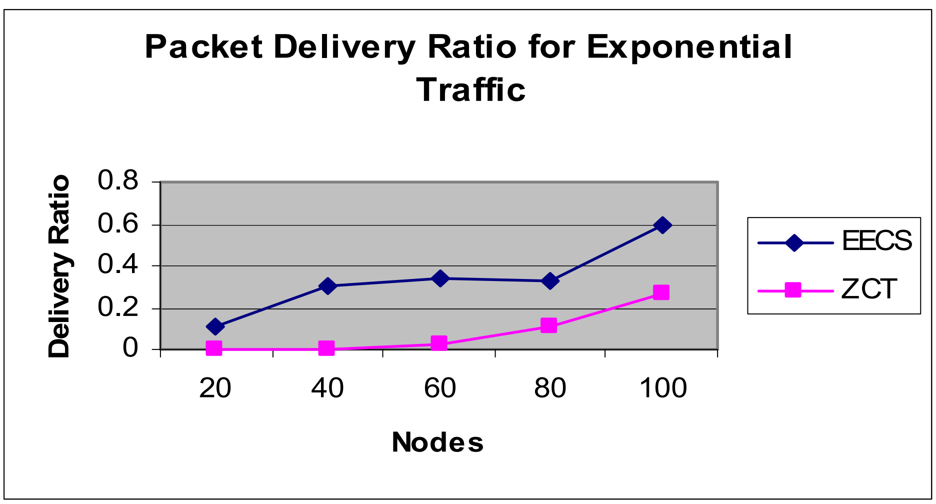

Fig 3.5 (b): Delivery Ratio for EXP Traffic

Figure 3.5 (a) and (b) show the packet delivery ratio obtained for CBR and EXP traffic, respectively, by varying the number of nodes.

For both CBR and EXP traffic, the delivery ratio increases, when the number of nodes is increased.

In both the traffics, the delivery ratio is higher for EECS by 62% and 81% when compared to ZCT. This improvement is due to the fact that EECS eliminates the interference and provides energy efficient scheduling to the traffic

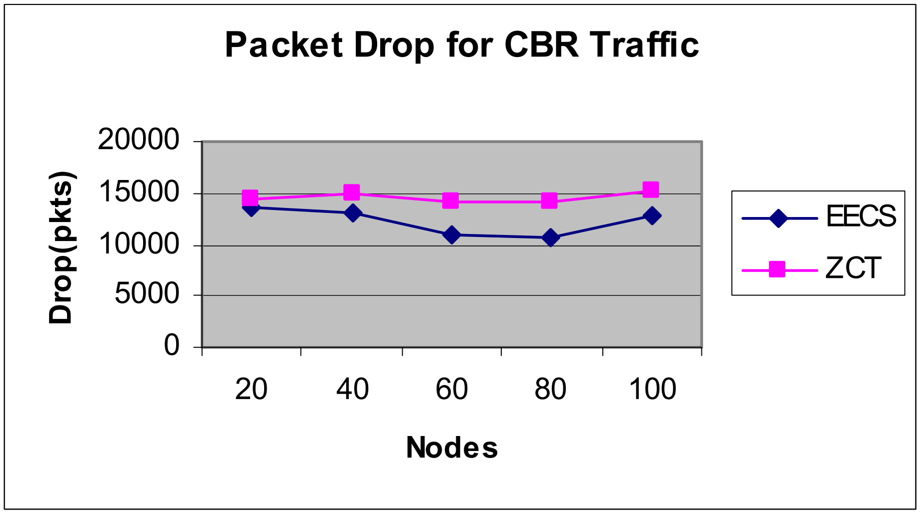

Fig 3.6 (a): Packet Drop for CBR Traffic

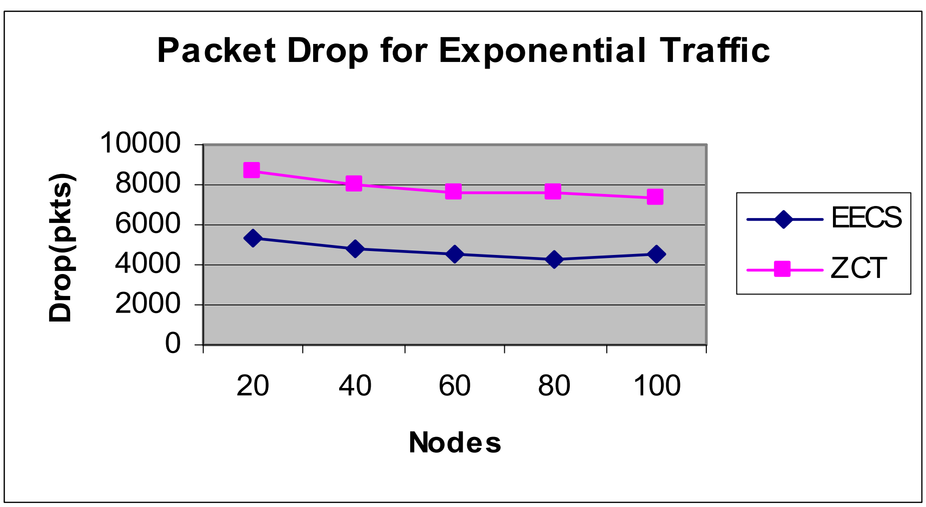

Fig 3.6 (b): Packet Drop for EXP Traffic

Figure 3.6 (a) and (b) show the packets dropped for CBR and EXP traffic, respectively, by varying the number of nodes.

For both CBR and EXP traffic, the packet drop slightly decreases, when the number of nodes is increased.

In both the traffics, the packet drop is less for EECS by 16% and 40% when compared to ZCT. This improvement is due to the fact that EECS eliminates the interference and provides energy efficient scheduling to the traffic

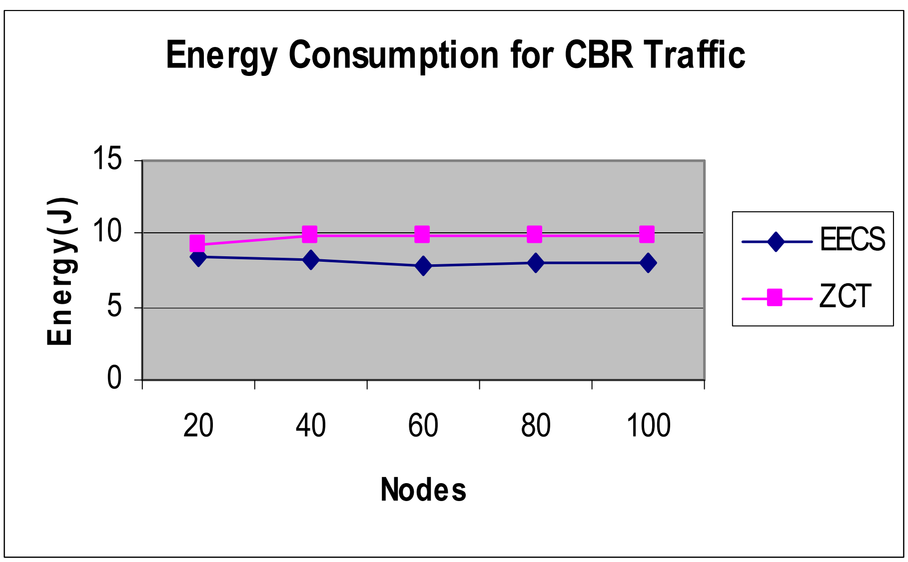

Fig 3.7 (a): Energy Consumption for CBR Traffic

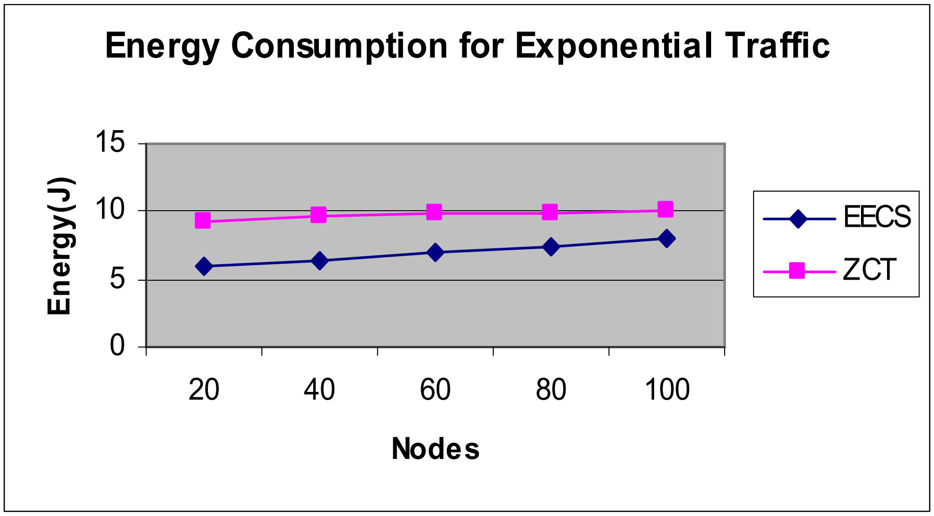

Fig 3.7 (b): Energy Consumption for EXP Traffic

Figure 3.7 (a) and (b) show the energy consumption for CBR and EXP traffic, respectively, by varying the number of nodes.

The energy consumption is almost constant for CBR traffic whereas it slightly increases for EXP traffic, when the number of nodes is increased.

In both the traffics, energy consumption is less for EECS by 16% and 28% when compared to ZCT. This improvement is due to the fact that EECS eliminates the interference and provides energy efficient scheduling to the traffic.

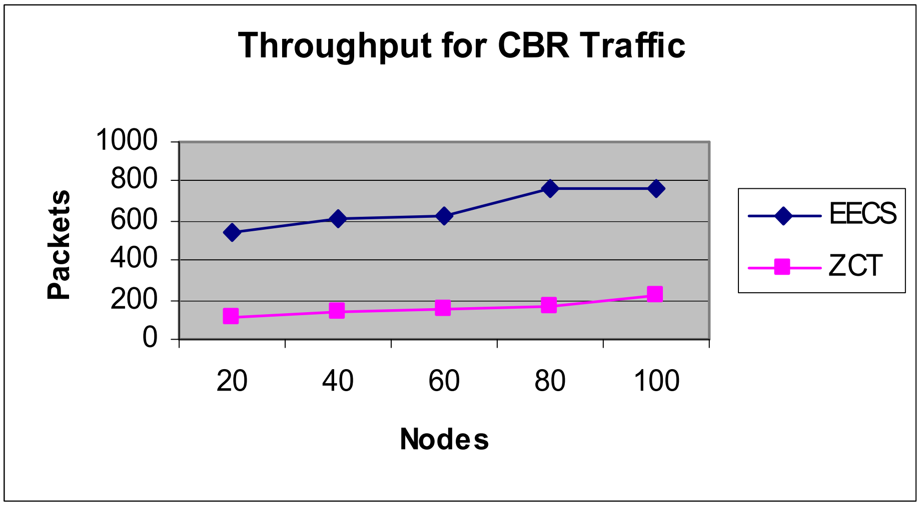

Fig 3.8 (a): Throughput for CBR Traffic

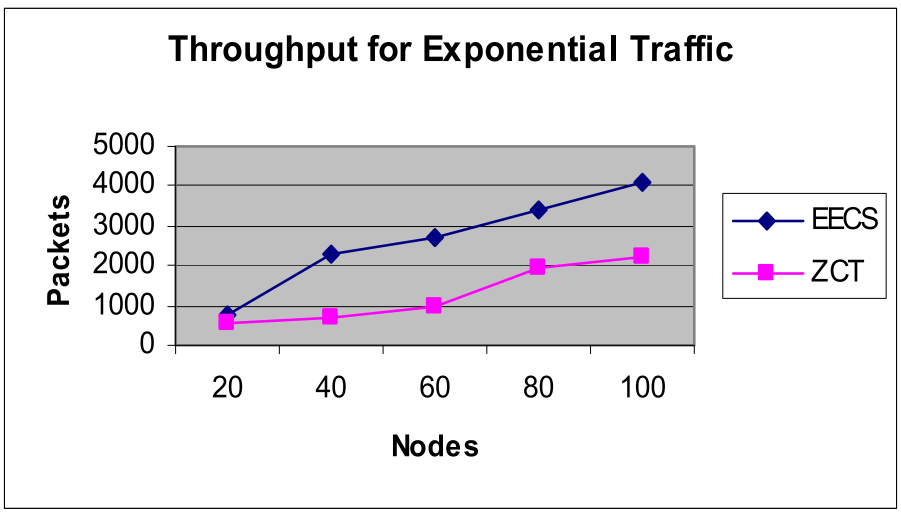

Fig 3.8 (b): Throughput for EXP Traffic

Figure 3.8 (a) and (b) show the throughput obtained for CBR and EXP traffic, respectively, by varying the number of nodes.

For both CBR and EXP traffic, the throughput slightly increases, when the number of nodes is increased.

In both the traffics, EECS has higher throughput by 76% and 49% when compared to ZCT. This improvement is due to the fact that EECS eliminates the interference and provides energy efficient scheduling to the traffic

Table 3.4 and 3.5 shows the percentage improvement of EECS over ZCT for CBR and Exponential traffic, respectively, when the nodes are increased.

Nodes	**Delay (%)**	**Delivery Ratio (%)**	**Packet Drop (%)**	**Energy (%)**	**Throughput (%)**
20	48.90	25.04	6.45	9.37	79.89
40	41.63	70.44	12.76	15.55	78.10
60	48.64	81.09	22.80	20.02	75.88
80	48.68	66.02	23.54	19.48	79.11
100	51.98	72.13	14.56	18.25	71.39

Table 3.4 Percentage Improvement of EECS for CBR Traffic

Nodes	**Delay (%)**	**Delivery Ratio (%)**	**Packet Drop (%)**	**Energy (%)**	**Throughput (%)**
20	21.96	95.23	39.50	34.73	28.93
40	15.80	98.79	40.41	33.95	68.48
60	26.47	94.02	41.35	29.35	64.99
80	35.63	66.31	43.28	26.19	41.36
100	33.63	55.15	41.41	20.56	45.54

Table 3.5 Percentage Improvement of EECS for Exponential Traffic

3.6 Conclusion

In this chapter, Energy Efficient Cluster Scheduling and Interference Mitigation have been proposed for IEEE 802.15.4 Network. In this technique, a time division cluster scheduling technique is considered that offers energy efficiency in the cluster-tree network. In addition, an interference mitigation technique is demonstrated which detects and mitigates the channel interference based on packet-error detection and repeated channel-handoff command transmission. The proposed technique provides an energy efficient interference detection and avoidance method in order to provide reliability during the data transfer. By simulation results, it has been shown that the proposed technique reduces the energy consumption and packet drop due to network collision and improves the packet delivery ratio and throughput.

CHAPTER-4

QOS AWARE INTER-CLUSTER ROUTING PROTOCOL FOR IEEE 802.15.4 NETWORKS

4.1 Overview

In this chapter, a QoS aware routing protocol has been proposed in the cluster tree network. It consists of modules such as reliability module, packet classifier, hello protocol module, routing service module. The data is transferred from MAC layer to network layer in reliability module which takes care of transmission of messages and acknowledgements. Packet classifier classifies the data and hello packets. The data packets are classified based on the priority. Hello protocol module constructs neighbour table and maintains information about neighbour nodes reliabilities. Moreover, using the routing service module, routing table is built and the data packets are classified into RSP and OP. The delay in the route is controlled using delay metrics, which is a sum of queuing delay and transmission delay.

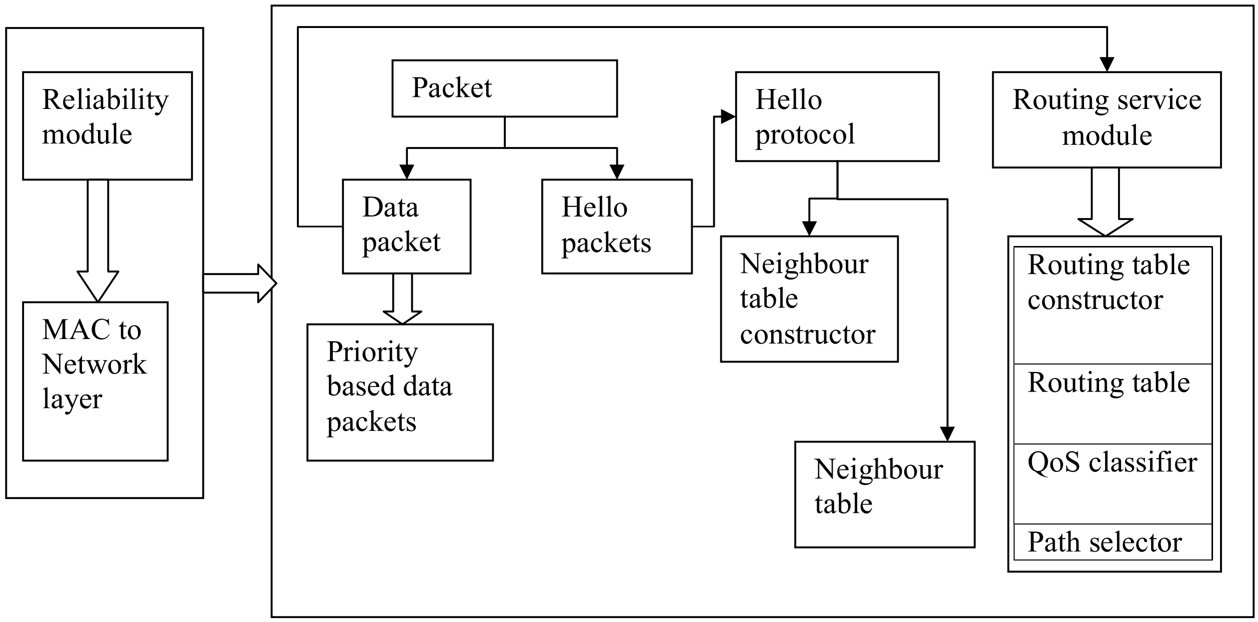

Fig. 4.1 Block diagram

4.2 Packet classification

The packet classification is made by using packet classifier. It differentiates the data packets and the hello packets. The packet classifier forwards the data and the hello packets to the routing service module and the hello protocol module.

4.3 Reliability module

Reliability module passes the information of successful data packets transmission acknowledgements from MAC layer to the network layer. It monitors the number of packets sent to neighbour node *j* and the number of acknowledgements received from neighbour node *j*.

From this information the network layer calculates the link reliability between node *i* to the neighbour node *j*

Link reliability= $R_{link(i,j)}$

The average probability of successful transmission after 4 seconds is given by,

$$\overline{\chi_i} = \frac{N_{Acks}}{N_{Trans}} \tag{4.1}$$

The link reliability can be calculated as,

$$R_{link(i,j)} = (1-\rho)R_{link(i,j)} + \rho \times \overline{\chi_i} \tag{4.2}$$

Where ρ is the average weighing factor that satisfies $0 < \rho \leq 1$.

The path reliability between node *i* and destination node Dst ($R_{path(I,Dst)}$) is calculated by using,

$$R_{path(i,Dst)} = R_{link(i,j)} \times R_{path(j,Dst)} \tag{4.3}$$

4.4 Hello protocol module

The HELLO packets are broadcast to the HELLO protocol module. This module consists of two sub-modules such as neighbour constructor table and neighbour table. In the neighbour constructor table the neighbour table is built according to the information obtained from the HELLO packet and MAC layer reliability module.

By receiving a HELLO packet, the neighbour cluster head node updates their neighbour table entries. A new entry is added into the neighbour table when a new node moves into the locality, and the existing entry is deleted when a neighbouring node breaks down. From this, when a HELLO packet is not received during a predefined period of time is determined.

After node *I* receives the Hello packet, the neighbour table constructor updates the Hello packet with its own $R_{path(i,Dst)}$. This new hello packet broadcasts the message to the other nodes.

$\mathbf{ID_{Dst}}$	$\mathbf{L_{Dst}}$	$\mathbf{ID_j}$	$\mathbf{L_j}$	$\mathbf{D_{(j,Dst)}}$	$\mathbf{E_j}$	$\mathbf{T_j}$	$\mathbf{R_{path(j,Dst)}}$

Table. 4.1. Hello Packet Structure

where $\mathbf{ID_{Dst}}$ – destination ID, $\mathbf{L_{Dst}}$ – destination location, $\mathbf{ID_j}$ – neighbour node j ID, $\mathbf{L_j}$ – neighbour node j location, $\mathbf{D_{(j,Dst)}}$ – distance between neighbour node j and destination, $\mathbf{E_j}$ – residual energy of node j, $\mathbf{T_j}$ – device type of node j, and $\mathbf{R_{path(j,Dst)}}$ – path reliability between neighbour node j and destination .

4.4.1 Neighbour table constructor

In addition to reliability, the metrics such as residual energy, delay and current position of nodes are added to uphold in the neighbour table.

The residual energy for the nodes is given by,

$$R_{E(i,j)} = T - T_c \tag{4.4}$$

Where T - total energy, T_c - Total energy consumed at time T.

The current position of the nodes can be estimated by the geographic location P_i. The delay in the route $\hat{d}(i)$ is controlled with the sum of queuing delay and transmission delay. The queuing delay contributes most significantly to the total latency followed by the transmission delay.

The queuing delays for each packet types $\hat{d}_q^i[packet.type]$ is given by

$$\hat{d}_q^i[packet.type] = (1-\eta)\hat{d}_q^i[packet.type] + \eta d_q^i[packet.type] \tag{4.5}$$

Where η - constant smoothing factor.

The transmission delay is measured as the time duration from the time at which the packet is ready for transmission (becoming the head of the transmission queue) to the time of successful transfer of its last bit. It is calculated as,

$$\hat{d}_{tr}^i = \frac{\sum_{n=1}^{P} d_{tr}^i(n) \times \omega_n}{\sum_{n=1}^{P} \omega_n} \tag{4.6}$$

Where $\omega_n = 1 - \dfrac{n - P/2}{P/2 + 1}, \quad P/2 < n \le P$

The overall delay control for a single node *i* can be calculated as,

$$\hat{d}(i) = \hat{d}_q^i + \hat{d}_{tr}^i \tag{4.7}$$

Neighbour table contains the fields of reliabilities for both hop-by-hop ($R_{link(i,j)}$) and end-to-end ($R_{path(j,Dst)}$), residual energy, current position and delay. With the reception of Hello packets the neighbour table is updated periodically.

ID_{Dst}	L_{Dst}	ID_j	L_j	$D_{(j,Dst)}$	E_j	T_j	$R_{path(j,Dst)}$	$R_{link(i,j)}$	$RE_{(i,j)}$	P_i	D_i

Table. 4.2. Neighbour table Structure

where $\mathbf{RE_{(i,j)}}$- residual energy for node *i* and node *j*, $\mathbf{P_i}$ – current position of node, and $\mathbf{D_i}$ – delay of nodes.

4.5 Dynamic data packet classification

Dynamic packet classifier is used to differentiate data packets based on their priority level. The four classes of data packets is given by ordinary data packets (OP), reliability-driven data packets (RP), delay-driven data packets (DP) and most critical data packets (CP).

- The CP packets are given the highest priority due to their stringent delay and reliability constraints.
- The next higher priority is given to DP packets which should be delivered within a predefined deadline, but may tolerate reasonable packet loss.
- Next to DP is the RP packets which should be delivered without loss, but do not need to be immediate or within a hard deadline.
- The lowest priority is given to the OP packets.

4.6 Routing service module

The main function of the routing service module is to build the routing table and to classify data packets into RSP (Reliability Sensitive Packet) and OP (Original Packet). The routing service module consists of routing table constructor, routing table, QoS classifier and path selector.

In the routing table, the next hop entries are selected based on the metrics such as reliability, high residual energy, delay and maximum of geographical process towards sink. The node with reliability less than predefined is dropped.

$\mathbf{ID_{Dst}}$	$\mathbf{L_{Dst}}$	$\mathbf{NH_E}$	$\mathbf{NH_{R1}}$	$\mathbf{NH_{R2}}$	$\mathbf{NH_{R3}}$	$\mathbf{R_{option1(i,Dst)}}$	$\mathbf{R_{option2(j,Dst)}}$	$\mathbf{R_{option3(j,Dst)}}$	$\mathbf{RE_{(i,j)}}$	$\mathbf{P_i}$	$\mathbf{D_i}$

Table. 4.3. Routing table structure

where $\mathbf{NH_E}$ – energy aware next hop, $\mathbf{NH_{R1}}$- 1st reliable next hop, $\mathbf{NH_{R2}}$ – 2nd reliable next hop, $\mathbf{NH_{R3}}$ – 3rd reliable next hop, $\mathbf{R_{option1(i,Dst)}}$ – 1st option reliability for sending reliability sensitive packets, $\mathbf{R_{option2(j,Dst)}}$ - 2nd option reliability for sending reliability sensitive packets, and $\mathbf{R_{option3(j,Dst)}}$ – 3rd option reliability for sending reliability sensitive packets.

4.6.1 Routing table constructor

The energy-aware routing algorithm (ERA) and the reliability algorithm are used in routing table constructor. ERA is used to find $\mathbf{NH_E}$ for OP (ordinary packet) and is calculated by using the residual energy and the geographic location. For RSP three possible paths were found to ensure the minimum required reliability. For the destination the three paths with highest reliability ($R_{path1(i, Dst)}$, $R_{path2(i, Dst)}$, $R_{path3(i, Dst)}$)

is chosen, along with the corresponding next hops (NH_{R1}, NH_{R2} and NH_{R3}) which is stored in the routing table.

The first reliability path option $R_{option1(i, Dst)}$ is the reliability of the highest path .i.e. $R_{path1(i, Dst)}$.

$$R_{option1(i, Dst)} = R_{path1(i, Dst)} \tag{4.8}$$

The error probabilities of the three paths are given by,

$$P_{error1} = 1 - R_{path1(i,Dst)} \tag{4.9}$$

$$P_{error2} = 1 - R_{path2(i,Dst)} \tag{4.10}$$

$$P_{error3} = 1 - R_{path3(i,Dst)} \tag{4.11}$$

The $R_{option2(i, Dst)}$ is calculated by using the error probabilities of the two paths having the highest reliability values.

$$R_{option\,2(i,Dist)} = 1 - (P_{error\,1} \times P_{error\,2}) \tag{4.12}$$

Error probabilities for all the three paths is given by,

$$R_{option\,3(i,Dist)} = 1 - (P_{error\,1} \times P_{error\,2} \times P_{error\,3}) \tag{4.13}$$

4.6.2 Routing table construction algorithm

INPUT – Neighbour table

1. **for** each destination Dst do
2. $\mathbf{NH_R}$= $\{all\ neighbor\ nodes\ j \in NH_{(i,Dst)}\}$
3. **if (**$\mathbf{NH_R}$ = = NULL**) then**
4. put NULL in $\mathbf{NH_{R1}}$, $\mathbf{NH_{R2}}$, $\mathbf{NH_{R3}}$, $\mathbf{R_{option1(i,Dst)}}$, $\mathbf{R_{option2(j,Dst)}}$, $\mathbf{R_{option3(j,Dst)}}$, $\mathbf{RE_{(i,j)}}$, $\mathbf{P_i}$, $\mathbf{D_i}$
5. **else**
6. sort $\mathbf{NH_R}$ in descending order of $R_{path(i,\ Dst)}$
7. $\mathbf{NH_R}$ = first neighbour node $j \in NH_R$
8. $\mathbf{R_{option1(i,Dst)}} = R_{path(i,\ Dst)}$
9. P_{error}= 1- $\mathbf{R_{option1(i,Dst)}}$
10. **if (**$|NH_R| > 1$**)**
11. $\mathbf{NH_{R2}}$ = second neighbour node $j \in NH_R$
12. P_{error}= P_{error} * (1- $\mathbf{R_{option1(i,Dst)}}$)
13. $\mathbf{R_{option2(j,Dst)}}$= 1- P_{error}
14. **end if**

15. **if (** $|NH_R| > 2$ **)**

16. $\mathbf{NH_{R3}}$ = third neighbour node $j \in NH_R$

17. $P_{error}= P_{error} * (1- \mathbf{R_{path(i,Dst)}})$

18. $\mathbf{R_{option3(j,Dst)}}= 1- P_{error}$

19. **end if**

20. **end if**

21. **end for**

4.6.3 QoS Classifier

The data packets from both the upper and packet classifiers are received by QoS classifier. The QoS classifier differentiates the packets into RSPs and OPs.

4.6.4 Path Selector

For each data packet the path selector checks the QoS requirement along with residual energy, delay and current position of nodes. Next it chooses the suitable next hop using the path selector algorithm. If the packet is RSP, the path selector sends the packets using a single path through NH_{R1} for which the reliability path is greater than R_{req}. Two paths are used for which the reliability exceeds the R_{req}. Three paths are used if the aggregate reliability is greater than R_{req}. If not the packet is dropped. If the packet is an OP, the path selector returns the next hop NH_E.

4.6.5 Path Selector Algorithm

INPUT – Routing table

1. **for** each data packets from node i($\mathbf{R_{(i,Dst)}}$, $\mathbf{RE_{(i,j)}}$, $\mathbf{P_i}$, $\mathbf{D_i}$) **do**
2. **if** data packet reliability sensitive packet (RSP)
3. **if** ($\mathbf{R_{option1(i,Dst)}} > \mathbf{R_{req}}$)
4. send to NH_{R1}
5. **else if** ($\mathbf{R_{option2(i,Dst)}} > \mathbf{R_{req}}$)
6. send to $\mathbf{NH_{R1}}$ and $\mathbf{NH_{R2}}$
7. **else if** ($\mathbf{R_{option3(i,Dst)}} > \mathbf{R_{req}}$)
8. send to $\mathbf{NH_{R1}}$, $\mathbf{NH_{R2}}$ and $\mathbf{NH_{R3}}$
9. **else**
10. drop the packet immediately
11. **end if**
12. **else if** data packet is Ordinary Packet (OP)
13. send to NH_E
14. **else**
15. drop the packet immediately
16. **end if**

17. **end for**

4.7 Overall algorithm specifications

1. Initially the packets are classified as data packets and hello packets.

2. The data packets were classified based on the priority and they are sent to the routing service module.

3. Using the reliability module successive data transmission is made from the from MAC layer to the network layer.

4. The hello packets are broadcast into the hello protocol module which consists of neighbour constructor table and neighbour table.

5. In the neighbour table in addition to reliability residual energy, delay and geographical routing of nodes are also added.

6. The node with reliability less than predefined is dropped. The geographical routing enables current position estimation.

7. The data packets are received by QoS classifier by which it differentiates the packets into RSPs and OPs.

8. Next for suitable next hop, the path selector checks the QoS requirement with residual energy, delay and current position of nodes.

4.8 Simulation Results

4.8.1 Simulation Setup

The performance of the proposed QoS Aware Inter-Cluster Routing Protocol (QAICR) is evaluated using NS-2 simulation. A network, which is deployed in an area of 50X50 m is considered. IEEE 802.15.4 MAC layer is used for a reliable and single hop communication among the devices, providing access to the physical channel for all types of transmissions and appropriate security mechanisms. The IEEE 802.15.4 specification supports two PHY options based on Direct Sequence Spread Spectrum (DSSS), which allows the use of low-cost digital IC realizations. The PHY adopts the same basic frame structure for low-duty-cycle low-power operation, except that the two PHYs adopt different frequency bands: low-band (868/915 MHz) and high band (2.4 GHz). The PHY layer uses a common frame structure, containing a 32-bit preamble, a frame length.

Table 4.4 summarizes the simulation parameters used.

No. of Nodes	21,41,61,81 and 101
Area Size	50 X 50m
Mac	IEEE 802.15.4
Transmission Range	12m
Traffic Source	CBR and Exponential
Packet Size	80 bytes
Antenna	Omni Antenna
Propagation	Two Ray Ground
Simulation time	50 seconds

Table 4.4: Simulation Parameters

4.8.2 Performance Metrics

Since QAICR is derived from the basic QoS-aware Peering Routing Protocol (QPRR), the performance of QAICR is evaluated and compared with QPRR (Zahoor et al., 2013). The performance is evaluated mainly, according to the following metrics: average Packet delivery ratio, packets received, packets dropped, and energy consumption.

4.8.3 Results

The number of nodes is varied as from 21 to 101 and the above metrics are measured for CBR and Exponential traffic. Table 4.5 and 4.6 shows the results for QPRR and QAICR techniques for CBR and EXP traffic, respectively, when the nodes are varied.

	CBR							
	Delivery Ratio		Drop		Energy		Throughput	
Nodes	QAICR	QPRR	QAICR	QPRR	QAICR	QPRR	QAICR	QPRR
21	0.4375	0.3491	5556	14536	7.9776	9.1221	3851	532
41	0.4116	0.2708	5780	14070	7.5042	8.2561	4697	1079
61	0.2421	0.1841	11019	19642	7.8686	8.7551	3690	1289
81	0.1840	0.1345	13112	29214	8.0670	8.6180	3488	1052
101	0.2057	0.1257	20701	29436	8.1065	8.8334	6230	778

Table 4.5: Results of QAICR and QPRR for CBR Traffic

	Exponential							
	Delivery Ratio		Drop		Energy		Throughput	
Nodes	QAICR	QPRR	QAICR	QPRR	QAICR	QPRR	QAICR	QPRR
21	0.3502	0.0562	2833	7625	6.40752	9.351997	1974	461
41	0.5882	0.0157	1676	6485	6.706877	9.513495	3348	108
61	0.4785	0.1266	3195	5385	6.462706	8.832892	3290	931
81	0.3263	0.0701	4298	13839	7.351205	8.386295	2370	1058
101	0.5991	0.0449	2525	13940	7.975085	9.858839	4126	69

Table 4.6: Results of QAICR and QPRR for EXP Traffic

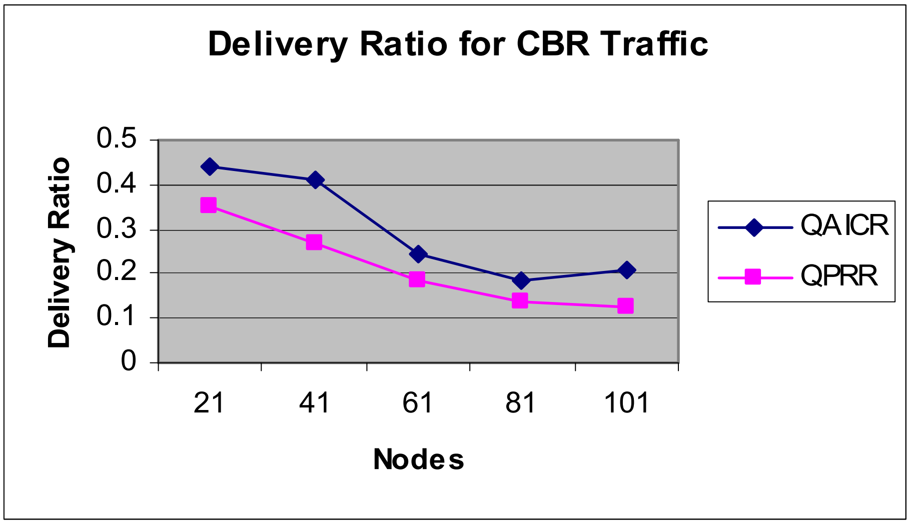

Fig 4.2 (a) Delivery Ratio for CBR Traffic

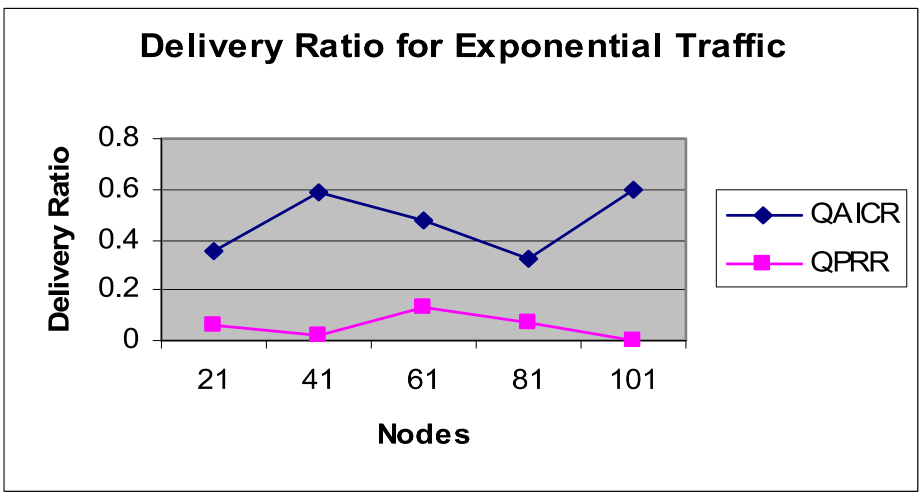

Fig 4.2 (b) Delivery Ratio for EXP Traffic

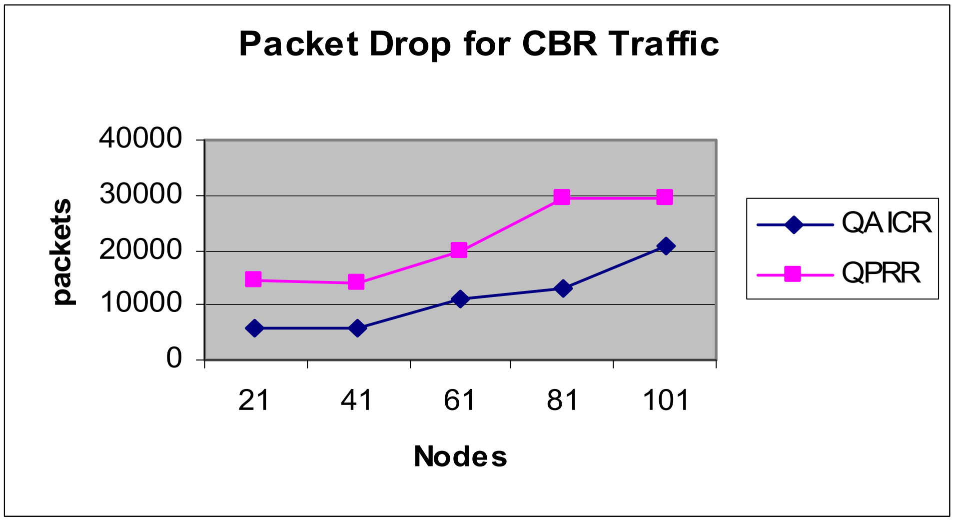

Fig 4.3 (a) Packet Drop for CBR Traffic

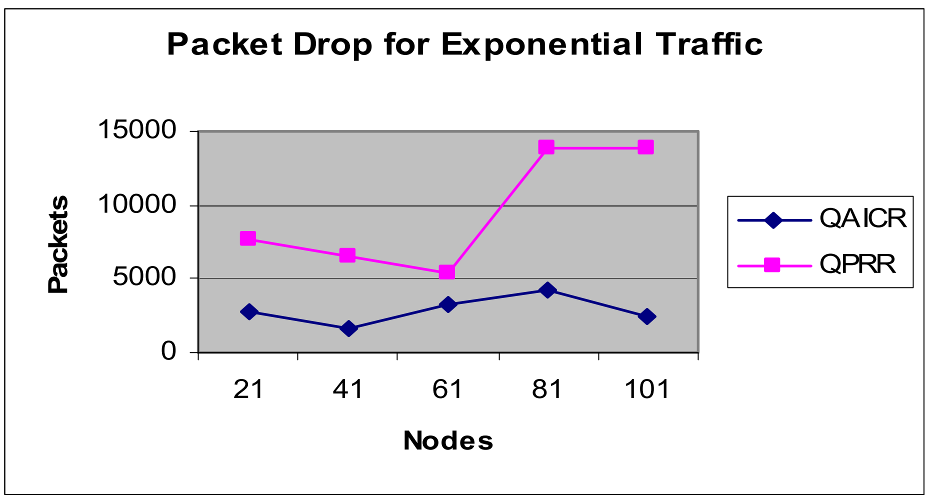

Fig 4.3 (b) Packet Drop for EXP Traffic

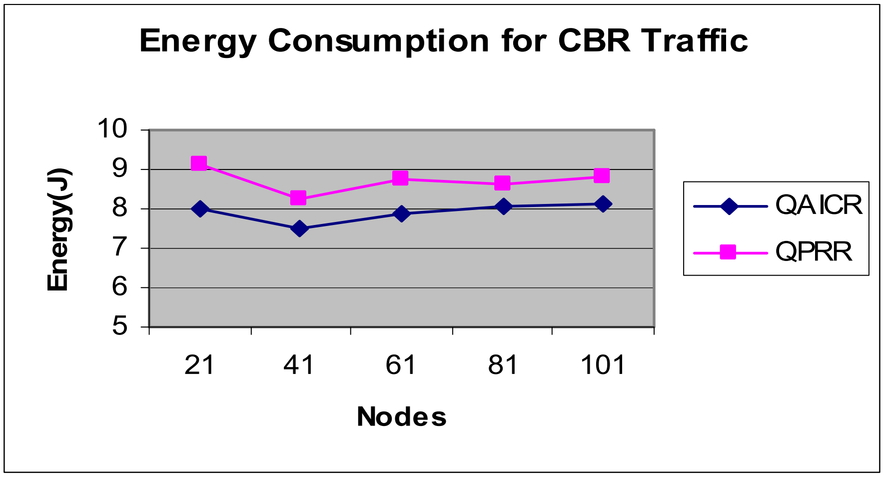

Fig 4.4 (a) Energy Consumption for CBR Traffic

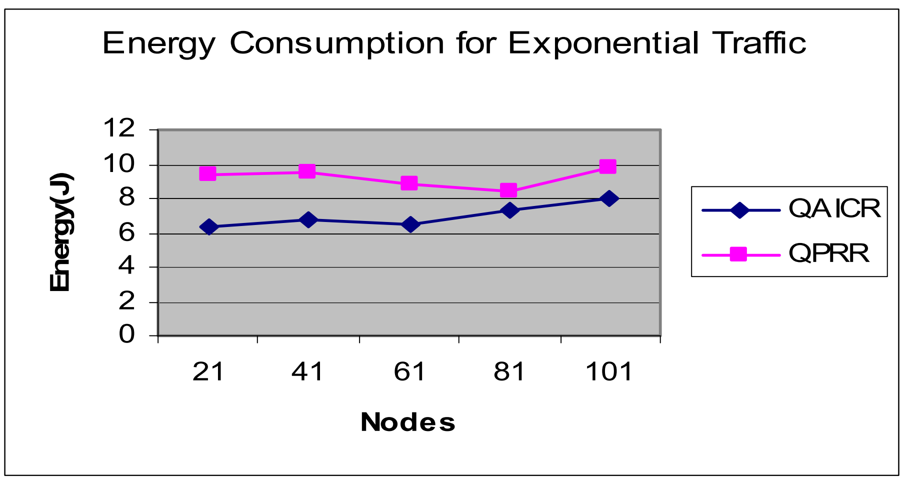

Fig 4.4(b) Energy Consumption for EXP Traffic

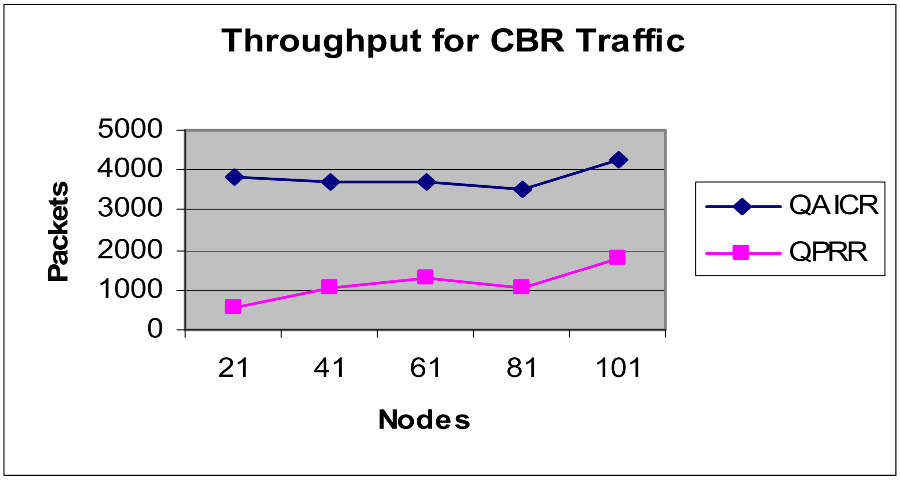

Fig 4.5(a) Throughput for CBR Traffic

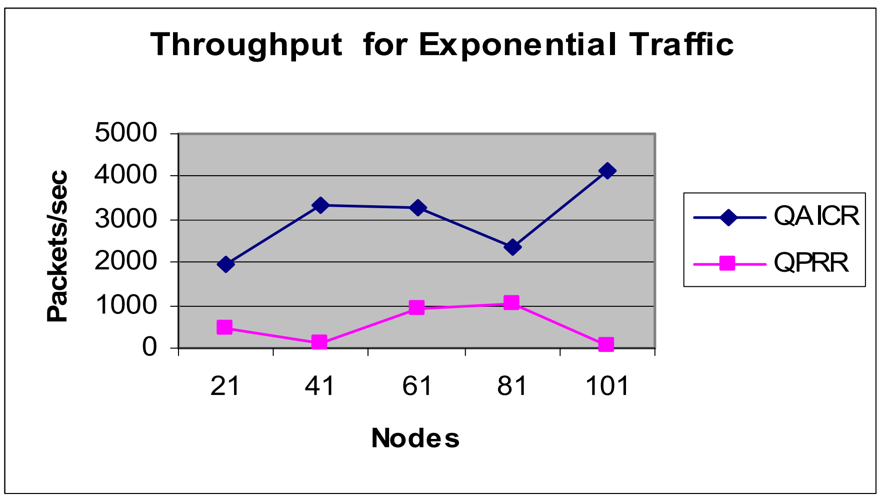

Fig 4.5(b) Throughput for EXP Traffic

Figures 4.2 (a) to 4.5 (a) show the packet delivery ratio, packet drop, energy consumption and throughput, respectively of QAICR and QPRR techniques for CBR traffic. It shows the increase in network size results in slightly increased packets drop and reduced delivery ratio. But the energy consumption and throughput has little impact over it. In all the figures QAICR outperforms QPRR in terms of delivery ratio by 28%, packet drop by 49% and energy consumption by 9% and throughput by 70%. This improvement is due to the fact that QAICR provides link reliability and eliminates the interference.

Table 4.7 shows the percentage improvement of QAICR over QPRR for the CBR traffic when the nodes are varied.

Nodes	Delivery Ratio (%)	Packet Drop (%)	Energy (%)	Packet Received (%)
21	20	61	12	86
41	34	58	9	77
61	23	43	10	65
81	26	55	6	69
101	38	29	8	57

Table 4.7 Percentage Improvement of QAICR for CBR Traffic

Table 4.8 shows the percentage of improvement of QAICR over QPRR for Exponential traffic when the number of nodes is varied.

Nodes	Delivery Ratio (%)	Packet Drop (%)	Energy (%)	Packet Received (%)
21	35	49	31	76
41	3	74	29	96
61	44	61	26	71
81	47	68	12	68
101	51	53	19	74

Table 4.8 Percentage Improvement of QAICR for EXP Traffic

Figures 4.2 (b) to 4.9 (b) show the packet delivery ratio, packet drop, energy consumption and throughput, respectively, for both the QAICR and QPRR techniques for exponential traffic. It shows the increase in network size results in slightly increased packets drop and reduced delivery ratio. But the energy consumption and throughput has little impact over it. In all the figures QAICR outperforms QPRR in terms of delivery ratio by 42%, packet drop by 61%, and energy consumption by 23% and throughput by 77%. This improvement is due to the fact that QAICR provides link reliability and eliminates the interference.

4.9 Conclusion

In this chapter, a routing protocol is designed in the cluster tree network which consists of few modules like reliability module, packet classifier, hello protocol module, routing service module. The data is transferred from MAC layer to network layer in reliability module which takes care of transmission of messages and acknowledgements. In the Packet classifier the packets are classified into the data and hello packets. The data packets are classified based on the priority. Hello protocol module constructs neighbour table and maintains information about neighbour nodes reliabilities. Next using the routing service module, the routing table is built. The delay in the route is controlled using delay metrics, which is a sum of queuing delay and transmission delay. Simulation results show that the proposed QAICR technique reduces the packet drop and energy consumption there by increasing the throughput and delivery ratio for both CBR and Exponential traffic flows.

CHAPTER-5

PSO BASED ADAPTIVE DATA RATE CONTROL FOR CLUSTERED ARCHITECTURE IN IEEE 802.15.4 NETWORKS

5.1 Overview

In this chapter, a network device regulates its data rate adaptively using the feedback message i.e. Congestion Notification Field (CNF) in beacon frame received from the receiver side for preventing congestion and packet dropping based on current network buffer status. The network device controls or changes its data rate based on CNF value. Along with this scalability is considered by modifying encoding parameters using Particle Swarm Optimization (PSO) to balance the target output rate for supporting high data rate. For scalability data rate control, quantizer parameter is used during encoding to maintain target output rate.

5.2 Data rate regulation using CNF

The network device in beacon-enabled LR-WPAN waits for a beacon message from the PAN coordinator. If the Guaranteed Time Slots (GTS) is not allocated to the network device, it has to transmit its data frames during the contention period based on the CSMA/CA procedure.

There are certain issues to be solved:

- It is difficult to transmit the data to the coordinator at a static data rate.

- If the LR-WPAN allocates slots to the network device using only the RTS/CTS procedure, it results in congestion in the coordinator, as it ignores the latter's capacity and capability.

- In case of a cluster-tree network, several CHs may want to transmit data frames from the network device to the coordinator at the same time and, as a result severe queuing delays may occur in the CH's network interface buffer. This may results in packet dropping.

- This phenomenon may even worsen if a lot of data frames converge into a small number of CHs and coordinators based on a static data rate.

- An increase in the number of dropped packets is not desirable from the viewpoint of the network throughput. Also, dropped packets lead to unnecessary retransmission and inefficient energy consumption.

The CH capacity is controlled based on current network interface buffer status thereby deploying an adaptive data rate control mechanism. Then CH is prevented from dropping of packets from the network devices.

The three premises required for the mechanism are as follows:

- The network interface buffer of the CH has a maximum storage capacity of L packets.

- The packet generation and arrival process from each network device to the CH follows a Poisson distribution.

- The service time for packets to be transmitted from the network interface buffer of the CH follows a general distribution. Consequently, the arrival rate per unit time at the CH can be described by the following equation.

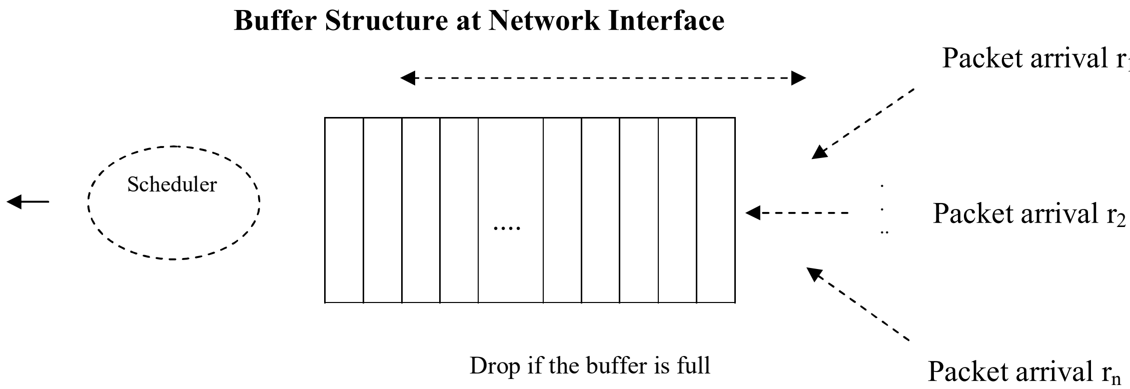

Fig 5.1: Network Interface buffer structure

As a result, the arrival rate per unit time at the CH can be depicted in the following equation.

$$r = \sum_{i=1}^{n} r_i \tag{5.1}$$

Where i=ith node, n= no. of nodes

The performance can be optimized by preventing overflow and underflow at the network interface buffer. If there is any overflow at the network interface buffer, unnecessary transmissions occur which reduce energy efficiency, and this results in a lower throughput. The large buffer allocation increases the queuing delay at the network interface buffer, which leads to TCP Retransmission. The retransmissions should be avoided as the requirement of low cost for LR-WPAN HW, hence it is preferred to make the buffer size small.

Therefore, packet dropping should be denied in spite of the small size network interface buffer by appropriately changing the value of r_i.

For supporting an adaptive data rate, the network devices should consider the delivery capability of the CH to the network devices.

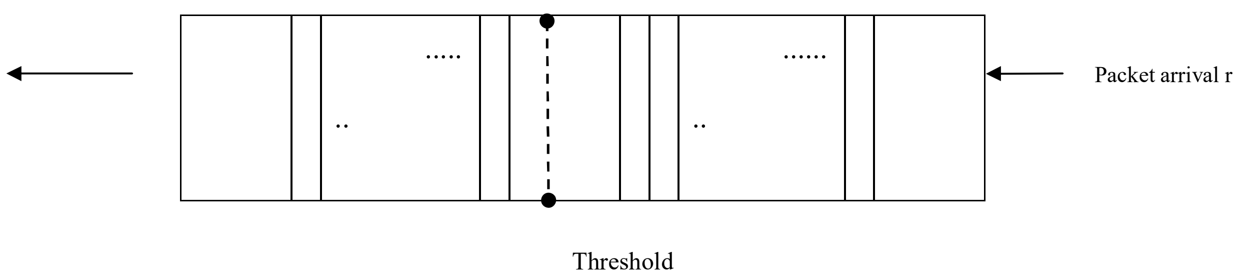

Fig 5.2: Network Interface buffer monitoring

As in fig 5.2, the CH always consistently or periodically monitors the amount of packets in its network interface buffer based on the threshold value. If the number of packets to be serviced is over a certain threshold which is configurable by the operator, the LR-WPAN deduces the current state as congestion. Simultaneously, the CH has to broadcast a beacon message to all network devices to inform them of this state of congestion.

2	1	4 or 10	0,5,6,10 or 14	2	k	m	1	n-1	2
Frame Control	Sequence number	Addressing Fields	Auxiliary Security Header	Super-frame Specification	GTS Fields	Pending Address Fields	CNF	Beacon Payload	FCS

Fig 5.3: Schematic view of beacon frame

The beacon message objective is network searching, delivering broadcast information, network coordination and synchronization such as for the allocation of Guaranteed Time Slots (GTSs).

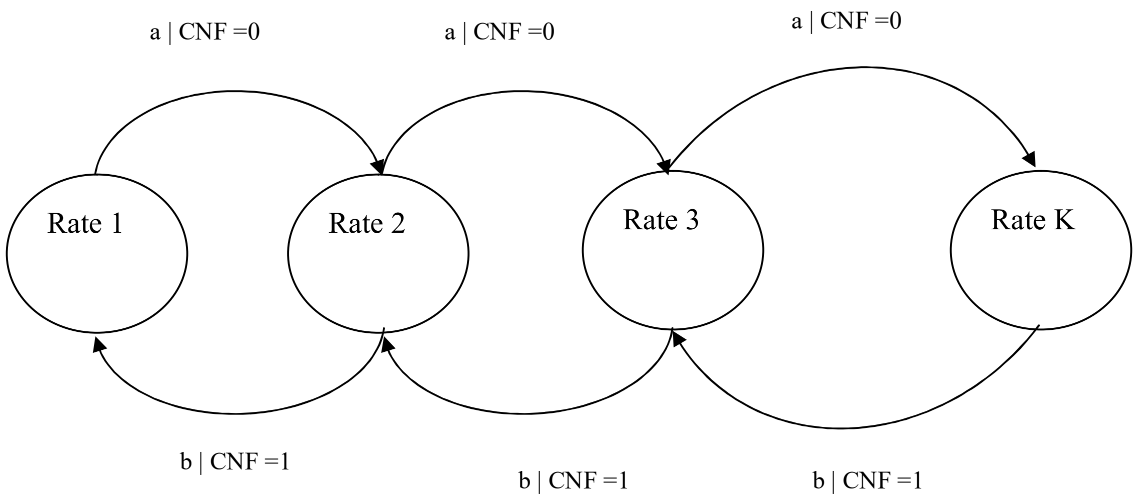

Fig 5.4: data rate control scheme

The LR-WPAN defines following four types of MAC frame namely Data, ACK, and Command and beacon message to support the various messages including the beacon message:

- **Super-frame Specification Field:** includes the parameter to depict the super-frame structure

- **Pending Address Specification Field:** includes all the numbers and types in the Address List Field

- **Addressing Field:** includes the list of devices to transmit packets to the PAN coordinator

- **Beacon Payload Field:** may be used when the PAN coordinator has a packet to broadcast over its coverage area.

Congestion Notification Field (CNF) occupies one octet in the payload field. CNF field is set to 1 when congestion occurs at the network interface buffer, else it is set to 0. This field may also include the identity of the CH.

Based on this CNF value, all of the network devices perform the data rate control scheme which is depicted in the following equation:

$$P\{D_{j+1} \mid D_j\} = a \; , \; P\{D_{j-1} \mid D_j\} = b \qquad (5.2)$$

Here, D_j is the current data rate of a certain network device and a and b are random probability parameters

(i) If this device receives a beacon message with CNF value= 0, it has to change its data rate to D_{j+1}.

(ii) Otherwise, if the device receives a beacon message with CNF value= 1, it has to change its data to D_{j-1}.

This control scheme is very simple to implement. The network device or flow could not guarantee the congestion.

$$D_i = \lim_{t \to \infty} r_i \;\; \forall i \qquad (5.3)$$

The transmission data rate of the network device is tried to be nearly equal to the arrival rate at the CH. D_i is the transmission data rate of the i[th] network device. This equation will be almost satisfied when there is little congestion at the CH. Therefore, the value of r_i will converge to D_i.

5.3. Data rate control using PSO

The encoding parameters are modified to maintain a target output bit rate thus providing the rate control. The Quantizer Parameter (QP) or step size is the most obvious parameter as increasing QP reduces coded bit rate, with lower decoded quality. Quantization has a significant impact on rate control which is set during encoding to maintain the bit rate at the target bit rate.

Different scalar quantisation (Q-scale) values influence the amount of compression. Q-scale value can be set for Prediction (P), Bidirectional (B) and Intra (I) frames separately on a scale of 1 to 31. Larger the Q-scale value more the video will be compressed and hence video can be easily transmitted but with reduced video quality. Hence, particle swarm optimization is used to balance the bit rate and maintain good video quality. With PSO, the output rate of the encoder can be closely controlled during the encoding process as it determines the optimum Q-scale size in an ad-hoc way. This approach should eliminate any data loss and packet drops.

The proposed intelligent system, based on CBR and PSO, should minimise data loss and distortion whilst ensuring that the decoder does not suffer from underflow or overflow. The target bit rate is calculated based on the number of frames in the GOP (n) and the minimum and maximum level of bits available by calculating the prediction P-frame rate.

If the previous frame is an I-frame, it is used as a reference to predict the next frame's complexity and is allocated a suitable number of bits and subsequently the quantize step size Q for the following P and B frames is calculated. The desired bit rate or target rate is expressed as

$$TR = \left[\frac{n}{fr(24)} \right] \tag{5.4}$$

Where TR is Target rate, n = Number of frames, fr= frame rate

The bit rate of an uncompressed video is determined using resolution and frame rate, and lossless video using approximations of quality

$$Bitrate = (a * y) * \frac{MF}{B} * rate \tag{5.5}$$

Where a, is the frame width, with 176 pixels, and y is the height with 144 pixels. The number 4 is the value of MF (motion factor), which is divided by 8 bits, and therefore, 1000 is the value of rate which resulting bit rate of frame. The value of frame bit rate is passed to the PSO for optimization.

In PSO, every particle is considered as a possible solution to the numerical optimization problem in a D dimensional space. In this search space, each particle contains its assigned location and velocity.

Let P_i denote the particle's position

Let V_i denote the particles velocity

Let L_{bp} be the local memory space

Let G_{bp} be the global memory space

Each particle contains a local memory space (L_{bp}) which stores the best position experienced by the particle by then and a global memory space(G_{bp}), which stores the best global position experienced by the particle by then. Using this information, the velocity of the particle can be estimated using Eq. (5.6). And Eq. (5.7) gives the updated position of the particle.

$$V_i = V_i + \gamma_1 * rand * (L_{bpi}-P_i) + \gamma_2 * rand * (G_{bp}- P_i) \qquad (5.6)$$

$$P_i = P_i + V_i \qquad (5.7)$$

Where γ_1 and γ_2 be the weighting constants.

r*and* = uniformly distributed random number in the range of [0, 1]

5.4 Simulation Results

5.4.1 Simulation Parameters

NS2 is used to simulate the proposed PSO based Adaptive Data Rate Control technique (PSOADRC). The IEEE 802.15.4 for wireless LANs is used as the MAC layer protocol. It has the functionality to notify the network layer about link breakage. In the simulation, the packet sending rate is varied as 10, 30, 50, 70 and 90Kbs. The area size is 50 meter x 50 meter square region for 50 seconds simulation time. The simulated traffic is Constant Bit Rate (CBR) and Exponential traffic.

The simulation settings and parameters are summarized in Table 5.1.

No. of Nodes	101
Area	50 X 50
MAC	802.15.4
Simulation Time	50 sec
Traffic Source	CBR and Exp
Rate	10, 30, 50, 70 and 90Kbs
Propagation	Two Ray Ground
Antenna	Omni Antenna

Table 5.1: Simulation parameters

5.4.2 Performance Metrics

Since PSO is applied in Adaptive Data Rate Control (ADRC) (Yeo et al. 2008) protocol, the proposed PSOADRC is compared with ADRC and the performance is evaluated. The performance of the new protocol is mainly evaluated according to the following parameters.

- Average Packet Delivery Ratio: It is the ratio of the number of packets received successfully and the total number of packets transmitted.
- Average end-to-end delay: The end-to-end-delay is averaged over all surviving data packets from the sources to the destinations.
- Throughput: The throughput is the amount of data that can be sent from the sources to the destination.
- Packet Drop: It is the number of packets dropped during the data transmission

5.4.3 Results and Analysis

The simulation results are as under:

A. Based on Rate (CBR)

The traffic sending rate is varied as 10, 30, 50, 70 and 90Kbs for CBR traffic. Table 5.2 shows the results of PSOADRC and ADRC for varying the CBR traffic rate.

Rate	CBR									
	Delay		Delivery Ratio		Drop		Energy		Throughput	
	PSOADRC	ADRC	PSOADRC	ADRC	PSOADRC	ADRC	PSOADRC	ADRC	PSOADRC	ADRC
10	3.632071	6.376918	0.517418	0.430408	2923	4378	9.013213	9.131943	3134	2105
30	5.751445	6.76918	0.4436	0.330408	13740	17378	9.080215	9.631943	4425	3105
50	6.388492	8.376918	0.316189	0.240408	20701	27378	8.006517	9.431943	9572	5105
70	6.760009	9.376918	0.22018	0.170408	33048	37378	8.030001	9.131943	9331	6105
90	6.594229	11.37692	0.20408	0.130408	47378	57378	7.931943	9.131943	9405	6705

Table 5.2 Results for CBR traffic when varying Rate

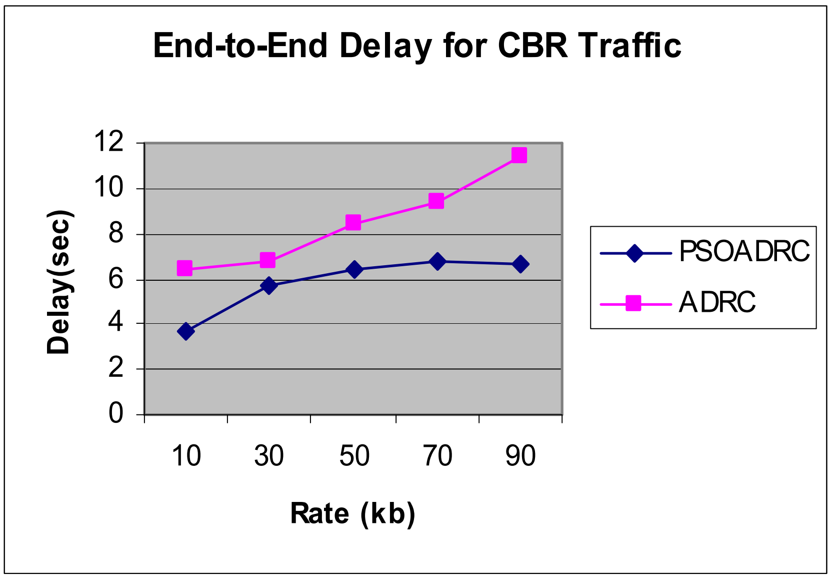

Fig 5.5: Rate Vs. Delay for CBR Traffic

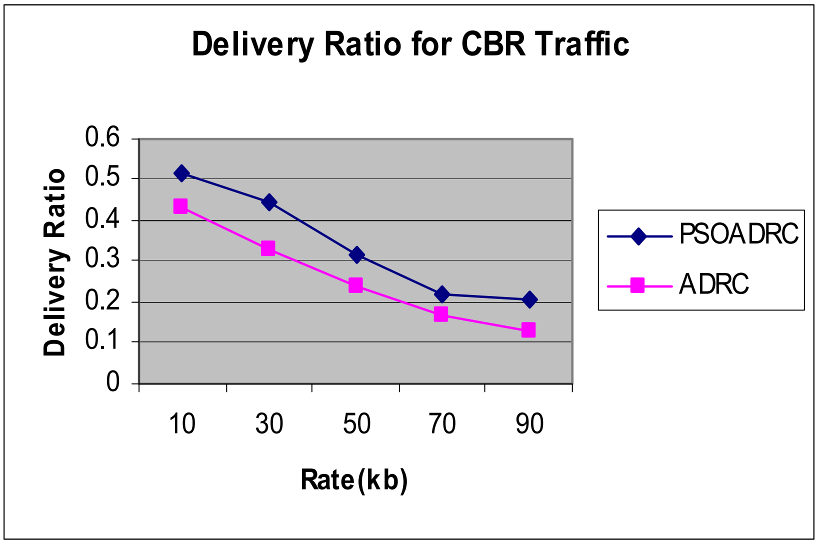

Fig 5.6: Rate Vs. Delivery Ratio for CBR Traffic

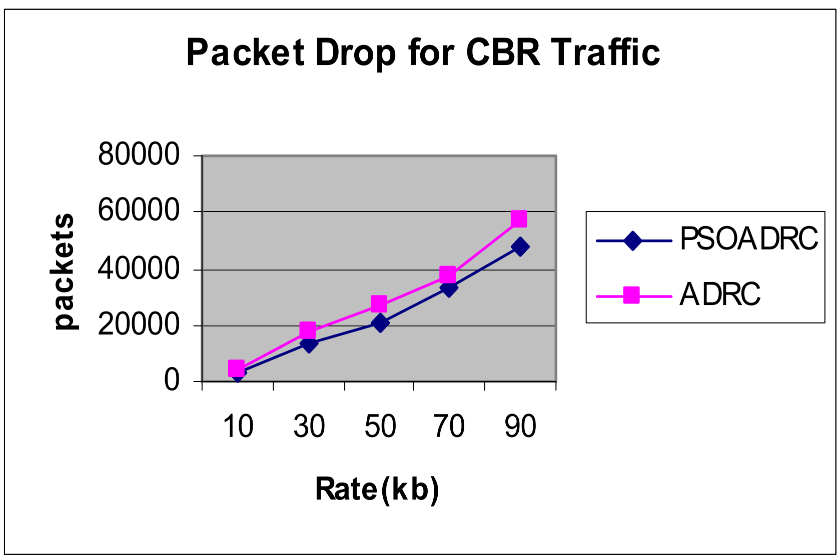

Fig 5.7: Rate Vs. Drop for CBR Traffic

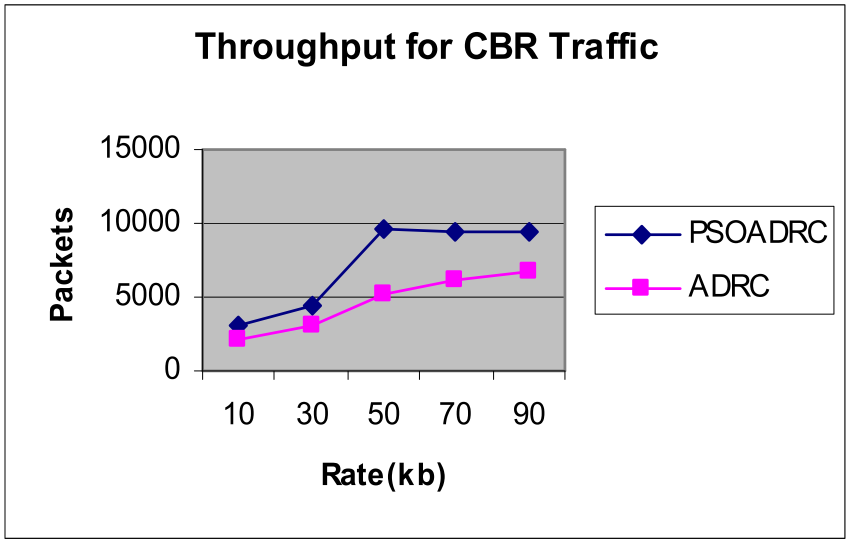

Fig 5.8: Rate Vs. Throughput for CBR Traffic

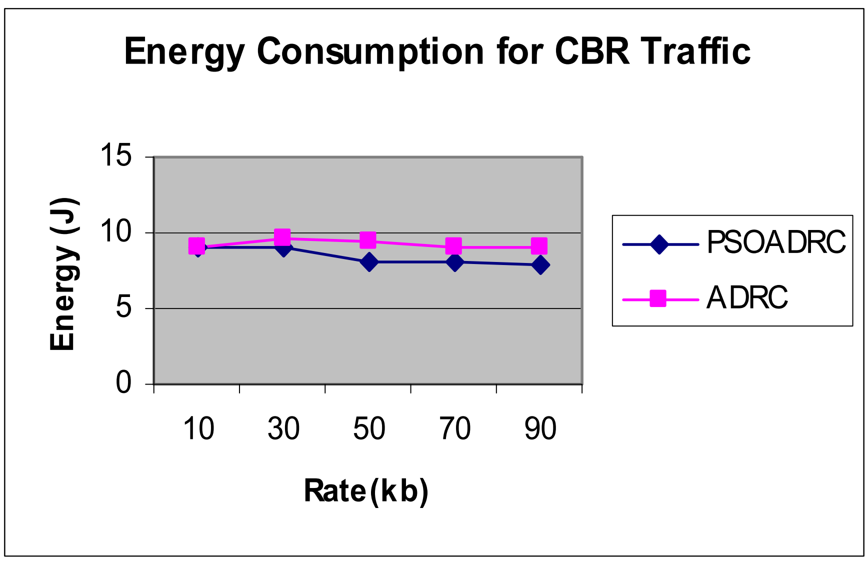

Fig 5.9: Rate Vs. Energy for CBR Traffic

Figures 5.5 to 5.9 show the results of delay, delivery ratio, packet drop, throughput and energy consumption by varying the rate from10Kb to 90Kb for the CBR traffic in PSOADRC and ADRC protocols. When comparing the performance of the two protocols, it is shown that PSOADRC outperforms ADRC by 30% in terms of delay, 25% in terms of delivery ratio, 21% in terms of packet drop, 9% in terms of energy consumption and 34% in terms of throughput. Table 5.3 shows the percentage improvement of PSOADRC over ADRC for varying the CBR rate.

Rate	Delay (%)	Delivery Ratio (%)	Drop (%)	Energy (%)	Throughput (%)
10	43.04347	16.81619	33.23435	1.300161	32.83344
30	15.03483	25.51668	20.93451	5.728107	29.83051
50	23.73696	23.96699	24.38819	15.11275	46.66736
70	27.90799	22.60514	11.58435	12.0669	34.57293
90	42.03853	36.09957	17.42828	13.14069	28.70813

Table 5.3 Percentage Improvement of PSOADRC for varying CBR Rate

B. Based on Rate (Exp.)

The traffic sending rate is varied as 10, 30, 50, 70 and 90Kb for Exponential traffic. Table 5.4 shows the results of PSOADRC and ADRC for varying the exponential traffic rate.

Rate	Exponential									
	Delay		Delivery Ratio		Drop		Energy		Throughput	
	PSOADRC	ADRC	PSOADRC	ADRC	PSOADRC	ADRC	PSOADRC	ADRC	PSOADRC	ADRC
10	1.036967	5.562103	0.999913	0.858812	800	1184	9.455663	10.0116	11510	7202
30	1.307805	4.821089	0.999794	0.668983	1345	3573	7.447597	9.995383	14854	7221
50	2.683128	4.345854	0.906509	0.572777	2525	5750	7.975085	9.991813	24483	7709
70	2.897138	4.650436	0.901902	0.488252	4013	8451	6.25714	9.98032	26895	8063
90	2.742233	4.828365	0.837981	0.465861	6931	10436	6.507292	9.962872	28848	9102

Table 5.4 Results for varying EXP Rate

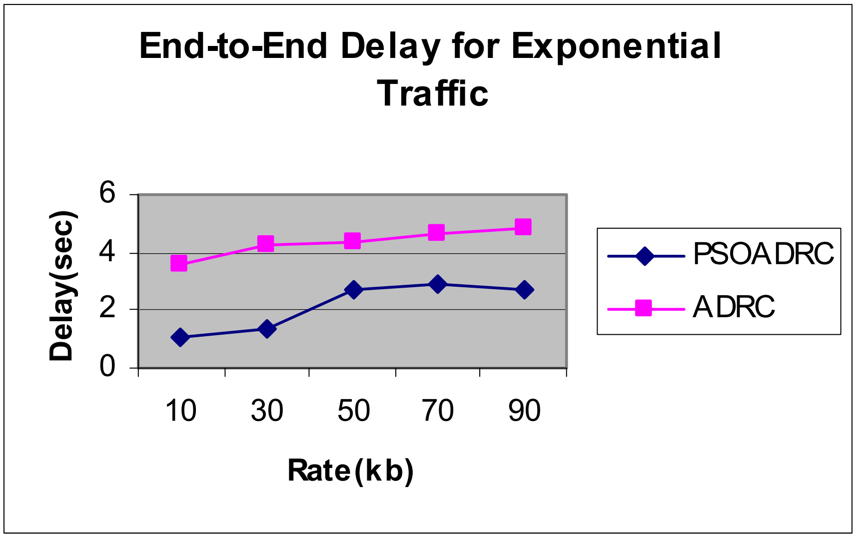

Fig 5.10: Rate Vs. Delay for EXP traffic

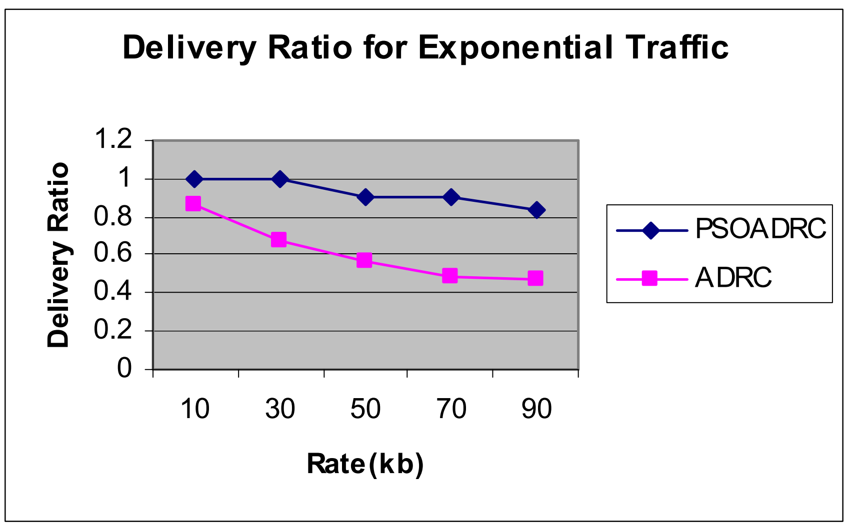

Fig 5.11: Rate Vs. Delivery Ratio for EXP traffic

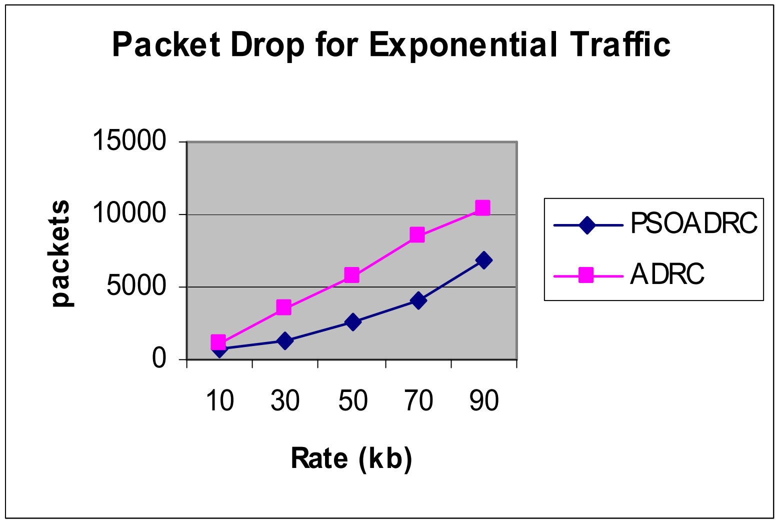

Fig 5.12: Rate Vs. Drop for EXP traffic

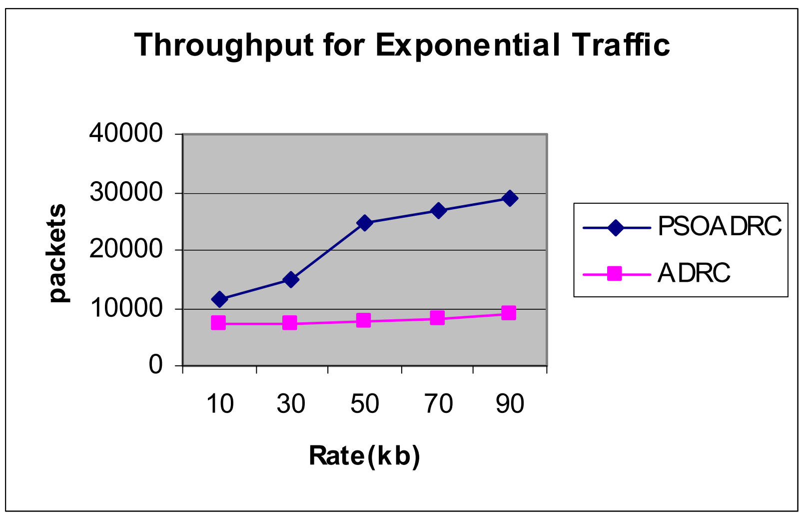

Fig 5.13: Rate Vs. Throughput for EXP traffic

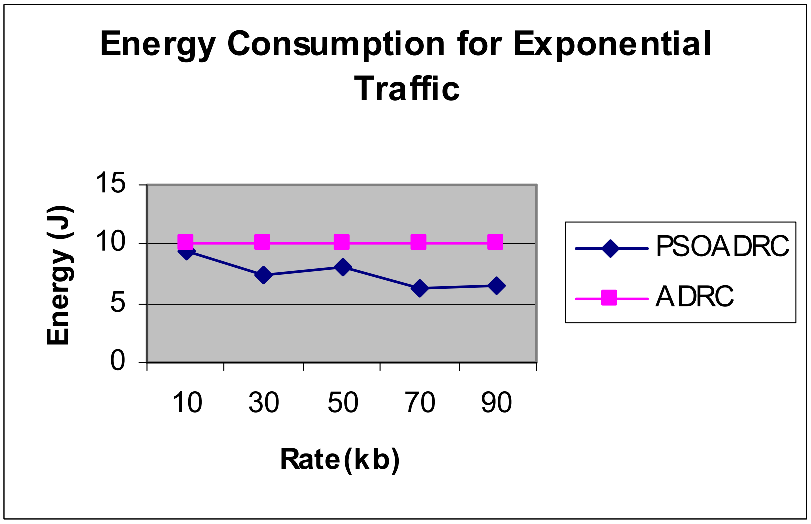

Fig 5.14: Rate Vs. Energy for EXP traffic

Figures 5.10 to 5.14 show the results of delay, delivery ratio, packet drop, throughput and energy consumption by varying the rate from10Kb to 90Kb for the Exponential traffic in PSOADRC and ADRC protocols. The delivery ratio obtained for CBR traffic is significantly low when compared to that of EXP traffic, since the rate control method adaptively reduces the packet drops due to bursty losses.

When comparing the performance of the two protocols, it is shown that PSOADRC outperforms ADRC by 51% in terms of delay, 34% in terms of delivery ratio, 47% in terms of packet drop, 24% in terms of energy consumption and 60% in terms of throughput.

Table 5.5 shows the percentage of improvement of PSOADRC over ADRC for varying the exponential traffic rate.

Rate	Delay (%)	Delivery Ratio (%)	Drop (%)	Energy (%)	Throughput (%)
10	81.35657	14.11133	32.43243	5.552938	37.42832
30	72.87325	33.08792	62.35656	25.48963	51.38683
50	38.26005	36.81508	56.08696	20.1838	68.51285
70	37.7018	45.86418	52.5145	37.30522	70.02045
90	43.20576	44.40673	33.58567	34.68458	68.44842

Table 5.5 Percentage Improvement of PSOADRC for varying exponential traffic Rate

5.5 Conclusion

A network device is developed to regulate its data rate adaptively using the feedback message i.e. Congestion Notification Field (CNF) in beacon frame received from the receiver side for preventing congestion and packet dropping based on current network buffer status. The network device controls or changes its data rate based on CNF value. Along with this, scalability is considered by modifying encoding parameters using PSO to balance the target output rate for supporting high data rate. For scalability data rate control quantizer parameter is used during encoding to maintain target output rate. By simulation results, it has been shown that the proposed PSOADRC technique attains higher throughput and delivery ratio while reducing the delay, packet drop and energy consumption.

CHAPTER-6

CONCLUSION AND FUTURE WORK

The present research succeeded in achieving the aim and objectives set for the study. In this research, various techniques including Energy Efficient Cluster Scheduling and Interference Mitigation, QoS Aware Inter-Cluster Routing Protocol and Adaptive Data Rate Control for Clustered Architecture for IEEE 802.15.4 Networks have been proposed. In the first model a cluster tree topology was built along with a scheduling technique to mitigate the interference. This was done by effectively modifying the underlying physical and MAC layers. Then for data forwarding, an inter-cluster routing protocol was developed, based on the designed cluster tree topology. This was done in the network layer. Finally, in case of traffic overload or congestion, the data rate is adaptively adjusted by the cluster heads. This was again done in the physical layer. Totally, we have designed a cluster tree architecture which provides interference free reliable data forwarding. These techniques proved very useful to reduce the energy consumption and the network collision, to enhance the performance, to mitigate the effect of congestion, and to admit real-time flows.

In chapter 1, the brief introduction about characteristics, applications and challenges of IEEE 802.15.4 Network, clustering and its types, inter-cluster routing, and scheduling have been explained that laid the foundation for the proposed techniques. In addition, interference mitigation and rate control in IEEE 802.15.4

Network have also been discussed. Finally, the chapter detailed the organization of the research into chapters.

Chapter 2 reviewed the existing works on the inter-cluster routing, scheduling, interference mitigation and rate control in IEEE 802.15.4 Network. The review of the system revealed the limitations of the existing protocols and motivated the present researcher to propose a new technique. The conclusion provides the overall problem identified in the existing system.

Chapter 3 discussed energy efficient cluster scheduling and interference mitigation for IEEE 802.15.4 Network in which a time division cluster scheduling technique is considered that offers energy efficiency in the cluster-tree network as the first phase of the present research. In addition, an interference mitigation technique is demonstrated which detects and mitigates the channel interference based on packet-error detection and repeated channel-handoff command transmission. Simulation results show that the proposed technique reduces the energy consumption and the network collision by enhancing the performance successfully.

Chapter 4 focused on QoS aware inter-cluster routing protocol for IEEE 802.15.4 Networks as the second phase of the present research. A routing protocol is designed in the cluster tree network, which consists of few modules like reliability module, packet classifier, hello protocol module, routing service module. The data is transferred from MAC layer to network layer in reliability module which takes care of transmission of messages and acknowledgements. Using the Packet classifier the packets are classified into the data and hello packets. The data packets are classified based on the priority. Hello protocol module constructs neighbour table and maintains information about neighbour nodes reliabilities. Furthermore, using the routing service module, routing table is built. The delay in the route is controlled using delay metrics, which is a sum of queuing delay and transmission delay.

Chapter 5 discussed adaptive data rate control for clustered architecture in IEEE 802.15.4 Networks to mitigate the effect of congestion and admit real-time flows. A network device is designed to regulate its data rate adaptively using the feedback message i.e. Congestion Notification Field in beacon frame received from the receiver side for preventing congestion and packet dropping based on current network buffer status. The network device controls or changes its data rate based on CNF value. Along with this, scalability is considered by modifying encoding parameters using PSO to balance the target output rate for supporting high data rate. For scalability data rate control, quantizer parameter is used during encoding to maintain target output rate.

Simulation results show that the proposed techniques reduce the packet drop and energy consumption. Moreover, they improve the throughput and packet delivery ratio when compared to the existing techniques.

Future Work

The technique proposed in the present research can be extended for other topologies like star and tree in ZigBee networks. The proposed technique has been simulated by using CBR and Exponential Traffic, the future researcher may apply it for TCP (Transmission Control Protocol). The interference considered here is for only cluster topology which detects co-channel interference through channel sensing. The nodes are static in the proposed model. The performance is not observed with heavy interference from IEEE 802.11b/g Wireless Local Area Networks (WLANs) which has lot of similarities with IEEE 802.15.4 such as operating in the same frequency band of 2.4GHz and using DSSS modulation technique. In future the analysis can be extended with heavy interference and mobility and the same proposed scheme can be implemented to other topologies.

Wireless Highway Addressable Remote Transducer (HART) was the first industrial Wireless communication technology to attain the level of international recognition. Its standard is based on the physical layer of IEEE 802.15.4. Despite the changes in MAC protocol, the physical protocol data unit (Ph-PDU) used by the Wireless HART is the same as IEEE 802.15.4. It can also be defined as a TDMA-based wireless mesh networking technology operating in the unrestricted 2.4GHz ISM radio band with stringent timing and security requirements of industrial automation process.

The actual increase in Wireless HART packet loss rely on WLAN channel configuration, the distance between the Wireless HART devices and the access points and specifically, the amount of WLAN traffic. Hence it should be carefully deployed before a Wireless HART network coexists with WLAN installations. Also Wireless

HART packet format reduces the possible aggregation effectiveness. A huge energy is wasted and the devices lifetime is shortened without packet aggregation.

The present MAC layer and physical layer of wireless HART networks need efficient power control and scheduling techniques for resolving the conflicts in transmissions.

Neither the Zigbee nor the Bluetooth assure end-to-end delay for the monitoring applications so as to perform sensor node communication within a second. Since Energy Efficiency is a problem in wireless HART The future researcher may apply the proposed techniques on Wireless HART.

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Appendixes

NS-2 SIMULATOR

NS-2 is an open source discrete event simulator. It used for the simulation of communication networks. It was developed at UC Berkely and first introduced in 1989 since then it has evolved substantially. It is written in C++ and OTcl. (Tcl script language with Object-oriented extensions developed at MIT) NS-2 supports protocols and models at Application level, Transport Protocols, Routing, Routing mechanisms, Link -layer Mechanism etc. To evaluate the performance, an easy to use scripting language can be used by the researchers to configure the network and observe the results. It is the widely used open source network simulator.

Though it can operate on multiple operating systems but it performs well with Linux based operating systems such as Ubuntu and RedHat where as configuring it on windows operating system is quite complex. Many simulation models are beyond the scope of NS-2. A thorough understanding is required for incorporating these modules in NS-2. There are lots of tutorials available online which may help the researcher who wants to use it for their models.

Advantages and Disadvantages can be summarized as follows

Advantages

- NS2 is accepted by international standard like IEEE
- Open source. It is freely available. It can be easily modified and compiled.
- It consists of built in protocols and algorithms for various layers.
- Adding new functionalities or plugging additional components are very easy.
- Results can be quickly obtained – more ideas can be tested in a smaller time frame.
- It provides Scheduling, routing and congestion control
- It support all types of Wireless networks which include Ad-hoc, cellular, GPRS, UMTS, WLAN Bluetooth, WiMax, UWB, Satellite And Sensor Networks like Wireless Sensor Networks (WSN), Wireless Body Area Networks (WBAN) or Wireless Bio Sensor Networks Underwater Wireless Sensor Networks (UWSN).
- It supports Emulation and tracing facility.
- It contains built-in graph tool and visualization tools.
- It has a forum to discuss and clear various technical doubts.

Disadvantages

1. Real system too complex to model. i.e. complicated structure.

2. Bugs are unreliable

B. EECS-21.tcl

```
=========================================================
set val(chan)           Channel/WirelessChannel      ;# Channel Type
set val(prop)           Propagation/TwoRayGround  ;# radio-propagation model
set val(netif)          Phy/WirelessPhy/802_15_4   ;# Physical Layer
set val(mac)            Mac/802_15_4                 ;# MAC Protocol
set val(ifq)            Queue/DropTail/PriQueue      ;# interface queue type
set val(ll)             LL                           ;# link layer type
set val(ant)            Antenna/OmniAntenna          ;# antenna model
set val(ifqlen)         50                           ;# max packet in ifq
set val(nn)             21                           ;# number of mobilenodes
set val(rp)             EECS                         ;# Routing protocol
set val(x)              50
set val(y)              50
set val(nam)            out.nam
set val(traffic)        EXP                          ;# cbr/exponential
set val(cp)             "$val(traffic)-$val(nn)"
set appTime1            2.0     ;#n seconds
set appTime2            10.6     ;# in seconds
set stopTime            50       ;# in seconds

# Initialize Global Variables
set ns_           [new Simulator]
set tracefd     [open out.tr w]
$ns_ trace-all $tracefd
set namtrace     [open $val(nam) w]
$ns_ namtrace-all-wireless $namtrace $val(x) $val(y)

$ns_ puts-nam-traceall {# nam4wpan #}              ;# inform nam that this is a trace
file for wpan (special handling needed)
Mac/802_15_4 wpanCmd verbose on
Mac/802_15_4 wpanNam namStatus on                 ;# default = off (should be turned
on before other 'wpanNam' commands can work)

# For model 'TwoRayGround'
set dist(5m)  7.69113e-06
set dist(9m)  2.37381e-06
set dist(10m) 1.92278e-06
set dist(11m) 1.58908e-06
set dist(12m) 1.33527e-06
set dist(13m) 1.13774e-06
set dist(14m) 9.81011e-07
set dist(15m) 8.54570e-07
set dist(16m) 7.51087e-07
set dist(20m) 4.80696e-07
set dist(25m) 3.07645e-07
set dist(30m) 2.13643e-07
set dist(35m) 1.56962e-07
set dist(40m) 1.20174e-07
```

```
Phy/WirelessPhy set CSThresh_ $dist(12m)
Phy/WirelessPhy set RXThresh_ $dist(12m)

# set up topography object
set topo       [new Topography]
$topo load_flatgrid $val(x) $val(y)

# Create God
set god_ [create-god $val(nn)]

set chan_1_ [new $val(chan)]

# configure node

$ns_ node-config -adhocRouting $val(rp) \
                 -llType $val(ll) \
                 -macType $val(mac) \
                 -ifqType $val(ifq) \
                 -ifqLen $val(ifqlen) \
                 -antType $val(ant) \
                 -propType $val(prop) \
                 -phyType $val(netif) \
                 -topoInstance $topo \
                 -agentTrace ON \
                 -routerTrace ON \
                 -macTrace ON \
                 -movementTrace OFF \
                 -energyModel "EnergyModel" \
                 -initialEnergy 10.1 \
                 -rxPower 0.3 \
                 -txPower 0.3 \
                 -channel $chan_1_

for {set i 0} {$i < $val(nn) } {incr i} {
        set node_($i) [$ns_ node]
        $node_($i) random-motion 0            ;# disable random motion
}

$ns_ at 0.0      "$node_(0) NodeLabel \"PAN Coor\""
$ns_ at 0.0      "$node_(0) sscs startCTPANCoord 1"          ;# startCTPANCoord
<txBeacon=1> <BO=3> <SO=3>
$ns_ at 0.3      "$node_(1) sscs startCTDevice 1 1"   ;# startCTDevice <isFFD=1>
<assoPermit=1> <txBeacon=0> <BO=3> <SO=3>
$ns_ at 1.3      "$node_(9) sscs startCTDevice 1 1"
$ns_ at 1.7      "$node_(13) sscs startCTDevice 1 1"
$ns_ at 2.3      "$node_(19) sscs startCTDevice 1 1"

$ns_ at 3.3      "$node_(2) sscs startCTDevice 1 1 1"
$ns_ at 3.5      "$node_(7) sscs startCTDevice 1 1 1"
$ns_ at 3.6      "$node_(11) sscs startCTDevice 1 1 1"
```

```
$ns_ at 3.8     "$node_(16) sscs startCTDevice 1 1 1"

$ns_ at 4.3     "$node_(3) sscs startCTDevice 0 0"
$ns_ at 4.5     "$node_(6) sscs startCTDevice 1 1"
$ns_ at 4.8     "$node_(12) sscs startCTDevice 1 0"
$ns_ at 5.1     "$node_(17) sscs startCTDevice 1 0"

$ns_ at 5.8     "$node_(5) sscs startCTDevice 1 1"
$ns_ at 6.0     "$node_(10) sscs startCTDevice 1 1"
$ns_ at 6.3     "$node_(14) sscs startCTDevice 1 1"
$ns_ at 5.6     "$node_(20) sscs startCTDevice 1 1"

$ns_ at 7.0     "$node_(4) sscs startCTDevice 0 0"
$ns_ at 7.3     "$node_(8) sscs startCTDevice 0 0"
$ns_ at 7.7     "$node_(15) sscs startCTDevice 0 0"
$ns_ at 6.8     "$node_(18) sscs startCTDevice 1 0"

puts "Loading Scenario and Connection File"
source ../scen/scen-$val(nn)
source ../scen/$val(cp)


$ns_ at $appTime1 "$node_(0) sscs stopBeacon"
$ns_ at $appTime1 "$node_(2) sscs startBeacon 4 4"
$ns_ at $appTime1 "$node_(7) sscs startBeacon 4 4"

Mac/802_15_4 wpanNam PlaybackRate 4ms
$ns_ at $appTime1 "Mac/802_15_4 wpanNam PlaybackRate 1.0ms"
$ns_ at [expr $appTime1 + 0.5] "Mac/802_15_4 wpanNam PlaybackRate 2.0ms"

$ns_ at $appTime1 "puts \"\nTransmitting data ...\n\""


  Mac/802_15_4 wpanNam FlowClr -p AODV -c tomato
  Mac/802_15_4 wpanNam FlowClr -p ARP -c green
  Mac/802_15_4 wpanNam FlowClr -p MAC -c navy

  #$ns_ at $appTime1 "$node_(10) add-mark m1 blue circle"
  #$ns_ at $appTime1 "$node_(20) add-mark m2 blue circle"
  #$ns_ at $appTime1 "$ns_ trace-annotate \"(at $appTime1) cbr traffic from node 10
to node 20\""

  Mac/802_15_4 wpanNam FlowClr -p cbr -s 10 -d 20 -c blue
  Mac/802_15_4 wpanNam FlowClr -p cbr -s 9 -d 17 -c green4


# defines the node size in nam
for {set i 0} {$i < $val(nn)} {incr i} {
	$ns_ initial_node_pos $node_($i) 2
}
```

```
# Tell nodes when the simulation ends
for {set i 0} {$i < $val(nn) } {incr i} {
    $ns_ at $stopTime "$node_($i) reset";
}

$ns_ at $stopTime "stop"
$ns_ at $stopTime "puts \"\nNS EXITING...\n\""
$ns_ at $stopTime "$ns_ halt"

proc stop {} {
    global ns_ tracefd appTime val env namtrace
    $ns_ flush-trace
    close $tracefd
    close $namtrace
    exit 0
}

puts "\nStarting Simulation..."
$ns_ run
```

---

2. scen-21 Scenario file

```
$node_(0) set X_ 20.0
$node_(0) set Y_ 25.0
$node_(0) set Z_ 0.0

$node_(1) set X_ 10.0
$node_(1) set Y_ 25.0
$node_(1) set Z_ 0.0

$node_(2) set X_ 10.0
$node_(2) set Y_ 15.0
$node_(2) set Z_ 0.0

$node_(3) set X_ 10.0
$node_(3) set Y_ 5.0
$node_(3) set Z_ 0.0

$node_(4) set X_ 0.0
$node_(4) set Y_ 15.0
$node_(4) set Z_ 0.0

$node_(5) set X_ 0.0
$node_(5) set Y_ 25.0
$node_(5) set Z_ 0.0

$node_(6) set X_ 0.0
$node_(6) set Y_ 35.0
```

```
$node_(6) set Z_ 0.0

$node_(7) set X_ 10.0
$node_(7) set Y_ 35.0
$node_(7) set Z_ 0.0

$node_(8) set X_ 10.0
$node_(8) set Y_ 45.0
$node_(8) set Z_ 0.0

$node_(9) set X_ 20.0
$node_(9) set Y_ 35.0
$node_(9) set Z_ 0.0

$node_(10) set X_ 20.0
$node_(10) set Y_ 45.0
$node_(10) set Z_ 0.0

$node_(11) set X_ 30.0
$node_(11) set Y_ 35.0
$node_(11) set Z_ 0.0

$node_(12) set X_ 30.0
$node_(12) set Y_ 45.0
$node_(12) set Z_ 0.0

$node_(13) set X_ 30.0
$node_(13) set Y_ 25.0
$node_(13) set Z_ 0.0

$node_(14) set X_ 40.0
$node_(14) set Y_ 25.0
$node_(14) set Z_ 0.0

$node_(15) set X_ 40.0
$node_(15) set Y_ 35.0
$node_(15) set Z_ 0.0

$node_(16) set X_ 30.0
$node_(16) set Y_ 15.0
$node_(16) set Z_ 0.0

$node_(17) set X_ 40.0
$node_(17) set Y_ 15.0
$node_(17) set Z_ 0.0

$node_(18) set X_ 30.0
$node_(18) set Y_ 5.0
$node_(18) set Z_ 0.0
```

```
$node_(19) set X_ 20.0
$node_(19) set Y_ 15.0
$node_(19) set Z_ 0.0

$node_(20) set X_ 20.0
$node_(20) set Y_ 5.0
$node_(20) set Z_ 0.0
```

C. CBR-21 Connection Pattern file for CBR traffic

```
# Setup traffic flow between nodes

proc cbrtraffic { src dst interval starttime stoptime} {
   global ns_ node_
   set udp_($src) [new Agent/UDP]
   eval $ns_ attach-agent \$node_($src) \$udp_($src)
   set null_($dst) [new Agent/Null]
   eval $ns_ attach-agent \$node_($dst) \$null_($dst)
   set cbr_($src) [new Application/Traffic/CBR]
   eval \$cbr_($src) set packetSize_ 80
   eval \$cbr_($src) set rate_ 50Kb
   #eval \$cbr_($src) set interval_ $interval
   #eval \$cbr_($src) set random_ 0
   ##eval \$cbr_($src) set maxpkts_ 10000
   eval \$cbr_($src) attach-agent \$udp_($src)
   eval $ns_ connect \$udp_($src) \$null_($dst)
   $ns_ at $starttime "$cbr_($src) start"
   $ns_ at $stoptime "$cbr_($src) stop"
}

   cbrtraffic 0 3 0.2 1.0 $stopTime
   cbrtraffic 0 18 0.2 1.0 $stopTime
   cbrtraffic 0 6 0.2 2.0 $stopTime
   cbrtraffic 0 12 0.2 2.0 $stopTime
```

D. EXP-21 Connection Pattern file for Exponential traffic

```
# Setup traffic flow between nodes

proc exptraffic { src dst interval starttime stoptime} {
  global ns_ node_
  set udp_($src) [new Agent/UDP]
  eval $ns_ attach-agent \$node_($src) \$udp_($src)
  set null_($dst) [new Agent/Null]
  eval $ns_ attach-agent \$node_($dst) \$null_($dst)
  set exp_($src) [new Application/Traffic/Exponential]
  eval \$exp_($src) set packetSize_ 80
  eval \$exp_($src) set rate_ 50Kb
  #eval \$exp_($src) set interval_ $interval
  #eval \$exp_($src) set random_ 0
  #eval \$exp_($src) set maxpkts_ 10000
  eval \$exp_($src) attach-agent \$udp_($src)
  eval $ns_ connect \$udp_($src) \$null_($dst)
  $ns_ at $starttime "$exp_($src) start"
  $ns_ at $stoptime "$exp_($src) stop"
}

  exptraffic 0 3 0.2 1.0 $stopTime
  exptraffic 0 18 0.2 1.0 $stopTime
  exptraffic 0 6 0.2 2.0 $stopTime
  exptraffic 0 12 0.2 2.0 $stopTime
```

E. Related Publications

1. Ben Saleh, Ahmed ; Sibley, Martin J N ; Mather, Peter, "Energy efficient cluster scheduling and interference mitigation for IEEE 802.15.4 network", Computer Science and Engineering Conference (ICSEC),2014,International, DOI: 10.1109/ICSEC.2014.6978202, Publication Year: 2014 (IEEE Conference publications)

2. Ben Saleh, Ahmed ; Sibley, Martin J N ; Mather, Peter, "QoS Aware Inter-Cluster Routing Protocol for IEEE 802.15.4 Networks", 17th UKSIM-AMSS International Conference on Modeling and Simulation 2015, DOI: 10.1109/UKSIM2015 Publication Year: 2015.(IEEE computer society)

3. Ben Saleh, Ahmed ; Sibley, Martin J N ; Mather, Peter, "Enhancement of the IEEE 802.15.4 Cluster-Tree Network with Energy Efficient Cluster Scheduling ", International Journal Of Engineering And Computer Science ISSN: 2319-7242Volume 4 Issue 4 April 2015, Page No. 11653-11660.