Real Time Topology Selection over Cluster Tree in Zigbee Network

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Abstract - Modeling and simulation of the fundamental performance limits of Wireless Sensor Networks (WSNs) is of paramount importance to undefirstand their behaviour under the worst-case conditions and to make the appropriate design choices. This is particular relevant for time-sensitive WSN applications, where the timing behaviour of the network protocols impacts on the correct operation of these applications. Furthermore, energy efficiency is a key requirement to be fulfilling these applications since the wireless nodes are usually battery-powered. In that direction this thesis contributes with an accurate simulation model of the IEEE 802.15.4/Zigbee protocols and an analytical methodology for the worst-case analysis and dimensioning of a static or even dynamically changing cluster-tree WSN where the data sink can either be static or mobile. The thesis is focused on the study of WSNs with cluster-tree topology because it supports predictable and energy efficient behaviour, which is suited for time-sensitive applications using battery-powered nodes. On the other side, in contrast with the star and mesh topologies, the cluster-tree topology expresses several challenging and open research issues such as a precise cluster scheduling to avoid inter-cluster collisions (messages/beacons transmitted from nodes in different overlapping clusters). Hence, the next objective is to find the collision-free periodic schedule of clusters' active portions, called Time Division Cluster Schedule (TDCS), while minimizing the energy consumption of the nodes and meeting all data flows parameters. The thesis also shows flow to apply the proposed methodologies to the specific case of IEEE 802.15.4/Zigbee beacon-enabled cluster-tree WSNs, as an illustrative example that confirms the applicability of general approach for specific protocols. Finally, the validity and accuracy of the simulation model and methodologies are demonstrated through the comprehensive experimental and simulation studies. Using the proposed analytical methodologies and simulation model, system designers are able to easily configure the IEEE 802.15.4/Zigbee cluster-tree WSN for a given application-specific Quality of Service (QoS) requirements prior to the network deployment.

Keywords - *Cluster-tree; energy efficiency; IEEE 802.15.4; Network Calculus; quality of service; real-time; simulation; wireless sensor network; ZigBee.*

I. INTRODUCTION

The tendency for the integration of computations with physical processes is pushing research on new paradigms for networked embedded systems design [1]. Wireless Sensor Networks (WSNs) have naturally emerged as enabling infrastructures for cyber-physical applications that closely interact with external stimulus. WSNs are mainly aimed at control and monitoring applications where relatively flow data throughput and large scale deployment are the main system features. Furthermore, energy efficiency and timeliness are key requirements to be fulfilled in these applications since the wireless nodes are usually battery-powered and the end-to-end delays of time-sensitive messages must be bounded. For example, the emergency response system in a disaster area or intruder alarm system on the border line [2, 3] both require time-bounded communications and long lifetime of entire network.

Wireless Sensor Networks may be installed and maintained for a fraction of the cost and time of an existing wired network. Wireless networks offer more flexibility and can provide sensing and actuating in previously hard-to-reach areas. In addition, WSNs may be installed in a hazardous or extreme environment where very specialized and costly procedures must be adhered. Since the wireless nodes are usually battery-powered, the network can be effectively used in environments where electricity is not available or some level of mobility is required (e.g. rotating parts of machines or linear position metering [4]). On the other side, using batteries requires effective power management.

Wireless Sensor Networks can be classified into two types, infrastructure-based networks and ad hoc (infrastructure-less) networks. The former is less flexible since it employs the pre-deployed and structured topology, but provides better support of predictable performance guarantees using deterministic routing protocols. Basically, the infrastructure-based networks rely on the use of contention-free MAC protocols (e.g. Time Division Multiple Access (TDMA) or token passing) to ensure collision-free and predictable access to the shared wireless medium, and the ability to perform end-to-end resource reservation. These represent important advantages of infrastructure-based networks when compared to what can be achieved in ad hoc networks, where contention-based MAC protocols and probabilistic routing protocols [5] are commonly used. The ad hoc network provides good flexibility to adaptive network changes, but at the cost of unpredictable performance. Hence, when predictable performance guarantees are the objective, it is suitable to rely on infrastructure-based WSNs such as cluster-tree. On the other side, the cluster-tree WSN expresses many challenging and open research issues in the area of real-time and energy efficient communications (e.g. a precise cluster scheduling to avoid inter-cluster collisions), which have been addressed in this thesis.

The WSN applications can be of many different types and can have different requirements [6]. For example, an environmental monitoring application that simply gathers temperature readings has less stringent requirements than a real-time tracking application using a set of wireless networked cameras. Therefore, it is crucial that sensor network resources are predicted in advance, to support the prospective applications with a predefined Quality of Service (QoS) such as end-to-end delay. Thus, it is important to have adequate methodologies to dimension network resources in a way that the requested QoS of the sensor network application is satisfied [5]. However, the provision of QoS has always been considered as very challenging due to the usually severe limitations of WSN nodes, such as the ones related to their energy, computational and communication capabilities, and due to communication errors resulting from the unreliable and time-varying characteristics of wireless channels [8]. Consequently, it is unrealistic to provide deterministic performance guarantees and support of hard real-time communications in a WSN. In general, no (wireless) communication channel is error-free thus being able to provide 100% guarantees.

Network communication protocols, e.g. at the data link layer, are able to detect most communication errors and, in some cases, correct some of them. The ultimate objective of communication protocols is to guarantee that messages arrive to the destination logically correct and on time. A corrupted or lost message can be detected by simple checksum or acknowledgement mechanisms, respectively, and it can be restored by a retransmission mechanism, for example. Note that all of these mechanisms are natively supported by the IEEE 802.15.4 standard [4]. However, each retransmission decreases throughput, increases the energy consumption of the nodes and the end-to-end communication delay such that a fair trade-o between reliability and timeliness of data transmission must be found. Even if the analysis has to deal with some unknown parameters, such as channel error, the maximum number of retransmissions must be bounded; otherwise, the analysis will not be possible. Using this bound, a system designer can perform capacity planning prior to network deployment to ensure the satisfaction of QoS requirements.

II. OVERVIEW OF IEEE 802.15.4 AND ZIGBEE

This chapter gives an overview to the most significant features of the IEEE 802.15.4 standard and Zigbee specification. It particularly focuses on the beacon-enable mode and cluster-tree topology that have ability to provide predictable QoS guarantees for the time-sensitive and energy efficient wireless sensor applications.

IEEE 802.15.4 [9] standard and Zigbee [5] specification stand as the leading communication technologies for large scale, flow data rate, flow cost and flow power consumption Wireless Sensor Networks (WSNs) (In 2012, 802.15.4-enabled chips will reach 292 million, up from 7 million in 2007 [12]). IEEE 802.15.4/Zigbee is quite flexible for a wide range of applications by adequately tuning their parameters (see Chapter 3). They can also provide real-time guarantees for time-sensitive WSN applications (see Chapters 4 and 5). Sometimes, people confuse IEEE 802.15.4 with Zigbee. The IEEE 802.15.4 standard specific the physical layer and medium access control (MAC) sub-layer, while the network layer and the framework for the application layer are provided by the Zigbee specification such that a full protocol stack is defined. Recently the Zigbee Alliance and the IEEE decided to join forces and Zigbee is the commercial name for the IEEE 802.15.4/Zigbee communication technology.

The IEEE 802.15.4 standard defines two main types of wireless nodes: a Full-Function Device (FFD) and a Reduced-Function Device (RDF). The FFD implements all the functionalities of the 802.15.4 protocol and can operate in three modes serving as a PAN (Personal Area Network) coordinator, a coordinator, or an end device. On the other hand, the RFD can operate only as an end device using a reduced implementation of the 802.15.4 protocol, which requires minimal resources and memory capacity. An end device must be associated with a coordinator and communicates only with it. Coordinators can communicate with each other, and they are capable to relay messages. One of the coordinators is designed as a PAN coordinator and it holds special functions such as identification, formation and control of the entire network.

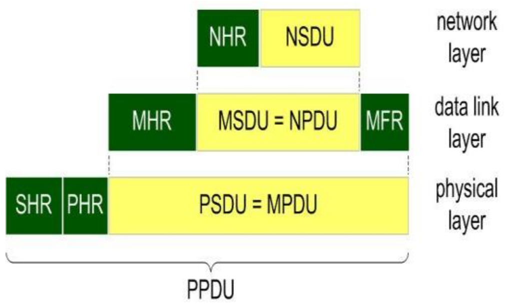


Fig.1: Structure of the IEEE 802.15.4/Zigbee frames

The data payload is passed from the application layer to the network layer, and it is referred to as the Network Service Data Unit (NSDU) (Figure 1). This payload is prefixed with a network header (NHR) of 64-bit size, which comprises frame control, addressing and sequencing information [10]. The NHR and NSDU form the Network Protocol Data Unit (NPDU), which is passed to the data link layer as the MAC payload, i.e. MAC Service Data Unit (MSDU). The maximum MAC payload that can be transmitted in a data frame is equal to aMaxMACPayloadSize (944 bits). The MAC payload is prefixed with a MAC Header (MHR) and appended with a

MAC Footer (MFR). The MHR contains the frame control field, data sequence number, addressing fields, and optionally the auxiliary security header. The MFR is composed of a 16-bit frame control sequence (FCS). The MHR, MSDU, and MFR together form the MAC Protocol Data Unit (MPDU). The maximum size of a MPDU is equal to aMaxPHYPacketSize (1016 bits). Hence, the minimum size of MAC Header is equal to 56 bits using 16-bit short addresses. The MPDU is passed to the physical layer as the Physical Service Data Unit (PSDU), which becomes the PHY payload. The PHY payload is prefixed with a Physical Header (PHR) of 8-bit size and a Synchronization Header (SHR) of 40-bit size enabling the receiver to achieve symbol synchronization. The SHR, PHR, and PSDU together form the Physical Protocol Data Unit (PPDU), which can be dispatched to a wireless channel.

A. Physical layer

The physical layer is responsible for data transmission and reception using a certain radio channel according to a specific modulation and spreading techniques. The IEEE 802.15.4-2003 [3] standard supports three unlicensed frequency bands: 2.4 GHz (worldwide, 16 channels), 915 MHz (North America and some Asian countries, 10 channels) and 866 MHz (Europe, 1 channel). The data rate is 250 kbps at 2.4 GHz, 40 kbps at 915 MHz and 20 kbps at 868 MHz In addition; four frequency band patterns have been added to the 868/915 MHz bands in the last revision of the standard (IEEE 802.15.4-2006 [7]). All of these frequency bands are based on the Direct Sequence Spread Spectrum (DSSS) or Parallel Sequence Spread Spectrum (PSSS) spreading techniques that have inherently good noise immunity. The standard also all flows energy detection, link quality indication, clear channel assessment and radio channel switching. We consider only considers the 2.4 GHz band with 250 kbps data rate, which is also supported by the TelosB motes [4] used in the experimental test-beds. In addition, the Zigbee specification is only defined for this frequency band.

B. Data link layer

The MAC sub-layer supports the beacon-enabled or non beacon-enabled modes that may be selected by a central controller of the WSN, i.e. PAN coordinator. In non beacon-enabled mode, the nodes can simply transmit messages using unslotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) channel access protocol. In fact, the "collision avoidance" mechanism is based on a random delay prior to transmission, which only reduces the probability of collisions. Thus, this mode cannot ensure collision-free and predictable access to the shared wireless medium and, consequently, it cannot provide any time and resource guarantees. On the other side, the beacon-enabled mode enables the synchronization of a WSN using periodic beacon frames, the energy conservation using flow duty-cycles, and the provision of collision-free and predictable access to the wireless medium through the Guaranteed Time Slot (GTS) mechanism. Thus, when the timeliness and energy efficiency are the main concerns, the beacon-enabled mode should be employed.

In beacon-enabled mode, beacon frames are periodically sent by a coordinator to synchronize nodes (i.e. coordinators or/and end devices) that are associated to it and to describe the structure of the super frame (Figure 2). Beacon Interval (BI) is defined as the time interval between two consecutive beacons, and it is divided into an active portion and, optionally, a following inactive portion. During the inactive portion, each associated node may enter a low power mode to save energy resources.

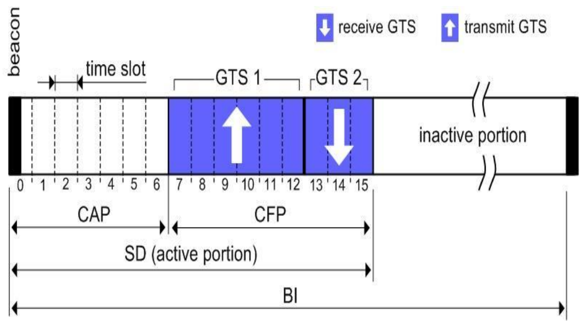
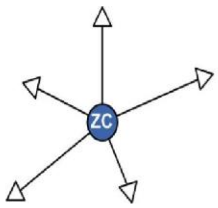


Fig.2: Super frame structure of IEEE 802.15.4.

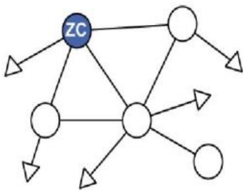
The active portion, corresponding to Super frame Duration (SD), is divided into 16 equally-sized time slots, during which data transmission is all flowed. These time slots are further grouped into a Contention Access Period (CAP) using slotted CSMA/CA for the best-e ort data delivery, and an optional Contention Free Period (CFP) supporting the time-bounded data delivery. Within the CFP, the coordinator can allocate Guaranteed Time Slots (GTS) to its associated nodes. The CFP supports up to 7 GTSs and each GTS may contain one or more time slots. Each node may request up to one GTS in transmit direction, i.e. from the associated node to the coordinator, or/and one GTS in receive direction, i.e. from the coordinator to the associated node. A GTS is activated upon a request, where a node explicitly expresses the number of time slots that it wants to allocate from its coordinator. The allocation of the GTS cannot reduce the length of the CAP to less than the value specified by aMinCAPLength constant (7.04 ms [9]) ensuring that commands can still be transferred when GTSs are being used. A node to which a GTS has been allocated can also transmit best-e ort data during the CAP. Note that there are neither beacons nor super frames in non beacon-enabled mode.

III. ZIGBEE NETWORK LAYER & TOPOLOGY

The Zigbee [10] network layer allows the network to spatially grow using multi-hop communications, without requiring high power transmitters. Responsibilities of the network layer include mechanisms used to associate to and disassociate from a network, apply security to outgoing frames, and routing frames to intended destinations.



(a) Star topology



(b) mesh topology

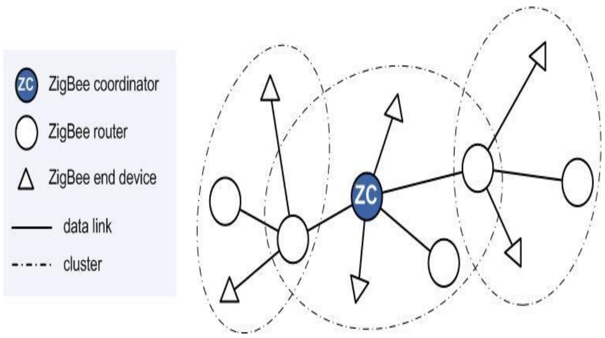


Fig.3: IEEE 802.15.4/Zigbee network topologies

Regarding the node's role in the network, Zigbee specification defines three types of nodes: Zigbee coordinator, Zigbee router and Zigbee end device. The node that is capable to directly associate other nodes and can participate in multi-hop routing is referred to as Zigbee router (ZR). Any FFD operates in coordinator mode can act as a Zigbee router. An FFD operating in PAN coordinator mode acts as Zigbee coordinator (ZC). Every WSN shall include one Zigbee coordinator that holds special functions such as identification, formation and control of the entire network. Zigbee coordinator also participates in routing once the network is formed. The node that does not allow association of other nodes and do not participate in routing are referred to as Zigbee end device (ZED). Any FFD or RFD can act as a Zigbee end device.

Star, mesh and cluster-tree are three logical topologies supported in the IEEE 802.15.4/Zigbee as shown in Figure 3. While IEEE 802.15.4 standard in the beacon-enabled mode supports only the star topology, the Zigbee specification has proposed its extension to the multi-hop cluster-tree and mesh topologies. In the star topology, the communications are centralized and established exclusively between a Zigbee coordinator and its associated Zigbee end devices. If a ZED needs to transfer data to another ZED, it sends its data to the ZC, which subsequently forwards the data to the intended recipient. To synchronize the associated ZEDs, the ZC emits regular beacon frames. Consequently, each ZED can enter a low power mode to save their energy whenever it is not active. The ZED can also request for the GTS ensuring predictable and contention-free medium access. The main advantages of star topology are its simplicity and predictable and energy efficient behaviour. The drawbacks are limited scalability and ZC as a single point of failure. The ZC's battery resource can be also rapidly ruined since all traffic is routed through ZC. Hence, the star networks are suitable for simple and small scale applications.

Infrastructure-less mesh topology and infrastructure-based cluster-tree topology allow more complex network formations to be implemented. The mesh topology differs from the star topology in that the communications are decentralized and any node can directly communicate with any other node within its radio range. The mesh network usually operates in ad hoc fashion that induces unpredictable end-to-end connectivity between nodes. In contrast with the star topology, the mesh topology provides good scalability and enhanced network flexibility such as redundant routing paths that increases end-to-end reliability of data transmission and ensures fair resource usage. In addition, this communication redundancy can eliminate single point of failure. On the other hand, the probabilistic routing protocol (e.g. Ad hoc On Demand Distance Vector (AODV) routing protocol defined in Zigbee) and contention-based MAC protocol cause unpredictable performance and resource bounds. Moreover, since the routing paths cannot be predicted in advance, the nodes cannot enter low power mode which leads to a useless waste of energy.

TABLE 1: STAR VS. MESH VS. CLUSTER-TREE TOPOLOGIES.

Property	star	mesh	cluster-tree
scalability	no	yes	yes
energy efficiency	yes	no	yes
network synchronization	yes	no	yes
redundant paths	no	yes	no
node mobility	partial	yes	partial
deterministic routing	yes	no	yes
contention-free medium access	yes	no	yes

Table 1 summarizes the important features of the above mentioned topologies as they are defined in the IEEE 802.15.4/Zigbee. Remind that the star and cluster-tree networks can operate on beacon-enabled mode, which can provide predictable resource guarantees (e.g. bandwidth and Buffer size), network synchronization and energy conservation. Note that the beacon-enabled mode is not permitted in mesh networks. In contrast with the star and mesh networks, the cluster-tree network requires precise cluster scheduling (Chapter 4) to avoid inter-cluster collisions (messages/beacons transmitted from nodes in different overlapping clusters). IEEE 802.15.4 standard and Zigbee specification admit the formation of the cluster-tree network but none of them imposes any algorithm or methodology to create or organize it. Thus, the cluster-tree topology expresses several challenging and open research issues in this area, which have been addresses in this work.

IV. SIMULATION & TOPOLOGY MODEL

In this chapter considers a static deployment of wireless nodes which defines the physical topology of WSN given by the bidirectional wireless links between every pair of nodes that are within transmission range of each other. The logical topology, based on a physical topology, defines a subset of wireless links to be used for data transmission. In the rest of the thesis, the notation topology will be used while meaning logical topology.

A. Cluster-tree topology model

One of the WSN topologies suited for predictable and energy efficient behaviour is a cluster-tree (Figure 4) where the routing decisions are unique And nodes can enter low power mode to save their energy. From the hierarchy point of view, the cluster-tree is directed tree (so called in-tree [43]) as depicted by solid arrows in Figure 4. On the other hand, from the data transmission point of view, the cluster-tree is undirected tree (i.e. the wireless links are bidirectional). The hierarchy of the cluster-tree topology is defined by parent-child relationships, in the sense that each solid arrow in Figure 4 leaves the child node and enters the parent node. Note that the in-tree has the following property: one node, called root, has no parent and any other node has exactly one parent.

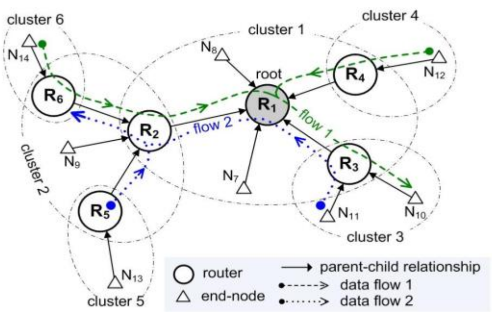


Fig.4: Cluster-tree topology with 2 time-bounded data flows

The routers and end-nodes are two types of wireless nodes in cluster-tree WSNs. The nodes that can participate in multi-hop routing are referred to as routers (R_i). The nodes that do not all flow association of other nodes and do not participate in routing are referred to as end-nodes (N_i). In the cluster-tree topology, the nodes are organized in logical groups, called clusters. Each router forms a cluster and is referred to as its cluster-head (e.g. router R_2 is the cluster-head of cluster 2). All of its child nodes (e.g. end-node N_9 and routers R_5 and R_6 are child nodes of router R_2) are associated to the cluster, and the cluster-head handles all their transmissions.

Throughout this work, the router and cluster-head are used interchange-ably since each router R_i acts as a cluster-head of cluster i for all its child nodes, and as a consequence, will send periodic beacons to keep them synchronized.

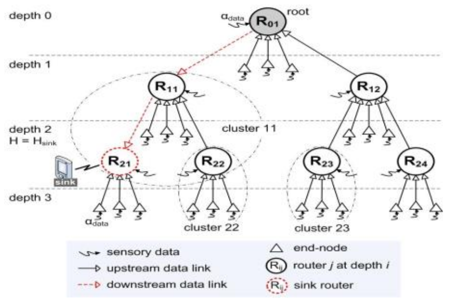


Fig.5: The worst-case cluster-tree topology model corresponding to a configuration where N^{MAX} end-node = 3, NMAX router = 2, Hsink = 2 and H = 2.

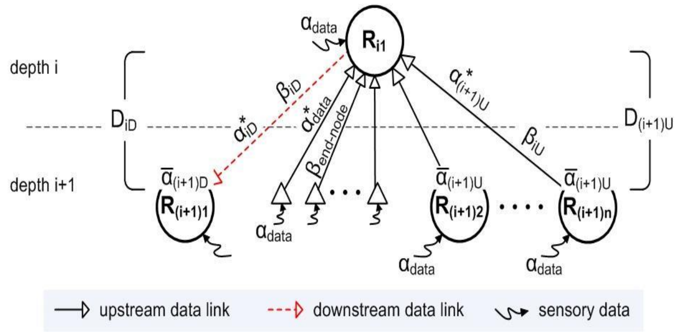


Fig.6: General data flow model with corresponding arrival and service curves.

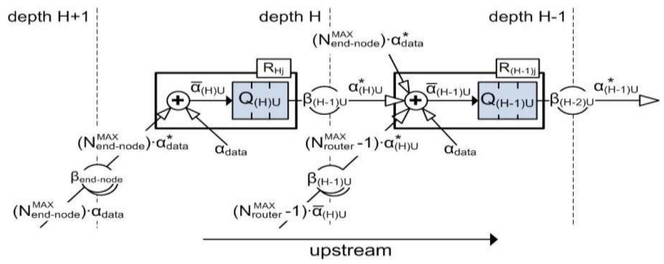


Fig.7: The queuing system model for the upstream direction

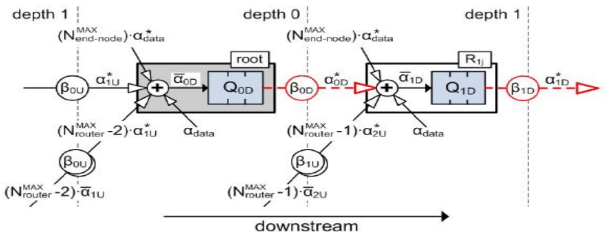


Fig.8: The queuing system model for downstream direction.

B. Per-router resources analysis

The aim is at specifying the minimum bandwidth of each upstream and downstream data links and the minimum Buffer size at each router needed to store the bulk of data incoming through the router's inputs.

C. Outcomes parameters

1. Topology design (logical, physical & depth level
2. Delay element
3. Lm-depth level, Cm-connection

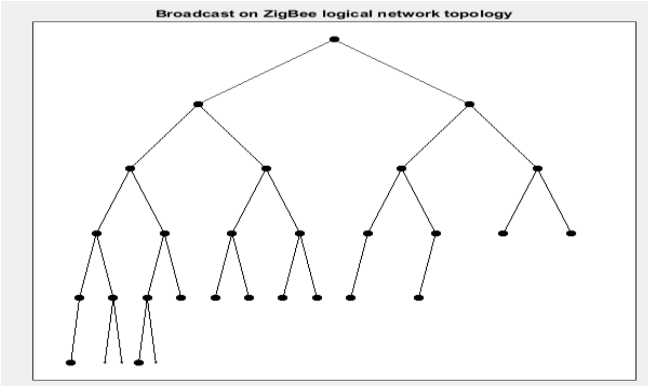
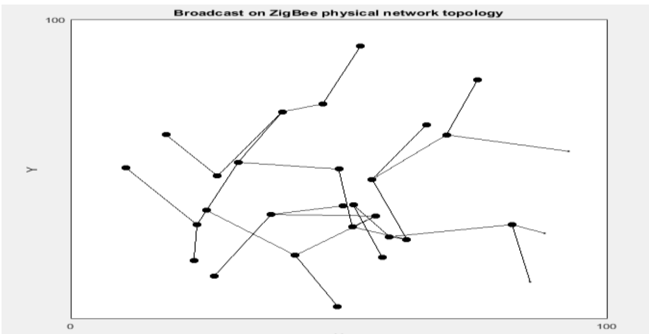
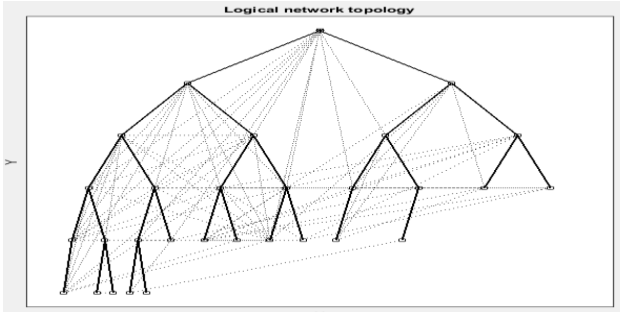
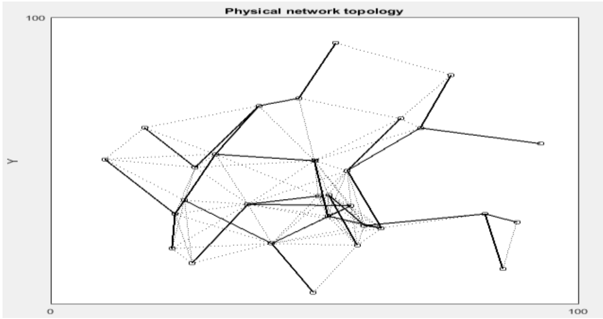


TABLE 4.1

Connct-ion Cm	Depth level Lm	No. of node	Num Already forward	Num Nonfor-ward	numRec-eive	Delay
2	2	10	3	4	20	8.6986 e-04
3	2	10	9	1	86	0.6454
4	2	10	6	4	62	0.7060
5	2	10	8	2	90	0.6454
2	3	15	15	0	188	0.6381
3	3	15	13	2	156	0.4905
4	3	15	12	3	150	0.4652
5	3	15	12	3	150	0.6454
2	4	20	18	2	274	0.4770
3	4	20	18	2	240	0.4852
4	4	20	18	2	240	0.6898
5	4	20	18	2	240	0.4963
2	5	25	24	1	356	0.4902
3	5	25	23	2	300	0.5799
4	5	25	23	2	300	0.6898
5	5	25	23	2	300	0.5799
2	6	30	26	4	388	0.4902
3	6	30	29	1	418	0.5828
4	6	30	29	1	418	0.5828
5	6	30	29	1	394	0.7743







Cm=2, Lm=5

V. RESULT AND CONCLUSION

As selection of depth and connection level you can easily find the broadcast zigbee topology, physical topology and logical topology. Following find are observe when selection of value of Cm and Lm.

- As depth level increase delay parameter increase and it maintain constant after a level
- As depth level increase number of receive increase
- As increase as connection or Cm value increase than number of Non forward node increase

In future scope we will increase the more parameter like bandwidth requirement, buffer or throughput requirement and delay parameter for upstream and downstream communication in zigbee structure.

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