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Enhancement of the IEEE 802.15.4 Cluster-Tree Network with Energy Efficient Cluster Scheduling

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Abstract

In ZigBee cluster-tree network, the existing literature works does not provide solution for power efficient scheduling. In addition, the technique to prevent network collision is not explained. In order to overcome these issues, in this paper, we propose Energy Efficient Cluster scheduling for IEEE 802.15.4 Cluster-Tree Network. In this technique, initially, the distributed Pull-Push-Relabel (PPR) algorithm is designed to adapt to a ZigBee cluster-tree network. Then, a time division cluster scheduling technique is considered that offers energy efficiency in the cluster-tree network by maximizing the Cluster Scheduling period in relative to beacon interval. Besides, it prevents resource requirements whereas fulfills some temporal requirements such as end-to-end deadlines of all the flows. By simulation results, we show that the proposed technique reduces the energy consumption and reduces the network collision.

1. Introduction

1.1 WPAN

WPAN stands for "Wireless Personal Area Networks". As defined by IEEE 802.15.4, WPAN comprises of radio devices that are characterized by low power, low data rate, short communication range and low cost. It is a new wireless technology that provides short-range connectivity between batteries operated portable radio devices such as mobile phones, head sets and personal digital assistants. WPAN technologies are continuously increasing in interest because of their ubiquitous mobile connections and their ability to provide new personal communication opportunities and services. Different WPAN infrastructures based on Bluetooth can be interconnected to enable sharing of information to allow interaction with the physical environment. The smallest Bluetooth enabled device in a WPAN is called as piconet that is established by at most eight nodes. Member devices of piconet can become member device of other piconets and hence forming a large network called as scatternet. They are expected to operated at the 2.4 GHz ISM (Industrial, scientific, Medical) band where no license is required using a FHSS (Frequency Hopping Spread Spectrum) technique. This technology is based on the Bluetooth specification and become an IEEE standard under the denomination of 802.15 WPANs.

WPANs are used to transfer information over quite short distances. Unlike wireless local area networks (WLANs), connection effected via WPAN involves little or no infrastructure. This feature allows small, short-range operation, reliable data transfer and a reasonable battery life, power-efficient, inexpensive solution need to be implemented for wide range of devices[1][2][3] [4].

1.2. IEEE 802.15.4 Model

IEEE 802.15.4 is an emerging standard, specially designed for low rate WPAN with a focus on enabling the wireless sensor network (WSN). It attempts to provide a low data rate, low power and low cost wireless networking on the device-level communication.

It is the standard for WPAN that provides physical (PHY) and medium access control (MAC) layers. Based on physical and medium access control (MAC) layers of IEEE 802.15.4, the upper –layer (including the network and application layers) specifications are defined by the ZigBee protocol stack. [6]. IEEE 802.15.4 networks support star, mesh and cluster-tree network. This network consist of two types of devices: (1) **Full Function Device (FFD**) (2) **Reduce Function Device (RFD).** FFD play a role of router that can connect to other FFD and RFD devices. In contrast RFD can only connect to FFD devices. ZigBee network defines three kinds of devices personal area network (PAN) coordinator, router and end device that can be described as follows:

- **Personal Area Network (PAN) coordinator**: It is a FFD device acting as the core component of the network and responsible to initiate the network by setting network's parameters which contain how many nodes can join to and the types of nodes (router and end devices) in this network.
- **Router device**: It is a FFD device that a PAN coordinator uses it as intermediate node to carry out the multi-hops routing message through the network from source nods to the sink node.
- **End device**: It is a RFD device acting as the leaf of the network with limit functionality.

It is designed to wirelessly interconnect ultra low-cost sensors, actuators and processing devices that will constitute the infrastructure to sense and affect the physical environment. Typical applications of IEEE 802.15.4 devices are predicted to be: (1) industrial control, (2) environmental and health monitoring, (3) home automation, entertainment and toys, (4) security, location and asset tracking, (5) emergency and disaster response. [5][7][8].

1.2.1 Issues to Improve Performance of IEEE 802.15.4 in WPAN

The IEEE 802.15.4 is a standard protocol for Low-Rate Wireless personal Area Network (LR-WPAN). Some of the issues that need to be considered to improve performance of IEEE802.15.4 in WPAN are as follows:

- At the MAC layer of IEEE 802.15.4 when there are multiple nodes the performance will decrease because of collisions. Moreover the slotted CSMA/CA algorithm cannot effectively avoid collisions on IEEE 802.15.4 that affects the transmission performance. [9].
- This standard targets low data rate communication in single-hop and multi-hop sensor network. But choosing a reliable, energy-efficient and 802.15.4 compatible routing protocol that can relay packets from PAN coordinator to the sensor node and vice-versa is not part of the standard. [10].
- Also Hidden Terminal Problem (HTP) in star network is found when multiple out of range nodes assumes a free channel and initiate time-overlapping packet transmissions, resulting in packet collision at the receiver node.
- FFD carry full 802.15.4 functionality and all features of the standard 802.15.4 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 limitation reduces significantly the node's operative lifetime. [10].

1.3 Problem Identification

In paper [6] they have proposed an adoptive-parent-based framework for ZigBee cluster-tree network. The main objective of this paper is to provide more flexible routing and to increase the

Drawbacks

- In the proposed scheme, they have not considered any method for energy efficiency in the network.
- They have not considered any method to avoid any collision in the network.

Generally, existing works did not provide solution for power efficient scheduling.

In this proposal, we design a Energy Efficient Cluster scheduling for IEEE 802.15.4 Cluster-Tree Network.

2. Literature Review

Li-Hsing Yen et al in paper [1] have proposed a node pair classification scheme. Based on this scheme, they have easily assessed the risk of slot reuse by a node pair. If the risk is high, slot reuse is disallowed; otherwise, slot reuse is allowed. This forms the essence of their ZigBee-compatible, distributed, risk-aware, probabilistic beacon-scheduling algorithm. Simulation results show that on average the proposed algorithm produces a latency only 24% of that with conventional method, at the cost of 12% reduction in the fraction of associated nodes. The drawback of the proposed they have not considered the energy efficiency and throughput in the network.

Yu-Kai Huang et al in paper [6] have proposed adoptive-parent-based framework for a ZigBee cluster-tree network to increase bandwidth utilization without generating any extra message exchange. To optimize the throughput in the framework, we model the process as a vertex-constraint maximum flow problem, and develop a distributed algorithm that is fully compatible with the ZigBee standard. The optimality and convergence property of the algorithm are proved theoretically. Finally, the results of simulation experiments demonstrate the significant performance improvement achieved by the proposed framework and algorithm over existing approaches. The drawback of the proposed method is that the larger buffer introduces larger latency in the network**.**

A.G.Ruzzelli et al in paper [10] have proposed V-route 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. V-Route allows enhancing 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. The drawback of this paper is that in the proposed method they have not considered about the throughput metrics in the network.

Zdenek Hanz alek et al in paper [12] have proposed a methodology that provides a Time Division Cluster Scheduling (TDCS) mechanism based on the cyclic extension of RCPS/TC (Resource Constrained Project Scheduling with Temporal Constraints) problem for a cluster-tree WSN, assuming bounded communication errors. The objective is 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. The scheduling tool enables 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. The future work includes investigating adaptive behavior of scheduling problem when new tasks are added to the original schedule.

Ismail Salhi et al in paper [13] have proposed CoZi, a new packet scheduling mechanism for large scale ZigBee networks. CoZi aims at enhancing the reliability of the data delivery and the bandwidth utilization of the network. Based on simple network coding, instead of the classic packet forwarding, their algorithm takes advantage of the shared nature of the wireless medium as well as the cluster-tree topology of IEEE 802.15.4 networks to increase the global throughput and to reduce transmissions in end-to-end and dissemination-based communications. The future work includes implementing some mechanism that will be energy efficient.

3. Proposed Solution

3.1 Overview

In this paper, we propose Energy Efficient Cluster scheduling for IEEE 802.15.4 Cluster-Tree Network. In this technique, initially the distributed pull-push-relabel (PPR) algorithm [6] is designed to adapt to a ZigBee cluster-tree network. Then a time division cluster scheduling technique is considered that offers energy efficiency in the cluster-tree network by maximizing the Cluster Scheduling period in relative to beacon interval. Besides, it prevents resource requirements whereas fulfills some temporal requirements such as end-to-end deadlines of all the flows.

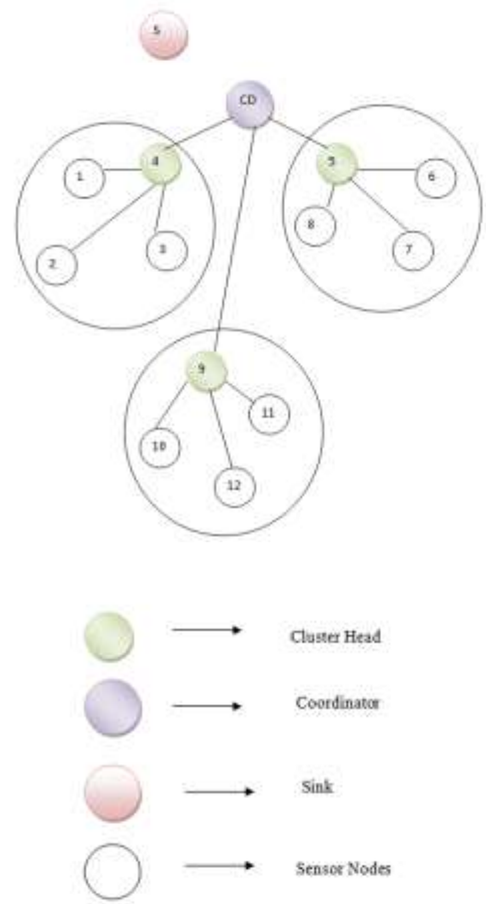

Fig 1 Proposed Cluster Tree Architecture

3.2 Definitions

Consider the following assumptions.

Let X be the set of vertices (routers) and E be the set of edges(communications links) of a graph G.

Let S and D be the source and destination

Let (x, y) be the pair of vertices (where x, y $\in$ X).

Consider vertex-constraint flow network Q = (X, E) with S and D.

Let v be the flow in Q.

Let H be the height

Let z be the excess flow

The terms involved in the PPR algorithm are defined in the following sections

3.2.1 Residual Capacity

It is defined as the amount of additional flow which can be added to vertex y before exceeding the capacity μ (y).

$$RC(y) = \mu(y) - \sum_{x \in X} \{v(x,y) \mid v(x,y) > 0\} \quad (1)\ [6]$$

Similarly, for any pair of vertices x, y $\in$ X, RC (x, y) is defined using following Eq

$$RC(x, y) = \mu(x, y) - v(x, y) \quad (2)\ [6]$$

The value of μ (x, y) is either zero or infinity.

i.e. If (x, y) $\in$ E,

Then

RC (x, y) = ∞

Else

RC (x, y) = - v(y, x)

End if

3.2.2 Residual Edge

The residual edge set RE is defined using the following Eq

$$RE = \left\{ (x,y) \middle| \begin{matrix} RC(y) > 0, if\ \mu(x,y) = \infty \\ RC(x,y) > 0, Otherwise \end{matrix} \right\} \quad (3)$$

[6]

This implies that the residual edge (x, y) is included in RE, if it allows a positive network flow from x to y.

3.2.3 Preflow

It is real value function of v: Y$\times$ Y$\rightarrow$R, that satisfies the capacity constraint, skew symmetry and relaxation of flow conservation rule.

$$\text{Rule: } \sum_{x \in X} v(x,y) \geq 0, \forall y \in X - \{S\} \quad (4)$$

[6]

i.e the total net flow into y excluding S is greater than zero.

3.2.4 Excess Flow

It is defined as the total net flow into y. It is shown using following Eq 5

$$z(y) = \sum_{x \in X} v(x,y) \quad (5)\ [6]$$

Also, If z(y) > 0

Then

$y \in X - \{S, D\}$ is to be overflowing.

End if

3.2.5 Vertex Height

A function H: Y $\rightarrow$N is a height function for v, if H(S) = |Y|, H (D) = 0 and H (x)$\leq$H(y)+1 for every RE (u, v). H estimates the direction of force imposed on the flow. i.e. flow moves downward from a higher vertex to lower vertex.

3.3 Distributed Pull-Push-Relabel (PPR) Algorithm

This algorithm is designed to adapt to a Zigbee cluster tree network of a specific scale. It involves a compound operation such that the vertices manipulate initial pre-flow until no overflowing vertex exists. Finally the source and sink reaches maximum. The basic operations involved in PPR algorithm are as follows [6].

1) Initialization: This is performed to generate an initial pre-flow in Q.
2) PULL (x, y): In this process, the lower vertex x pulls the flow of a higher vertex y downward to itself.
3) PUSH: In a process, a higher vertex x pushes the overpulled flow back to a lower vertex y along the edge (x, y$\in$X).
4) RELABEL: This operation enables a vertex x to increase its height.

3.3.1 INIT (x)

During initialization, initial v in every adjacent vertex of S is filled with μ_{max} and other vertices are empty. For S, H(S) is set to X. For each adjacent vertex y, H(y) is set to zero and z(y) is set to μ (y). The network flow within and outside S are updated accordingly. For every x, H(x) and z(x) are set to zero and the network flow within and outside of the vertex is set to zero.

3.3.2 PULL-PUSH-RELABEL (x)

Initially, x performs a pull operation to pull the flows from each adjacent vertices. If x cannot be pulled by any adjacent vertex, it executes push operation to push any overpulled flow back to each of its adjacent vertices. Following these operation, if x still overflows with RC from x to y, then the flow cannot be pushed or pulled from x to y due to the height of vertices. This can be overcome by relabeling x to enhance the height.

The distributed PRR algorithm is given in Algorithm-1.

Notations:

X: Set of vertices;
E: Set of edges of a graph G;
S; D: Source; Destination;
(x, y): Pair of vertices;
Q: Vertex-constraint flow network;
v: Flow in Q;
H; z: Height; Excess flow;

Distributed Pull-Push-Relabel (PPR) Algorithm

1.1 $\forall x \in X$ *, do*
1.2 INIT (x)
i. If x is S, then {
H (x) $\leftarrow$ *|X|* $\forall y \in adj(x)$*;*
do H(y) $\leftarrow$*0, z(y)*$\leftarrow$ μ *(y),*
v(x,y)$\leftarrow$ μ *(y),v(y,x)*$\leftarrow$ μ *(y) };*
ii. Else if x $\notin$ *Adj (S) then {*
H (x) $\leftarrow$*0, z (y)* $\leftarrow$ *0,* $\forall y \in adj(x)$*;*
do v (x, y) $\leftarrow$*0, v (y, x)* $\leftarrow$*0 };*
1.3 While there exists any overflowing vertex, do $\forall y \in adj(x)$*;*
1.4 Do PULL-PUSH-RELABLE (x)

i. $\forall\, y \in adj(x)$ *, do PULL(x, y);*

ii. If x is not pulled by any other vertex then {

$\forall\, y \in adj(x)$ *, do PUSH (x, y) and RELABEL (x)};*

1.5 Process terminates only when no more over-flowing vertices exists.

Algorithm-1 PRR Algorithm

3.4 Time Division Cluster Scheduling (CS_{td})

3.4.1 Dynamic and Stationary mode

Every cluster period corresponding to beacon interval (BI) is divided into dynamic and stationary mode. [12]

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

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

Let T_{BS} be the base superframe period

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 6 and 7 [12]

$$T_{BI} = T_{BS}.\, 2^{O_{BI}} \tag{6}$$

$$T_{SF} = T_{BS}.\, 2^{O_{SF}} \tag{7}$$

3.4.2 Channel sensing technique

Let CNT_S be the channel sensing counter

The channel sensing is performed during stationary period exclusive of dynamic intervals of neighboring clusters. The interference is detected based on the following hypothesis related to lack and existence of interference signal

$$Hyp_0\text{: } RX\,(i) = \tau(i) \tag{8}$$

$$Hyp_1\text{: } RX\,(i) = IR(i)\, S(i) + \tau(i) \tag{9}$$

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

(8) and (9) indicates absence and presence of interference, respectively.

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

$$\eta = \begin{cases} 0; \lambda < E_{th} \\ 1; \lambda \geq E_{th} \end{cases} \tag{10}$$

where E_{th} = energy threshold

λ = test statistics

$$\lambda = \frac{1}{a}\sum_{i=1}^{a}\left| RX\,(i)^2 \right| \tag{11}$$

3.4.3 Cluster Scheduling Algorithm

The main aim of this technique 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 (BI). Also, it prevents resource requirements such as inter-cluster collision and fulfills temporal requirements such as end-to-end deadlines of all the flows.

Let us assume that a cluster tree topology 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. Consider the length of the minimum contention access period as aMinCAPLength.

The proposed cluster scheduling algorithm is illustrated in Algorithm-2.

Notations:

R_j: Router;

N_i; C_j: Node; Cluster;

x_{ij}: Adjacent matrix;

y_{ij}: Collision matrix;

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;

Cluster Scheduling Algorithm

Initialization

1.1 If R_j is the parent router of N_i then {

1.1a x_{ij}= 1};

1.2 Else {

1.2a x_{ij}=0};

1.3 If C_j is within collision domain of C_i then {

1.3a y_{ij} =1};

1.4 Else {

1.4a y_{ij} = 0};

Estimation of dynamic mode

1.5 T_{SF} is estimated based on the data flow within the given cluster.

1.6 Consider O_{SF} =0;

1.7 For each N_j within C_i, the number of allocated time slots for all flow is estimated in transmitter and receiver side using Eq. (7) and (8);

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

1.9 If $\left(\sum_j \lambda_j^{tx} + \sum_j \lambda_j^{rx}\right) \leq 16 - [A_{min}/c]$,

(where A_{min}=aMinCAPLength) then {

i.O_{SF} = O_{SF} +1;

ii. Recalculate length of each GTS};

1.10 };

Estimation of Beacon Interval

1.11 BI value is iterated from minimum to maximum value;

1.12 BI_{max} given by max (O_{SF}) is rounded off to the nearest BI value towards T_{SR} among all the flows;
1.13 BI_{min} given by min (O_{SF}) is rounded off to the nearest BI towards all the clusters T_{SF};
1.14 If a optimal CS_{td} is found for given BI, time schedule then {
1.14a O_{SF} = O_{SF} +1;
1.14b Iteration is repeated with new BI;
1.15 Else {
1.15a The iteration is repeated until O_{SF} = max (O_{SF}) or till optimal CS_{td} is found };

Algorithm-2 Cluster Scheduling Algorithm

All the clusters have equal BI, which is defined using O_{BI}. However, it contains various T_{SF}, which is defined by O_{SF} in order to ensure efficient bandwidth utilization [12]. For each N_j within C_i, the number of allocated time slots need to be estimated for all flows towards transmitter and receiver side using Eq. (12) and Eq.(13) respectively.

$$\lambda_j^{tx} = \left\lceil \frac{T_{GTS1}}{c1} \right\rceil \quad (12)$$

$$\lambda_j^{rx} = \left\lceil \frac{T_{GTS2}}{c2} \right\rceil \quad (13)$$

where T_{GTS1} and T_{GTS2}=period of guaranteed time slot (GTS) for entire data transmission
c_1 and c_2 = period of time slot (equivalent to T_{SF}/16)

Advantages
- It increases the throughput.
- It provides efficient utilization of bandwidth in the network.
-

4. Simulation Results
4.1. Simulation Setup

The performance of the proposed Energy Efficient Cluster based Scheduling (EECS) is evaluated using NS2 [21] simulation. A network which is deployed in an area of 50 X 50 m is considered. The 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.

The simulated traffic is CBR with UDP source and sink. Table1 summarizes the simulation parameters used.

Table 1: Simulation Parameters

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

4.2. Performance Metrics

The performance of EECS is compared with the Push-Pull Re-label (PPR) protocol. The performance is evaluated mainly, according to the following metrics.
.
.
The simulation results are presented in the next section.

4.3 Results

The number of nodes is varied as 21,41,61,81 and 101.

The End-to-End delay is averaged over all surviving data packets from the sources to the destinations and the results are shown in Figure 2. From the figure, we can see that delay of EECS is 26% less than PPR, since the cluster scheduling algorithm fulfills the end-to-end deadlines of all the flows.

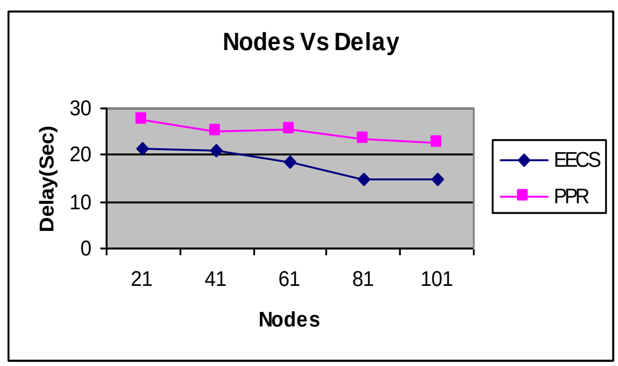

Figure 2 Nodes Vs Delay

Figure 3 shows the packet delivery ratio of both the protocols when the nodes are increased. The average packet delivery ratio is calculated as the ratio of the number of packets received successfully to the total number of packets transmitted. From the figure, we can see that the delivery ratio of EECS is 81% higher than PPR, since the cluster scheduling algorithm prevents as inter-cluster collisions.

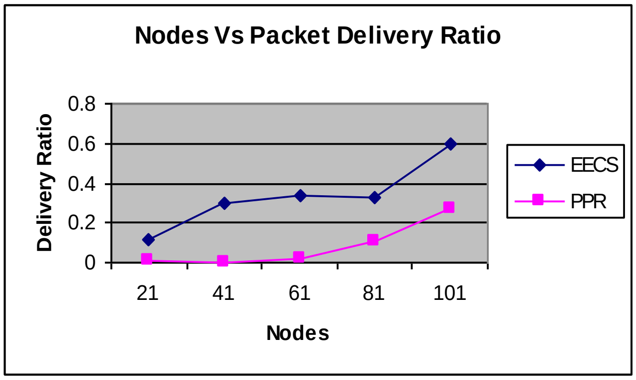

Figure 3 Nodes Vs Delivery Ratio

Figure 4 shows the packet drop occurred for both the protocols when the nodes are increased. From the figure, it can be seen that the packet drop is 41% less in EECS when compared to PPR, since the cluster scheduling algorithm prevents as inter-cluster collisions.

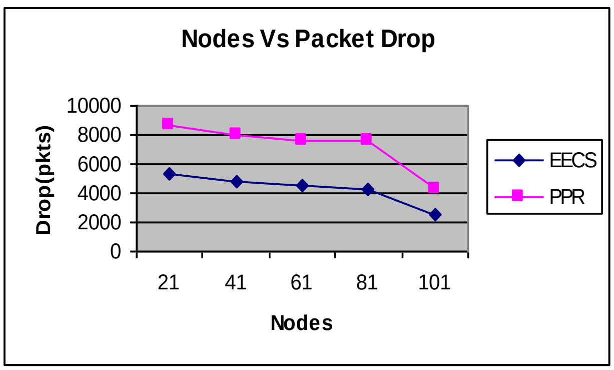

Figure 4 Nodes Vs Drop

Figure 5 shows the energy consumption of both the techniques, which is the average energy consumed by the nodes for the transmission process. From the figure, we can see that energy consumption of EECS is 28% less when compared to PPR, since the Cluster Scheduling period is maximized in relative to the beacon interval.

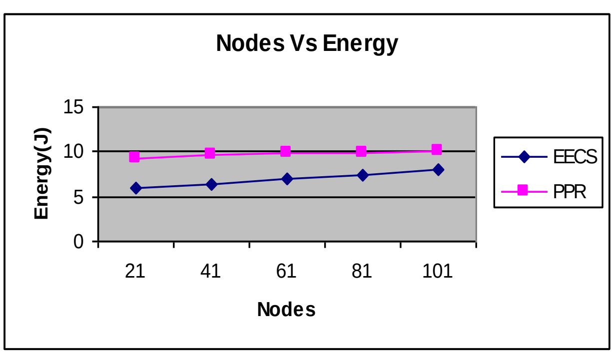

Figure 5 Nodes Vs Energy

Figure 6 shows the number of packets successfully received by the receiver. From the figure, we can see that the EECS has received 49% more packets than PPR, since the cluster scheduling algorithm fulfills the end-to-end deadlines of all the flows and prevents as inter-cluster collisions.

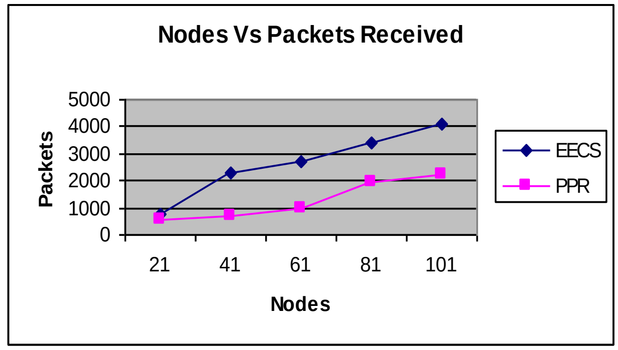

Figure 6 Nodes Vs Throughput

5. Conclusion

In this paper, we have proposed Energy Efficient Cluster scheduling for IEEE 802.15.4 Cluster-Tree Network. In this technique, initially the distributed pull-push-relabel (PPR) algorithm is designed to adapt to a ZigBee cluster-tree network. Then a time division cluster scheduling technique is considered that offers energy efficiency in the cluster-tree network by maximizing the Cluster Scheduling period in relative to beacon interval. Besides, it prevents resource requirements whereas fulfills some temporal requirements such as end-to-end deadlines of all the flows. By simulation results, we have shown that the proposed technique reduces the energy consumption and reduces the network collision.

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