Adaptive Routing Protocol with Power-Control Mechanism for Wireless Sensor Networks

Sandhya Rachamalla† and Anitha Sheela Kancharla††

† Osmania University, Hyderabad, India, †† Jawaharlal Nehru Technological University, Hyderabad, India

Summary
Reliability, Power efficiency and timeliness are the critical issues in Wireless Sensor Networks (WSNs). The engineers must fulfill the QoS requirements imposed by the applications(users).To satisfy QoS metrics such as Reliability, timeliness and energy efficiency, these WSNs must overcome major obstacles such as dynamic environmental changes, limited energy/range/memory/ computational capabilities of nodes in WSNs. This paper proposes an adaptive routing protocol Power-control Delay-Aware Routing and MAC Protocol (PCDARM) for Wireless Sensor Networks. This protocol aims to route the packets along multiple paths with differential delay between these multiple paths bounded in a range and with energy constraints in forwarding packets between nodes of the network considering link reliability. This protocol achieves to reduce delay and energy consumption with increase in packet delivery ratio. It utilizes TDMA based slot allocation method for transmission of packets with sleep and wake-up cycles for the nodes in the network. It even reduces the latency of anode in accessing the medium with slot re-use mechanism. Numerical results show that the delay experienced by the packets is less in PCDARM. The results show that the proposed protocol also out performs DEAR protocol in terms of energy consumption and packet delivery ratio.

Key words:
Reliability, timeliness, differential delay, TDMA based slot allocation, slot re-use, Latency, Quality of Service, Wireless Sensor Networks.

1. Introduction

Wireless sensor networks (WSNs) have gained worldwide importance in recent years due to simple design structure and usage of low cost sensors. The sensors can sense, measure and gather information from environment or from the places where they are placed to sense. Smart sensor nodes are low power devices equipped with one or more sensors, a processor for computations, and memory for storage, a power supply, a radio transceiver to receive from other nodes and to transmit towards sink or base station (BS) and an actuator for mobility. WSNS have great potential for many applications in scenarios such as military target tracking, surveillance, and habitat monitoring, medical diagnosis and so on [1]Deployment of a sensor network in these applications can be random or uniform manner. Creating a network of these sensors can assist rescue operations in a disaster area. Sensor nodes have the ability to communicate with each other or directly to an external base station. A greater number of sensors allow for sensing over larger geographical regions with greater accuracy [2]. Sensor nodes coordinate among themselves to produce high quality information about the physical environment [3].

Routing in WSNs is very challenging due to the relatively large number of sensor nodes to build in large area. Almost all applications of sensor networks require data from multiple sources to a particular BS. Sensor nodes are tightly constrained in terms of energy, processing and storage capabilities. Thus they require careful resource management. Data collected by many sensors in WSNs is typically based on common phenomena that there is a high probability that this data has some redundancy [2]. These routing mechanisms have considered the characteristics of sensor nodes along with the application and architecture requirements. Almost all routing protocols can be classified as data-centric, hierarchical, QoS based or location based [4].

This paper explores the idea of incorporating QoS parameters in making routing decisions for forwarding packets i.e. (i) Reliability, (ii) Latency, (iii) energy efficiency and (iv) timeliness. Traffic is routed with reliability in an energy efficient manner to achieve a longer network lifetime.

2. Related Work

Routing and transmitting data from sensors to the base station is probably the most important function in WSNs. In communication networks, including WSNs, routing is commonly along the shortest path. But some protocols are not able to support applications which require a certain minimum end-to-end bandwidth together with a bounded start-up delay to meet high user satisfaction especially in resource-limited WSNs.

2.1 Delay aware routing

In many cases, splitting the traffic over multiple paths may provide a low cost solution than finding a single path meeting requested capacity. So, simultaneous routing along multiple disjoint paths can result in increased resiliency against network failures .The concept of using

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power control in the routing of the delay sensitive packets is a combination of two-hop based real-time routing protocols could improve both the energy consumption and real-time performance[15] improving dead line miss ratio. Hence the idea introduces a newly and challenging area of research. Furthermore, it is expected that this integration improves performance more than the method that only use two-hop neighbor's information with fixed transmission and remaining power [14]. In [8], they have discussed about power control combined with routing protocol for WSNs. Its function is same as AODV (Ad hoc on-Demand Distance vector) in addition to the power control metric calculation. Here the path is calculated with lowest transmitted power selection algorithm. This protocol chose the path with high remaining energy of nodes compared with threshold level of remaining energy. If the threshold level is too low, the nodes with low energy stop working and affect the life time of the network. So, determination of threshold level is an important issue. In [10] they have presented Delay-bounded Energy-constrained Adaptive Routing (DEAR) problem with reliability, differential delay, and transmission energy consumption constraints in WSNs. These are based on time based polynomial solutions. Delay calculations include transmission delay and propagation delay. While considering the transmission delay, the allocation of packets along disjoint paths will have different amounts of delay associated with them. In this protocol, without considering the transmission delay, there is no impact on the delivery of packets in whatever may be the packets allocated. It is difficult to satisfy the differential delay requirement and reliability requirement providing feasible solution after considering transmission delay. Also if the flow rate is greater than packet demand, the corresponding path drops the connection request.

2.2 Power control routing in WSNs

Power control technique is necessary for the WSN as it guarantees that the total power in transmitting a packet is minimized. This technique is processed by when the nodes in the network use beacon messages of routing protocol to exchange information between them. One node sends beacon message to its neighbors using default transmission power. After receiving this message its neighbors send acknowledgement to the transmitting node. The Power loss is then calculated, which is the difference between the transmitting power and receiving power. A sensor node find out its neighbor nodes by counting the number of beacon messages it has received from its neighbors. After this, each node adjusts its power level, from this the power control is easy [6][8][16]. Transmission power control aims to reduce the overall transmission power of a network by adjusting the transmission power at each node [6]. Power control is based on four methods, which are the one combined with routing protocol, based on node degree, node direction and on proximity graph [1]. Power control in network layer changes network topology to optimize network routing through adjusting transmission power. Power control in MAC layer adjusts transmission power according to neighbors' distance and channel conditions, to improve network capacity or decrease nodes implemented in the network, and integrate the above two methods. It employs the former one to adjust the network topology and optimize routing, and uses the latter one to adjust transmission power while sending frames [5]. Increasing and decreasing the transmission power has both effects, such as increasing power may lead to interference and decreasing power may lead to high end-to-end delay. So the transmission power should be set to optimum level in order to get all possible benefits and to avoid the negative effects.

The needs of power control are

- An efficient utilization of the energy resources.
- Increase in lifetime.
- Minimum transmission power.
- Reduce collision probability
- Reduce power consumption of nodes [6].

However, the transmission power adjustment requires an independent training process, increasing the complexity and the signaling cost of the network. Also, the combination of individual techniques may not be straight forward and lead to inconsistencies [7].

2.3 Link Reliability requirement in WSNs

SAR [17] is the first routing protocol for WSNs that create multiple trees routed from one-hop neighbors of the sink taking the QoS metric on each path and the priority level of each packet. In RPAR [18] a node will change its transmission power by its transmission count towards destination. It does not consider residual energy and reliability.

SPEED [19] and MMSPEED [20] are for real-time applications of sensor networks. SPEED is based on geometric routing protocols and uses non-deterministic forwarding to balance each flow among multiple routes. . It integrates MAC and network layer routing to maintain uniform speed across the network such that delay in transmitting packet is proportional to the distance towards sink. Geographic forwarding is used to route data towards sink selecting a neighbor from the set of those with a relay speed higher than that of desired speed. Back pressure re-routing mechanism is used to re-route traffic around congested areas if necessary. MMSPEED [20] focuses on differentiated QoS options for real-time applications with multiple deadlines. Differentiated QoS options both in timeliness and reliability domain are provided. For timeliness, multiple QoS levels are supported by providing multiple data delivery speed options. For reliability, multiple reliability requirements are supported by probabilistic multipath forwarding. It employs localized geographic forwarding using immediate neighbor information without end-to-end path discovery. It also utilizes dynamic compensation which compensates for inaccuracy of local decision as a packet travels towards its destination. This protocol is adaptive to network dynamics. But it does not include energy metric during QoS routing selection. The idea of incorporating link reliability with two-hop routing is proposed in [21]. It calculates dynamic 2-hop velocity as per the desired deadline and energy is efficiently balanced among the nodes. It needs the calculation of 2- hop velocity, delay estimation and forwarding metric, which are updated periodically with broadcast messages.

3. Problem Definition

Consider a Wireless Sensor network graph G = (X, L), where X is the number of nodes and L represents set of links between the nodes of the network. The objectives are

- To obtain Power control in the network there by improving energy efficiency.
- To reduce end-to-end packet delay.
- To improve packet delivery ratio.

3.1 Assumptions in Network model

In our network model, the following assumptions are made.

- WSN consists of (N-1) nodes and a sink, all of which are randomly distributed in the field.
- The nodes are aware of their positions using GPS with respect to sink. Many localization techniques are available for this purpose [11][12][13].
- Each node needs to know its neighboring nodes current status, i.e. its ID, residual energy, link reliability etc. This can be done with initial HELLO message broadcasting.
- All the nodes are powered by a non renewable energy source i.e. when this energy supply is exhausted the sensors becomes non-operational.
- Nodes are assumed to be stationary else additional HELLO messages are required to update neighborhood information.
- All the nodes are aware of their residual energy and have same transmission range and transmission rate.
- All nodes share the same wireless medium. The sensors are neighbors if they are in the transmission range of each other and can directly communicate with each other. IEEE 802.11, a MAC protocol is assumed which ensures that among the neighbors in the broadcast range, only intended receiver keeps the packet and all other neighbors discard the packet.
- The network density is assumed to be enough to prevent void situation.
- The bandwidth of each link between the nodes is assumed to be constant.

4. Proposed Algorithm

The proposed protocol has two phases (i) Routing phase and (ii) Mac phase. Initially in routing phase, a multipath routing scheme is proposed based on Link reliability, Energy and Delay constraints. Fig 1 shows the block diagram with Routing and MAC phases. Then using TDMA scheduling in MAC phase, a distributed slot assignment is done at each node for its transmission. Further sleep and wake up cycles are assigned for each node for power efficiency and slot re-use technique is used for reducing latency.

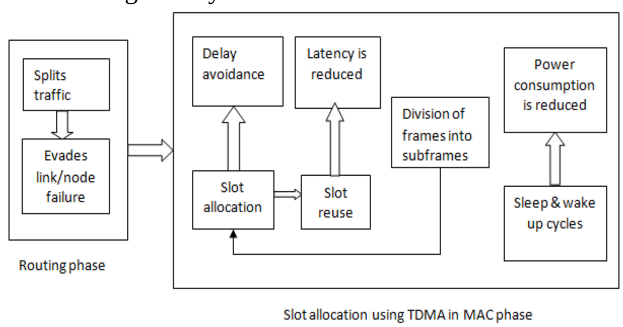

Fig 1 Block diagram showing routing and Mac phases

4.1 Routing phase

The proposed routing protocol has three components in routing phase.

a. Energy constraint metric
b. Differential Delay estimation
c. Adaptive Link reliability estimator

4.1.1 Energy constrained metric:

Consider a link *(x, y)* on a path. The energy consumed in transmitting a packet from node *x* to node *y* be *w (x, y)* and the packets to flow from *x* to *y* be *E(x, y)*. During the routing process the node *x* must satisfy the following energy constraint.

$$\sum_{y \in adj(x)} E(x,y).w(x,y) \leq \alpha(x) \quad (1)$$

where $\alpha(x)$ is the residual energy of node *x*.

4.1.2 Differential delay metric:

Let $P = \{p_1, p_2, p_3, \ldots. p_m)$ be the set of paths from source node S_0 to BS and let d_h and d_l be the highest and lowest path delays in *P*, then the differential delay is given by $d_P = d_h - d_l$. Let P^R be the path set selected for multiple routing from a source node to BS such that any path p in P^R must satisfy the differential delay constraint:

$$d_{min} \leq d(p) \leq d_{max} \quad (2)$$

where $d(p)$ is the delay of path p.

The delay of any path p in the set P^R is defined as

$$d(p) = \sum_{e \in p} d(e) + \sum_{v \in p} t(v) \quad (3)$$

where $d(e)$ is the propagation delay of a link e in path p. The propagation delay of path p is sum of propagation delays of all the links in path p.

As in [10], the transmission delay on a node v is given as

$$t(v) = \frac{q}{r} \quad (4)$$

q is the packet size in bits and r is the transmission rate in *bps*. If there are n nodes on path p, then the total transmission delay of path p is given by $(n\text{-}1).\ t(v)$. If the transmission rate is 10 Kbits and the packet size 1Kbits, then the transmission delay by a node v for sending this packet is 0.1 seconds. And if there are 5 nodes in a path p, then the total transmission delay of the path p is given by 0.4 seconds.
Most wireless sensors have 100 meters transmission range [38 dear]. The propagation takes place at the speed of light, 3 x 10^8 meters/ second. Hence, for 100 meters link e between two nodes, with the speed of light, the propagation delay $d(e)$ is 3.33 x 10^{-7} second. IEEE 802.15.4 wireless sensor networks standards [38 dear] show that the radios can provide standard data rate at 250 Kbps and higher data rate up to 2 Mbps. The transmission delay in sending small packet of 1 K bits needs 0.5 milli seconds for higher data rate. The transmission delay is far greater than propagation delay, hence cannot be neglected.

4.1.3 Adaptive Link Reliability Estimation.

The Link reliability estimation is determined as in [10]. Let R be the new connection request from source node S_0 and base station BS. Let the number of packets proposed for transmission is Q. The adaptive reliability requirement $x\%$ and let P be the set of multiple paths available for transmission of proposed packets Q from the source node S_0 to base station BS. Each path p from S_0 to BS is associated with the packet allocation £(p) i.e. the packets allocated for transmission along the path p. The adaptive reliability estimation used in routing the packets from source S_0 to BS is determined as follows.

i. The size of the aggregated packet of all the paths in the set P be q(P) and is should not be less than Q

$$\sum_{p \in P} £(p) = q(P) \geq Q \quad (5)$$

ii. Route the packets such that any link failure along any path p does not affect more than $x\%$ of the total packets.

Consider a link (u, v) on a path p and $d(\dot{e})$ be the link delay. During the routing time interval [0, d_{max}], packets allocated to the link should not be greater than $x\%.\ Q$.

$$\sum_{i=0}^{dmax-d(\dot{e})} £[u(i), v(i + d(\dot{e}))] \leq x\%.\ Q \quad (6)$$

4.1.4 An Example of WSN and Routing Phase.

Consider a simple WSN with four nodes, where node A is the source node and C is the sink. If Q = 10 packets are proposed for routing from source A along three paths p_1 (ABC), p_2 (AC) and p_3 (ADC) to destination. If the reliability requirement is 50 %, and delays of these paths be d(p_1) = 5 , d(p_2) = 3 and d(p_3) = 6. If the differential delay requirements are d_{min}= 2 and d_{max}= 5, then the paths p_1 and p_2 are chosen for routing as they satisfy delay requirements. If source node A has enough energy to forward the proposed packets along selected paths, then they are routed with link reliability requirement i.e. not more than 5 packets are routed along p_1 or p_2.

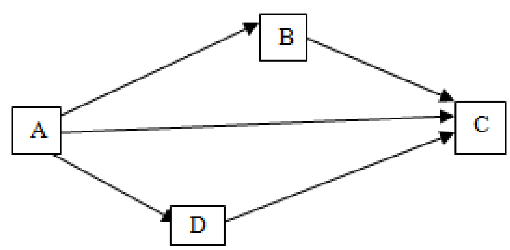

Fig 2 A simple WSN with Source A and Sink C

The routing through multiple paths is done by selecting the path set P^R which satisfies the given delay bound constraints, reliability and energy constraints. The selection of the path set P^R is given in **Algorithm 1.**

Let X is the number of nodes randomly distributed in the sensing area with base station assumed to be at the center of the sensing area. Let the resultant network graph be G. For every new connection request R from a source node S_0 to BS, the simple **Routing Algorithm 1** runs in the network layer.

Algorithm 1 Routing Protocol (G, S_0, BS, d_{max}, d_{min}, Q, $x\%$)

1. **for** each new connection request R from a node S_0 to BS in G **do**
2. Assume the found path set is P
3. **if** there exists a path sub-set P^R such that the path set P^R satisfies the delay constraint (2) **then**

4. Find the data flow *F* along path set P^R which satisfies energy constraint (1) and adaptive reliability constraint (6)
5. **if** flow $F \geq Q$
then
6. Return the set P^R
7. **else**
8. Drop the connection request *R*
9. **end if**
10. **end if**
11. **end for**

The multipath routing is advantageous over single path in the sense that it utilizes the resources efficiently and avoids the depriving of energy of the set of nodes involved in single path connection. In this routing technique the paths which supports the energy constraint (1), reliability constraint (6) and delay constraint (2) are selected for routing. Only the nodes which have sufficient energy in transmitting the packets are selected for transmitting/forwarding packets towards the sink or BS. And the delay range { d_{max}, d_{min} } in transmitting the packets over the disjoint multiple paths is also known. The link reliability requirement is also satisfied along links of selected paths. This routing technique can also be used in real-time applications where this delay bound is tolerable.

4.2 MAC phase

Slot allocation for the nodes is carried at MAC level. The position of a node in the network is represented by the radial distance D from the sink and angular distance A relative to geographical north axis passing through the sink (while moving in clockwise direction) as shown in Fig 3. To provide the ease of multi hop communication, the entire sensing area is divided in the form of tiers. This model of dividing the sensing area is used in [9]. Each tier is of radial width R, the transmission range of a node. The tier close to the sink is the first tier$T_1$and assume that there are H tiers in the sensing area. This division of network area into tiers helps in slot allocation in TDMA frames. T_H is the farthest tier from the sink. TDMA *Superframe* is divided into *subframes*, which are assigned to different tiers. The *subframes* are reused across the tiers such that the transmissions do not interfere. Nodes in two different tiers can transmit at the same time when they are at least 2R apart.

Based on the position of the node and the sink, the radial and angular distances are calculated. The slot allocation for transmission of packet is done at each node level starting from the farthest node in the last tier T_N. All the nodes in the tier T_N are given slots in first *subframe* of the *Superframe* based on the radial and angular distances calculated in an increasing order. Data flows inward hopping from outer tier to inner tier and reach the BS. The tiers can be grouped for slot reuse. The nodes belonging to the each group can transmit during same *subframe*. The tiers belonging to the same group as T_i are:

$$T_{i+3j}, \text{ where } j = 1,2,3,\ldots.. \qquad (5)$$

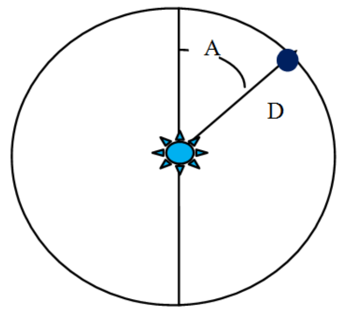

Fig 3. Representation of a node

Consider a sensing area divided into six tiers based on transmission range R_x. The *Superframe* is given as the one consisting three *subframes*. The *subframes* slots are reused as shown Fig 3.

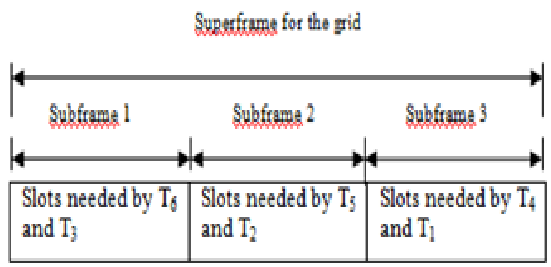

Fig 4. TDMA Superframe format for 6 tier network

Once the *subframe* allocation is done for tiers, the node level slot assignment is done. Nodes can transmit only during their slots assigned to them. For this a simple algorithm (**Algorithm 2**) is run at MAC layer.

Algorithm 2 Node level Slot assignment **(**T_i, *rad_distance*, *angle_distance*)

1. /* T_i *is the tier ID of the node */*
2. /* *rad_distance is the radial distance of the node from the sink*/*
3. /**angle_distance is angular distance of the node from the sink*/*
4. Insert *rad_distance, angle_distance* into sorted location array[]
5. **K** is the index of the node's location information in sorted location array[]
6./* this node is the k^{th} node in the tier*/
7. Calculate P_i and U_i using (7) and (8) respectively.
8. Mark the transmission slot in *Superframe* (P_i + U_i *+1)*

The network maintains a sorted array which indexes nodes according to their location. Each entry in the sorted array is a node's location in terms of its radial distance and angular distance in the tier, which is then used to assign slot only during which it can transmit. After knowing the transmission slot the node can know the slots in which it must be in receiving mode or in listen mode. It remains in listen mode for all the slots before its transmission slot. For all other slots node remain silent or go to sleep mode. The node has to wake-up only for transmission and reception. In this way, sleep and wake-up cycles helps in power control mechanism and reduces the latency for each node in accessing the medium with slot re-use technique.

4.2.1 Calculation of transmission cycle of a node

To find the transmission cycle of a node in a tier T_i and if the node is the k^{th} node in the tier as per its radial and angular distances, the calculation of the transmission slot for the node is as follows. Let the number of slots assigned to the outer tiers before T_i tiers in the *Superframe* is given by

$$P_i = \begin{cases} \sum_{l=(i+1) mod\ N}^{N} S(l) & if\ i\ mod\ N \neq 0 \\ 0 & if\ i\ mod\ N = 0 \end{cases}$$

(7)

where N is the number of *subframes* in the *Superframe* and *S(l)* is the number of slots assigned to i^{th} *subframe* of *Superframe.*

The number of slots assigned in the *subframe* to the nodes before this node be U_i and is given by

$$U_i = (k-1) \quad (8)$$

Hence this node transmits in the slot $(P_i + U_i + 1)$.

4.2.2 Calculation of size of Superframe.

Consider a six tier network and the *Superframe* format is as shown in Fig 4. *subframe 3* is shared by tiers T_1 and T_4. Let the size of *subframe* actually needed by T_1 be S_1 and that of T_4 be S_4 and if S_4 is greater than S_1, then the size of the *subframe 3*, *S(l3)*, is given by

$$S(l3) = Max(S_1, S_4) \quad (9)$$

Generally, the i^{th} *subframe* of *Superframe*, *S(i),* is given by

$$S(i) = Max(S_i, S_{i+N}, S_{i+2N} \ldots\ldots) \quad (10)$$

Thus, the number of slots in the *Superframe* is given by

$$SF = \sum_{i=1}^{N} S(i) \quad (11)$$

where N is the number of *subframes* in the *Superframe.*

Duration of each time slot is taken to be the duration for which packet of 512 bytes can be transmitted over a link of 10 Mbps bandwidth, i.e. $\frac{512\ x\ 8}{10}\ \mu s$ = 0.4096*ms*. The data rate is taken 2000 kbps.

5. Performance Evaluation

The Network simulator (NS2)[22] is used to simulate the proposed architecture. The nodes are deployed in a 1000 meter x 1000 meter region. The simulation settings and parameters are summarized in Table I. We simulated PCDARM for two different scenarios of network, changing network density and changing transmission range of the nodes. Our protocol is compared with DEAR protocol for the scenario1 of increasing the number of sensor nodes and the transmission range of a node is kept constant 250 meters. The Q value and the reliability equirement is 3 and 66% respectively. The transmission rate is taken 50 Kbps.

TABLE I. SIMULATION SETTINGS FOR PCDARM

Parameters	*value*	*Parameters*	*value*
Area size	1000 m X 1000m	Initial energy	12.3 J
Mac	IEEE 802.11	Transmission power	0.660 W
Simulation time	50 s	Receiving power	0.395 W
Traffic source	CBR	Idle power	0.035 W
Packet size	512 bytes	Transmission rate	50 Kbps

For scenario 1, as shown in Fig 5, PCDARM provides less delay when compared with DEAR. The delay shown in results is the average end-to-end delay. The DEAR protocol cannot give guaranteed delay as PCDARM protocol. At MAC level our protocol has slot assignment for the nodes to access the medium. This provides contention free medium access. Hence the packet delivery ratio (PDR) is high for our protocol shown in Fig 7. Further, the slot reuse technique helps in reducing the delay of the node in accessing the medium. Hence, the delay is less in PCDARM. As the number of nodes increases, the delay also increases with the increase in the number of hops for transmission and with the increase in the size of *Superframe*

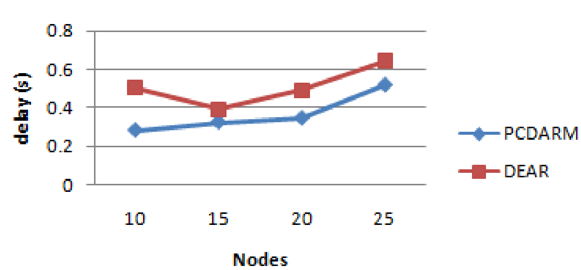

Fig 5. Effect of number of nodes on avg end-to-end delay

Fig 6 shows the graph of residual energy versus number of nodes. Because of sleep and awake cycles in the TDMA based frame format for transmission and reception, our protocol consumes less power than DEAR. Hence the residual energy of each node with PCDARM protocol is high. As node number increases, more packets for transmission, but routed along multiple paths with large number of nodes included for transmission. Hence the residual energy almost remains constant.

For scenario 2, changing the transmission range of sensor nodes in the network, keeping the number of nodes constant 25. The effect of changing the transmission range of nodes on the parameters end-to-end delay, residual energy and Packet Delivery Ratio (PDR) are shown in Fig 8, 9 & 10 respectively. For this scenario too, the delay is less for PCDARM when compared with that of DEAR because of the dynamic slot allocation for transmission of packets for the nodes and slot re-use technique.

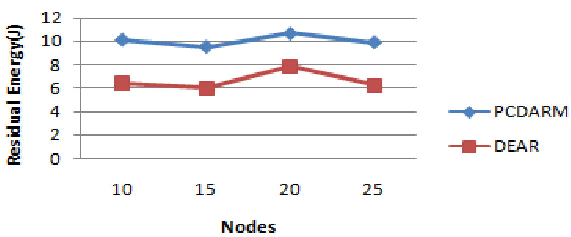

Fig 6. Effect of number of nodes on residual energy.

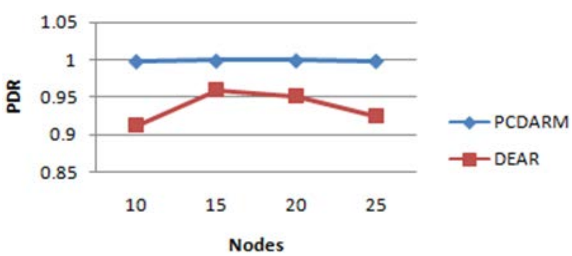

Fig 7. Effect of number of nodes on Packet delivery ratio (PDR).

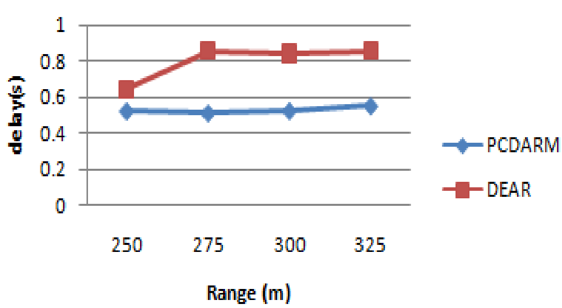

Fig 8. Effect of transmission range of nodes on avg. end-to-end delay.

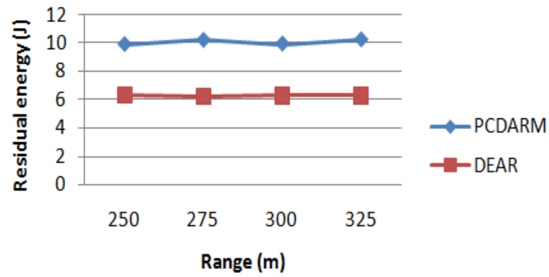

Fig 9. Effect of transmission range of nodes on Residual energy.

The residual energy and Packet delivery ratio are high in scenario 2 for our protocol. This is due to the sleep and wake-up cycles provided in PCDARM protocol and there is no such power control mechanism in DEAR protocol. The Energy is efficiently utilized and this further increases the lifetime of the network and helps in delivering more number of packets.

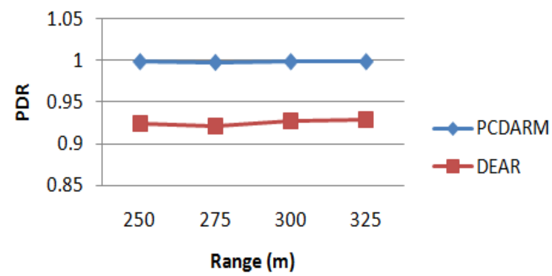

Fig 10. Effect of transmission range of nodes on PDR

6. Conclusion

The PCDARM protocol is presented in this paper. The dynamic power control mechanism of TDMA frame structure for nodes to transmit and receive packets along with the slot re-use technique helps in guaranteed delay with effective utilization of energy by the nodes in the network. Our protocol performs efficiently consuming less power and delay is low with high delivery ratio of packets. The proposed protocol shows scalability feature with effective performance in the scenario 1 of changing the network density. For the scenario 2 also, our protocol outperforms DEAR in terms of critical parameters of WSNs, i.e. delay, energy and PDR. The characteristics of the PCDARM can be exploited while choosing various operating parameters of the protocol.

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Sandhya Rachamalla received the B.Tech from Jawaharlal Nehru Technological University, Hyderabad during 2000 - 2004 and M.Tech. degrees in Digital Electronics and Computer Electronics from Jawaharlal Nehru Technological University, Ananthapur during 2006- 2009. Her areas of interest are Wireless Communications, Wireless Sensor Networks and Routing Protocols. She has nine publications in various International and National Conferences and Journals. She is presently pursuing Ph.D from JNTUH, Hyderabad and working as an Assistant Professor in Electronics & Communications Engineering Department of University College of Engineering, Osmania University, Hyderabad, India

Dr. K. Anitha Sheela is graduated in B. Tech. (ECE) from REC, Warangal during May,1993 and completed ME in Systems and Signal Processing from College of Engineering, OU, during 1995-1997 and Ph. D from JNTU, Hyderabad during 2003 to 2008. She had worked as Testing Engineer at Onyx Industries for 2 years and has been in teaching for more than a decade. She has 26 papers published in various National and International Conferences and Journals. Her areas of interest are Wireless Networks, Speech Processing, Pattern Recognition, Image Processing, DSP Processors and Neural Networks .She is Fellow of IETE and life member of ISTE. She is presently working as an Associate Professor in ECE Dept of JNTU, Hyderabad, guiding 5 Ph.D. scholars. She is Ph. D adjudicator for Sri Satya Sai University, Prasanthi Nilayam