

Layer Based Query Dissemination & Reliable Data Acquisition Mechanism for Wireless Sensor & Actuator Networks

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Abstract

Wireless Sensor & Actuator networks take actuation decisions based on the data collected by the deployed set of sensor nodes. The method of data acquisition, leading to decision making, could be semi-automated or fully automated. In either case, the reliable delivery of information assumes critical importance since it has a direct impact on the decision making process for subsequent action by the actuator network. This paper presents in details a novel methodology “Layer Based Time Constrained Reliable Data Acquisition Mechanism” LTCRDM, which can be utilized for reliable delivery of information, sensed periodically or in response to a query, by the sensors deployed over a geographical area to a centralized sink where the decision for eventual actuation is taken. Since the latency and reliability requirements in a WSN are stringent, the mechanism detailed attempts delivery of maximum packets with minimum latency to ensure that estimation of the sensed event is accurate leading to correct decision making. The methodology ensures relatively low packet loss as compared to standard packet delivery mechanisms with latency time constraints. The algorithm for dissemination of query (LQDM) in the deployed nodes is also presented. Authors have provided detailed algorithm, results of simulation and observations using IEEE 802.15.4 PHY & MAC as underlying layers. Experimental results over a test-bed are also presented. A critical analysis of the results is presented for comparison against the standard methodologies in vogue.

Index Terms—*Wireless Sensor Networks, Wireless Sensor & Actuator Networks, Reliability, Data Acquisition, Event Detection, Semi-automated WSN, Query dissemination, Centralized Decision making*

1. Introduction

Wireless Sensor Networks (WSN) owe their genesis to the concept of ubiquitous computing which was proposed by Marc Weiser in his seminal paper [1] in 1991 and is today widely known as Pervasive Computing. WSNs have emerged as an acceptable methodology for sensing events and acquire data spread over various locations in a geographic area to implement the concept of Pervasive Computing [2]. Various applications of Wireless Sensor Networks include Building Automation [8], Defence [9], Forest-Fire Detection [10], Agriculture [11], Lighting control [12], HVAC [13], Target

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Tracking [14], Disaster Management [15], Industry [16] and more. The low cost, inexpensive and untethered wireless sensor nodes use wireless link to communicate and collaborate with each other. The sensor nodes are low on resources including memory, computational capabilities, battery life, sensing capability and are prone to hardware and communication failure [2]. The problem is exacerbated by the unpredictable behaviour of the wireless medium. The reliability of the WSN, in terms of the task of acquiring data from the nodes and transferring to the sink, is adversely affected because of factors like network congestion, packet collision, environmental noise, channel characteristics, energy & resource constraint [2]. The lack of reliability of data acquisition in WSN has a direct impact on the ability of the sink to estimate the actual occurrence of the events at the sink.

The evolution of Wireless Sensor & Actuator Networks (WSNA) has made a significant value addition to the impact and scope of utilization of WSNs in real life applications including agriculture, lighting [4, 5, 6, 7] etc. Instead of being restricted to the task of collection of information, the network now has control over the actuation element(s) thus having a direct bearing on the environment in which the deployed network is sensing. Unlike the sensor nodes, the actuator nodes are not constrained in terms of resources [3] and the actuation is based on the information collected by the deployed sensor nodes; therefore in context of a WSAN, the reliability of the data acquisition process assumes greater significance, lest the actuation results in catastrophic events.

Since the effect of the actuation of an Actuator is generally limited over an area, only sensors deployed in that area will be able to sense the effect of the actuation. It therefore becomes necessary to ensure that the information sensed by these limited sensors, sent in the form of packets, reaches the decision making entity for it to decide correctly. Additionally, for WSANs, the issue of network latency also assumes importance as estimation of event and resultant actuation needs to be time bound [3]. Multiple techniques have been proposed to achieve these objectives including use of additional nodes to increase coverage [20] while preventing loss of data because of node failure, usage of multi-path routes to deliver packets [21], identification and bypassing of congestion hotspots [22], usage of explicit, implicit and hybrid acknowledgments for confirmation of packet delivery [23], fault tolerant design [24], detection and re-transmission of lost packets [25], recovery of partially distorted received information [26], scheduling of nodes for increased lifetime [27], maximization of QoS parameter [28], utilization of location awareness for efficient delivery of packets [29] and more.

In this paper the authors present a mechanism which has twin focus viz reduction of network latency and increase in the Packet Delivery Ratio (PDR), thus increasing the reliability of data acquisition of the network. The mechanism divides the deployed nodes into layers based on their distance from the sink and attempts to deliver the packets with low latency (LTRDM-C). The mechanism is optimized for a single sink solution. A mechanism for dissemination of query in the network, in the layered scenario is also presented. The algorithm assumes utilization of IEEE 802.15.4 PHY & MAC in the underlying layers. The remaining paper is organized as follows- Section II presents the problem statement, Section III surveys the Existing Solutions, Section IV provides definition of reliability, Section V lays down the objectives of the solution, Section VI & VIII present the proposed solutions, Section IX presents the Performance Analysis, Section X presents the conclusions and possibilities about the future work.

2. Problem Statement

The sensor nodes in a WSAN perform the task of sensing information and pass it on to the decision making entity while the actuator nodes control the actuation entity. In case

of Centralized Decision Making (CDM) approach (Semi-automated approach) [3], the sensors deliver the collected information to a centralized sink which decides upon the actuation plan which it communicates to the various actuators (Figure 1(a)). The transmission of sensed information by the deployed nodes could be periodic or based on receipt of query. Decision making relies entirely upon the reliability of the information collected by the deployed nodes, which places certain requirements on the sensor network:

- a) All events detected by the sensors and data collected by them must reach the sink/actuator without fail despite variations in acquisition mechanism viz

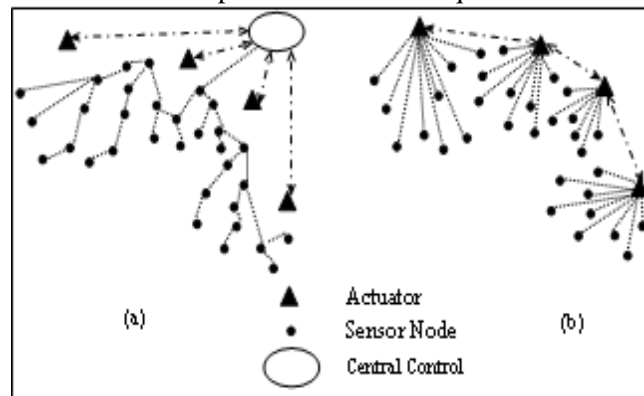


Figure 1. a) Centralized Decision Making (Semi-automated) 2) Distributed Decision Making in WSN (Automated)

periodic, query based or hybrid.

- b) The acquisition mechanism must be rugged, fault-tolerant and energy efficient to ensure long network life-time
- c) Minimal network latency T_{NLT} must be ensured so that decision making is timely [30]

3. Related Work

Many protocols and techniques have been proposed by researchers over the years to improve upon the reliability of data acquisition. Some techniques focus on fault tolerant design where the network is able to deliver the packet in spite of temporary or permanent faults introduced in the network [31] while some techniques focus on maximizing the packet delivery [32]. Such methods prepare multi-path routes between the source nodes and destination nodes and keep changing the route dependent upon parameters like path success rate [24] etc. Some methodologies focus on achieving a balance between energy efficiency and packet delivery [33] while some focus on maximizing a chosen QoS parameter [34]. A host of techniques deliver very good network throughput with the assumption that the nodes are geographically aware i.e. they are aware of their own location as well as the location of other nodes and the sink [35]. Some techniques focus on delivery of packets in multi-sink scenario [21]. Techniques like swarm intelligence have also been adopted by many researchers to demonstrate protocols which offer reliability of data acquisition while using wireless sensor networks [36]. While most of the protocols focus on upstream propagation of collected information, there are some which focus on downstream query dissemination [37]. Some protocols [17] have been simulated using IEEE 802.11 PHY & MAC while others have used IEEE 802.15.4. Some techniques support periodic data acquisition while others support event based data acquisition, query based data acquisition or a combination of these. Each proposed technique has attempted to optimize certain parameters while balancing others. In some cases, the researchers have validated the simulation results by conducting experiment on a

test-bed of MICAz or IRIS motes. Although most of the techniques are based on recovering the lost information by re-transmission of the lost packet, there are some which recover lost or damaged information by using redundancy techniques [26, 38, 39, 40, 41, 42]. Sadgoppan et al [18] have presented a query dissemination mechanism ACQUIRE which utilizes the Local update and forward mechanism for dissemination of query in the network. Liang et al [19] proposed Typhoon, a mechanism for dissemination of large objects, including queries, to nodes in a network. A combination of spatially-tuned timers, prompt retransmissions, and frequency diversity are proposed by authors to reduce contention and promote spatial re-use. Another query dissemination mechanism GARUDA [17] provides sink-to-sensors reliability in wireless sensor networks. The algorithm uses techniques like WFP pulse, core structure approximating the minimum dominating set and two-stage recovery process besides others to ensure reliable delivery of query. However, none of these mechanism is designed for working in a layered architecture.

4. Definition of Reliability in WSN

The concept of reliability of data acquisition has been defined in different contexts by researchers [30, 43, 44]. The traditional definition of reliability of a system, as mentioned in the theory of reliability [55], is as below:

$$Reliability(t) = e^{-\lambda t} = e^{-t/m} \quad (1)$$

where λ is the failure rate, m is MTBF. This definition is valid in context of a WSNAs also as it acts as system with physical sub-entities as sensors and actuators. Since these elements act collaboratively as a single system, the definition of reliability of a system must be applicable. Authors have defined reliability in terms of coverage [3], Packet delivery, security of data, availability and network latency. Effectively all these represent the ability of the network to ensure sufficient information at sink for it to estimate an event accurately and timely. Vuran et al [35] defined the concept of reliability in terms of estimation of the event at sink based on the data received from the deployed sensors. The observed event estimation distortion D at the sink in a decision interval ΔT of has been derived as a function of f which is the reporting frequency. It is assumed that the observed signal is wide-sense stationary as a zero mean Gaussian random process with σ^2 . The channel noise is a additive white Gaussian noise, $(0, \sigma_n^2)$. Then, D can be written as [45]

$$D = \sigma^2 + \frac{\sigma^4}{\Delta T f (\sigma^2 + \sigma_n^2)} + \frac{\sigma^6}{(\Delta T f (\sigma^2 + \sigma_n^2))^2} \sum_{k=1}^{\Delta T f} \sum_{l=k}^{\Delta T f} e^{-\frac{(|k-l|)}{\theta}} - \frac{2\sigma^4 \theta}{\Delta T^2 f (\sigma^2 + \sigma_n^2)} \sum_{k=1}^{\Delta T f} \left(2 - e^{-\frac{k}{f\theta}} - e^{-\frac{(\Delta T - k)}{\theta}} \right) \quad (2)$$

where the covariance function $e^{-\frac{|m-n|}{\theta}}$ depends on the time difference between signal samples at m and n and the covariance coefficient θ . It can be seen that D depends on f and ΔT . Optimal f will lead to increase in accuracy of estimation and to maximization of the network lifetime. As the number of packets depends on both f and ΔT determine the reliability of the data acquisition mechanism. The expression indicates that the Reliability of Data Acquisition is directly proportional to the packets of information reaching the sink within the given time constraint on the network latency time. Following conclusions can be drawn:

- Reliability of Data Acquisition & estimation at Sink/Actuators will be higher if Effective Packet Delivery Ratio (Eq. 2), considering the constraint on Network Latency Time, ΔT , is high and is approaching unity.

- For achieving a fixed value of reliability, the number of nodes that are required to be ON to detect an event at a given time will be low for high Effective Packet Delivery Ratio.
- Network life-time would increase as more nodes can remain in sleep mode
- Tolerance to faults, within a limit, which does not compromise the ability of the centralized sink to faithfully re-construct the event sensed by it will maintain good reliability

It may be observed that the traditional definition of Packet Delivery Ratio [46] is modified here to a parameter *Effective Packet Delivery Ratio* which is defined as:

$$Effective\ Packet\ Delivery\ Ratio = \frac{\text{Packets received at Sink within } T_{NLT\ max}}{\text{Total Packets sent by the nodes}} \quad (3)$$

where T_{NLTmax} refers to the upper bound on the network latency.

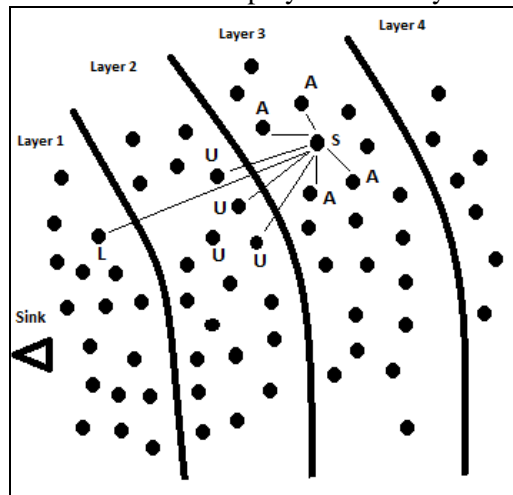
5. Objectives

Based on section II , III & IV above the objectives can be enumerated as below:

- a) ensure higher reliability by delivery of sufficient amount of the gathered information, by the deployed sensor nodes, to the centralized sink for it to be able to faithfully and successfully re-construct or estimate the event This translates into a high value of Effective Packet Delivery Ratio (Equation 3), approaching unity.
- b) ensure delivery of sensed information within constraint placed on T_{NLT}
- c) ensure limited fault tolerance and increased network life
- d) ensure effective and quick query dissemination to all nodes in the network

6. Proposed Solution

The proposed algorithm provides a strategy for efficient routing of the packets containing the sensed information from the sensor nodes to the centralized sink which is decision making point for the WSN. IEEE 802.15.4 [47] standard is used for the PHY & MAC layer. Nodes are assumed to be deployed randomly. Unlike Wireless Sensor



S: Source node, A: Adjacent Neighbour, U: Upstream Neighbour, L: Layer Bypass Neighbour

Figure 2. Layer Formation Process & Layer Based Neighbours for Centralized Decision Making (Semi-automated)

Networks, this standard does not allow direct communication between the ordinary nodes i.e RFDs. This problem is resolved by assuming that all nodes are FFDs and act as Coordinators as defined in the standard and are able to communicate with each other with one node (not Sink) acting as the PAN Coordinator. Beaconless mode is assumed thus the contention is resolved using CSMA/CA algorithm built-in the MAC layer of IEEE 802.15.4. It is assumed that all nodes sense the same set of information and perform periodic sensing and transmission of information.

A. Design Philosophy for LTCRDM-C

The aim of the data acquisition mechanism is to ensure that maximum number of packets sent by the sensor nodes reach the sink /actuator with low latency. For low latency, the number of hops is reduced by dividing the nodes into layers, based on distance from sink, such that the immediate neighbours (downstream and upstream) of any node are in the next layer rather than being nearest nodes. Low latency is further ensured by assigning priority to the neighbour nodes based on signal strength, residual battery life and packet propagation success ratio which is based on Ant Colony methodology. This prioritization ensures a higher probability of choosing the path with minimum re-transmission requirements thus reducing latency significantly.

For increasing effective packet delivery ratio, explicit acknowledgement is enforced at every hop within the delay constraints. In case of loss of acknowledgement itself, propagation of duplicate re-transmitted packet is prevented by utilizing implicit acknowledgement. Every node is aware of its immediate topology and maintains a table of its neighbour nodes in downstream, upstream and lateral gradient which ensures multiple routes at every hop for forwarding the packet to the sink. Reliability check at every hop further ensures immediate re-transmission of packet, if needed, thus further reducing delay propagation to sink in form of data packets. The query dissemination mechanism starts from the sink and spreads through the layers of the network with a mechanism which ensures that duplicate response to a repeat query is not elicited.

B. Layer & Neighbour Discovery Phases

The objective of the first part of this algorithm is to categorize the sensor nodes, deployed randomly, into layers such that the nearest neighbour is more towards the sink rather than the source node. The objective of this approach is to reduce the number of hops that a packet will take to reach the sink/actuator. Link Quality Indicator (LQI) value, provided by the IEEE 802.15.4 PHY-MAC as an indicator of the quality of radio link between the transmitter and the receiver, is used as an indicator of the tentative between the transmitter and the receiver. Each node initializes its variable $Layer_no_node$ to 0 and $myfinaldestination$ variable to the sink address in case of centralized decision making mechanism (LTCRDM-C). Initially the Sink node transmits a Layer Information Packet (Figure 4) with the $Layer_no_packet = 0$. All the nodes which receive this transmission and satisfy the condition

$$LQI_{recvd} > LQI_{low} \ \&\& \ Layer_no_node == 0 \quad (4)$$

assign a new value to their $Layer_no_node$ variable

$$Layer_no_node = Layer_no_packet + 1. \quad (5)$$

All these nodes are now part of Layer 1. A selected set of nodes out of the nodes of this layer with

$$LQI_{recvd} > LQI_{low} * 1.2 \quad (6)$$

now transmit, with random delay in-between, the Layer Information Packet with $Layer_no_packet = Layer_no_node$ i.e. value 1. All the nodes which receive this packet and

satisfy the condition at equation (4) assign their $Layer_no_{node}$ variable with value as per equation (5). These nodes now are part of Layer 2. The above mentioned process is repeated till all nodes are segregated into Layers as shown in Figure 2. This completes the Layer forming phase of the algorithm. The neighbour discovery phase of the algorithm starts after completion of the Layer forming phase.

Packet Type	Layer No.	Dest. Address	Layer Information Packet
Packet Type	Layer No.	Batt. Status	Neighbour Discovery Packet Layer 1 / Other Layers
Packet Type	Layer No.	Batt. Status	Node Addr 1 -- Node Addr 4

Batt. Status: Battery Status, Dest. Address: Destination Address

Figure 3. Structure of Payload Packet Types used during Layer & Network Discovery Phase

Node Address	Priority	Layer No.	Batt. Status	LQI	PS	SR	RF

Layer No: Layer Number, Batt. Status: Battery Status, LQI: Link Quality Indicator, PS: Packets Sent, SR: Success Ratio, RF: Recent Failure

Figure 4. Table Structure for Downstream Neighbour Table, Upstream Neighbour Table, Adjacent Layer Table & Layer Bypass Table

The objective of the Neighbour Discovery Phase is to fill up the following neighbour information tables at each node viz. *Downstream Neighbour Table*, *Upstream Neighbour Table*, *Adjacent Layer Table* & *Layer Bypass Table*. The structure of the tables is shown in Figure 4. These tables contain the information regarding the selected neighbours of each node in the upstream layer (towards sink), adjacent Layer (same layer as node) and Layer Bypass i.e. the layer beyond the upstream layer of the current node. The Downstream Neighbour Table contains the information about the nodes in the Downstream layer (layer higher than the current node), for which the current node is a upstream neighbour. The upper limit on the number of neighbour node entries in each of the tables is programmable.

The table also stores the values Packets Sent (PS), Success Ratio (SR) & Recent Failures (RF) for each of neighbour node entry. The Success Ratio is an indicator of the congestion at a given node and is updated every time a packet is either successfully delivered or not delivered to that neighbour. These parameters become useful at the time of deciding the next hop neighbour.

The neighbours for each node are initially chosen based on a function which takes into account the LQI of the signal received from the possible neighbour nodes and their battery status. The battery status is a figure which indicates that the battery of the node is in one of the current states viz Fresh, Medium or Low. Nodes with higher values of LQI and Battery Status are given higher priority.

$$Neighbour\ Priority = f_n(LQI, Battery\ Status) \quad (7)$$

The phase is initiated by broadcast of *Neighbour Discovery Packet Layer 1* (Figure 3) by those nodes of Layer 1 which are closest to the outer boundary of Layer 1 and satisfy

the condition $LQI_{recvd} > LQI_{low} * 1.2$. This is done to avoid flooding of network. All nodes of Down-stream layer which receive the packets fill up their *Upstream Neighbour Table* based on the function at (7) while the same packet information is used by the nodes within Layer 1 to fill their *Adjacent Neighbour Table*. The *Upstream Neighbour Table* of nodes in Layer 1 consists of only one entry corresponding to the Sink and there is no entry in the *Layer By-pass Table*. After a brief delay, the nodes in Layer 2 begin broadcast of *Neighbour Discovery Packet Other Layers* (Figure 3) with random delay between the transmissions. The random delay is to avoid packet collision. The significant difference in this packet is that the information pertaining to the selected Upstream Neighbours for these nodes is also transmitted which is used by the nodes in Layer 1 to update their Down-stream Neighbour Tables. Thus the Layer 1 nodes now know about the Layer 2 nodes who have selected them as their Upstream neighbours. This process is repeated till all Layers are covered. At completion of this phase, the one hop topology of the network is known to each node and storing it does constrain upon the low memory availability.

Layer & Neighbor Discovery Algorithm for LTCRDM-Centralized
Step 1: On wake up Complete Network Association Process
Step 2: Set $Layer_No_{node} = 0$ & $myfinaldestination =$ <i>Address of sink</i> . All nodes except sink remain silent till $Layer_No_{node}$ is assigned.
Step 3: Sink Node broadcasts Layer Information Packet with $Layer_No_{packet} = 0$
Step 4: if ($LQI_{recvd} > LQI_{low}$ && $Layer_no_{node} = 0$) then $Layer_no_{node} = Layer_no_{packet} + 1$ else ignore packet
Step 5: Nodes with $Layer_No_{node} <> 0$ broadcast Layer Info Packet with $Layer_No_{packet} = Layer_No_{node}$
Step 6: Repeat Step 4 & 5 till all nodes are assigned a valid $Layer_No_{node}$
Step 7: Nodes with $LQI_{recvd} > LQI_{low} * 1.2$ of Layer 1 broadcast <i>Neighbor Discovery Packet Layer 1</i>
Step 8: if $Layer_No_{packet} = Layer_No_{node}$ then <i>Insert_Adjacent_Layer_Table</i> <i>Update_Adjacent_Layer_Table</i> else if $Layer_No_{packet} < Layer_No_{node}$ then <i>Insert_Upstream_Layer_Table</i> <i>Update_Upstream_Layer_Table</i> end if
Step 9: for nodes in Layer 2 with $LQI_{recvd} > LQI_{low} * 1.2$ Prepare list of Upstream neighbors Broadcast Neighbor Discovery Packet Others
Step 10: if $Layer_No_{packet} = Layer_No_{node}$ then <i>Insert_Adjacent_Layer_Table</i> <i>Update_Adjacent_Layer_Table</i> else if $Layer_No_{packet} > Layer_No_{node}$ then <i>Insert_Downstream_Layer_Table</i> <i>Update_Downstream_Layer_Table</i> else if $Layer_No_{packet} < Layer_No_{node}$ then <i>Insert_Layer_Bypass_Table</i> <i>Update_Layer_Bypass_Table</i> end if
Step 11: Repeat Steps 8, 9 & 10 for all Layers
Step 12: Neighbor Discovery phase Completed

C. Packet Delivery Mechanism Phases

The mechanism proposed for forwarding of packets from the nodes to sink meets the objectives outlined in Section V i.e. focus is on high Effective Packet Delivery Ratio with a reasonable degree of fault tolerance. A node may transmit an originating packet i.e. containing information it has sensed or may simply forward a packet towards sink.

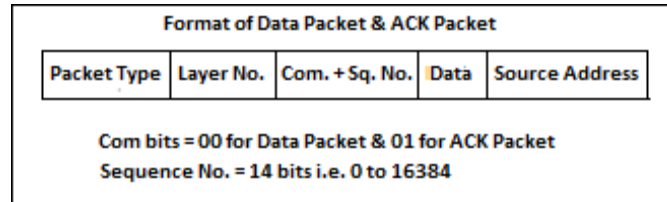
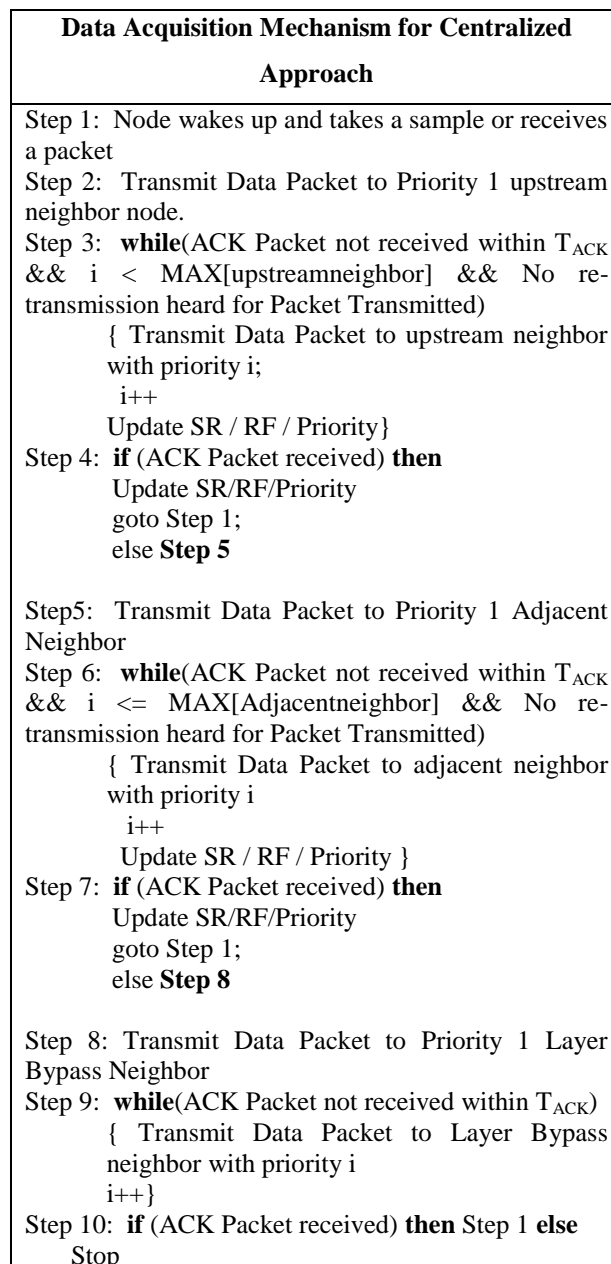


Figure 5. Format of Payload for Data Packet & ACK Packet. The Difference is in the Command Bits which Differentiate between the Two Packets



The common algorithm for the two cases is given above.

D. Case –I: Node is Originating Node

The Originating node may have data to send periodically or it may do so in response to a query. When a node has a packet to send, it looks for the highest priority neighbour in its *Upstream Neighbour Table*, makes a unicast broadcast of the Data Packet (Figure 5) and starts a timer at the same time. On successful receipt of data packet, the receiving node broadcasts an explicit acknowledgement ACK packet (Figure 5). Receipt of ACK packet completes transmission process for current packet. In case the originating node does not receive the *ACK Packet* in the specific turnaround time T_{ACK} , the originating node assumes failure and re-transmits packet to the neighbour with the next higher priority and then repeats the process till the time it has exhausted all the neighbours listed in this table. However, in case data packet is received and the ACK packet is lost then it may result in unnecessary re-transmission. This problem is solved by use of implicit acknowledgement mechanism. If the source/forwarding node overhears the transmission of the ACK packet for the same data packet by

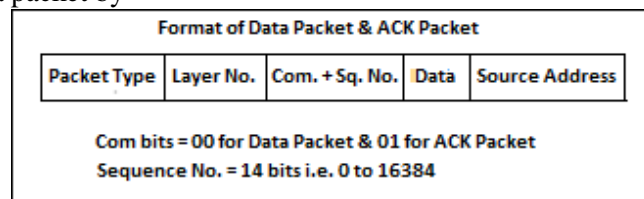


Figure 5. Format of Payload for Data Packet & ACK Packet. The difference is in the Command bits which differentiate between the two packets

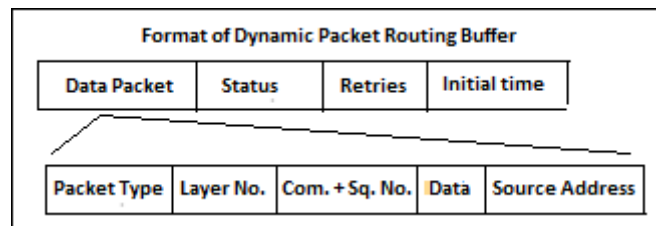


Figure 6. Format of Dynamic Packet Routing Buffer at Every Node

a node from the upstream layer, it assumes that the data packet has reached the upstream layer and it aborts the re-transmission thus preventing duplication of packet and saving on energy.

In case all neighbour entries in *Upstream Neighbour Table* are exhausted and packet remains undelivered then similar process is repeated but with neighbours chosen from *Adjacent Neighbour Table* i.e. neighbours within its own layer.

Once all the neighbours in the *Adjacent Neighbour Table* are exhausted and in case the packet still remains undelivered, the originating node looks into its *Layer By-Pass Table* for information about the neighbour in the layer beyond the downstream layer. This step is expected to cut down significantly on the transmission time since one complete layer of nodes is being by-passed. If there is no response from the nodes in the *Layer Bypass Table* then the packet is deemed to have been dropped.

For every success or failure of packet, the parameters SR, RF, PS & Priority entries in the neighbour tables, corresponding to that neighbour node, are updated.

E. Case –II: Node is Forwarding Node

In case the node is acting simply as a forwarding node i.e. forwarding a packet received from another upstream or adjacent neighbour node then the mechanism is quite similar to the one defined in the case of an Originating node. Once the current node receives a packet, it stores the packet in its *Dynamic Packet Routing Buffer* and transmits an *ACK Packet* to the source node so that it gets a confirmation of receipt of the packet and can remove it from its *Packet Routing Buffer*.

Then it initiates the process of looking for the appropriate neighbour to which the packet can be forwarded to enable it to reach the sink in a similar manner as described earlier. On successful delivery of packet, its entry is removed from the *Dynamic Packet Routing Buffer*. The *dynamic Packet Routing Buffer* is not memory intensive since it contains information only about the packets that are un-forwarded as yet. This ensures that the number of entries in this buffer remain limited.

F. Congestion, Failure Detection & Priority Re-assignment

Non-Receipt of the ACK Packet from the neighbour node indicates failure of delivery which could be attributed to congestion, buffer overflow or node failure. The parameter Packets Sent (PS), Success Rate (SR) and Recent Failure (RF) are updated depending upon the receipt of the ACK packet. Depending upon the current values of these parameters the priority of the neighbour nodes in the respective neighbour tables is changed. This is done to ensure that neighbours with better success rates are assigned higher priority which will have a positive impact on both reliability of delivery as well as on the Network Latency Time.

G. Upper Bound on Network Latency

An estimate of the upper bound on the Time delay vis a vis the number of hops that can be made in the delivery mechanism can be made based on the equations provided below. Following set of equations shows the Upper Bound on the delay between the time of sensing of information at a node and the time when the packet is just about to be deemed as having been dropped. For a Node at Layer 1 the maximum time before packet is deemed to have been dropped is represented by

$$T_{\text{MAXLAYER1}} = (T_{\text{TRANSMIT}} + T_{\text{ACK}}) * (D_n + A_n) \quad (8)$$

Where D_n is the number of downstream neighbours & A_n is the number of adjacent neighbours of the Node under consideration as listed in its *Adjacent Neighbour Table*. For a Node at Layer 2 the maximum time before a packet is deemed to have been dropped is represented by:

$$T_{\text{MAXPERLAYER2}} = (T_{\text{TRANSMIT}} + T_{\text{ACK}}) * [(D_{n0} + D_{n1} + D_{n2} + \dots + D_{nk}) + A_{n0}] + T_{\text{MAXLAYER1}} \quad (9)$$

Where D_{n0} is the number of downstream neighbours of the node under consideration, as listed in its *Downstream Neighbour Table*, while D_{n1} , D_{n2} are the number of downstream neighbours of the k adjacent neighbours of the node under consideration and A_{n0} is the number of adjacent neighbours of the node under consideration. The formula can be generalised for a node at Layer M

$$T_{\text{MAXPERLAYER (M)}} = (T_{\text{TRANSMIT}} + T_{\text{ACK}}) * [(D_{n0} + D_{n1} + D_{n2} + \dots + D_{nk}) + A_{n0}] + T_{\text{MAXLAYER(M-1)}} + \dots + T_{\text{MAXLAYER1}} \quad (10)$$

T_{TRANSMIT} is the time taken by a node to transmit a packet and this includes the delay because of CSMA/CA action at MAC layer and the jitter delay at the Network layer. T_{ACK} is the programmable time for which the network layer of the transmitting node waits

for the receipt of the *ACK Packet* from the node to which it has transmitted the *Data Packet*. $T_{MAXLAYER(k)}$ is the maximum delay time at each layer.

Given a value of time constraint on the delivery time of packets in a given network, using the formulae mentioned at equations (8) (9) & (10) it is possible to calculate the number of layers i.e. number of hops in a network. Alternately, given a network with specific number of hops, it is possible to predict whether the Time Constraint on the delivery time of the packet can be met.

7. Query Dissemination in Layered Nodes

Established query dissemination mechanisms are not designed to function in a scenario where the nodes are divided into layers. The query dissemination mechanism is expected to ensure that the query initiated by a sink (in Centralized Decision Making Scenario) is disseminated to each relevant node in the network with minimal amount of duplication of query.

The objectives for the query dissemination mechanism can be stated briefly as below:

1. Ensure that the query emanating from the sink (in Centralized Decision Making Scenario) is received by each node in the network.
2. Minimum duplication of the query should occur in the network thus avoiding implosion to the extent possible
3. Ensure that the nodes are able to reject a query which has been received and responded earlier
4. Minimum amount of time should be taken for disseminating the query into the network
5. Energy consumption in the network for dissemination of query should be as less as possible to ensure long life-time of the network.

8. Proposed Solution for Query Dissemination

Since the query dissemination mechanism is expected to function in the layer based architecture, the design of the dissemination mechanism has to ensure that the query is uniformly distributed among the nodes in the various layers. The query dissemination mechanism, Layer Based Query Dissemination Mechanism for Centralized decision making scenario (LQDM-C), is quite similar to the layer formation mechanism mentioned in section 4.5 since in both the cases the origin point of the mechanism is at the sink.

It is assumed that Layer & Neighbor Discovery Phase of the LQDM has already been completed successfully. Each node therefore knows its *Layer_No* and has its Neighbor Tables viz. *Upstream Neighbor Table*, *Downstream Neighbor Table*, *Adjacent Neighbor Table* & *Layer-bypass Table* ready.

Figure 7 shows the structure of the query packet. A unique Query Sequence Number is generated by the sink for each query initiated by it for the purpose of identifying the query.

The query dissemination starts from the Sink which broadcasts the query with the *Layer_No* set to 0 and the QSN number updated along with the updated Query field. All the downstream nodes, which meet the condition

$$Layer_No(node) = Layer_No(packet) + 1 \quad (11)$$

receive the query. On receiving the query the node checks whether this query has already been received earlier by comparing the Query Sequence Number against the Queries stored at the *Query Storage Table*, whose structure is provided at Figure 8. If the query has not been serviced earlier, then the query is inserted at the top of the *Query*

Query Storage Table	
	Query Sequence Number
	Query Sequence Number
	Query Sequence Number
	Query Sequence Number
	Query Sequence Number

Figure 8. Query Storage Table for LQDM for Centralized Decision Making Scenario

9. Performance Evaluation

This section presents the details of the performance evaluation tests carried out using the two mechanisms viz. LTCRDM-C & LQDM-C. Simulation was carried out for evaluation of both LTCRDM & LQDM while experimental validation of results was carried out for LTCRDM using an IRIS mote test bed.

A. Common Simulation setup for LTCRDM-C

Varied simulation setup was used to evaluate the different performance parameters of the network. All simulation was carried out using IEEE 802.15.4 PHY & MAC layers. Simulation has been done using QualNet™ Network Simulator. The common simulation setup is provided below:

Table 1. Common Simulation Parameters for LTCRDM-C

Simulation Parameter	Value
PHY Layer	IEEE 802.15.4 PHY
MAC Layer	IEEE 802.15.4 MAC
Data Rate	250 kbps
Antenna Height	0.1 m
Antenna Power	0.0db
Antenna Gain	0.0db
Noise Factor	10.0
CCA Mode	Carrier Sense
Beacon Order	15
MAC Propagation Delay	1 us
MAC Retransmission	03
MAC Acknowledgement	On
Node Deployment Area	40 m x 40 m *
Nodes Deployed	70 / 50 / 20 *
Node Deployment Method	Random
Packet Size	50 bytes

Comparison has been made against two very popular and standard algorithms namely AODV [69] and DSR [44]. The reasons for choosing the two as benchmarks are as follows:

- a) Both are standard algorithms which are widely implemented and used as a reference. A modified version of AODV is used in Zigbee™ [34].
- b) Both use the traditional method of selection of neighbor nodes i.e. nearest node

c) AODV represents the on-demand approach while DSR represents the dynamic routing mechanism, both being fault tolerant approaches.

B. Impact of Layering Mechanism on Network Latency

Fifty nodes are randomly deployed. Post deployment and after completion of layering, it is observed that number of nodes in Layer 1 is 20, Layer 2 is 17 and Layer 3 is 13. One hundred packets are first transmitted by each of the nodes in Layer 1 and the average time for the packets to reach the sink (T_{NLT}) is found. The next time, 100 packets are transmitted by each of the nodes in Layer 2 and the average time for the packets to reach the sink (T_{NLT}) is calculated. Similar exercise is done for Layer 3 nodes. No constraint was however, put on T_{NLT} and comparison was made by using AODV & DSR as transport mechanisms for the same deployment. The results obtained are depicted in Figure 9. As expected the average time for reliable delivery of information in case of LTCRDM is significantly lower than what is observed for AODV & DSR. Unlike LTCRDM, AODV attempts to find out the complete path between source and destination node in case the immediate neighbor does not have the oath to the destination which increases network latency. LTCRDM has significant advantage over this approach as the prioritized neighbor route information is pre-available at the time of transmitting the packet and in case of temporary or permanent loss of connectivity with some of the neighbors, sufficient connectivity still exist to transfer the packet to the next layer towards the sink. Further using the layer based approach optimizes the number of hops between the sources and the sink thus reducing the latency significantly. The observations therefore support the contention made that using the layer based approach, instead of the traditional nearest neighbor approach, has a significant reduction in the Network Latency Time T_{NLT} .

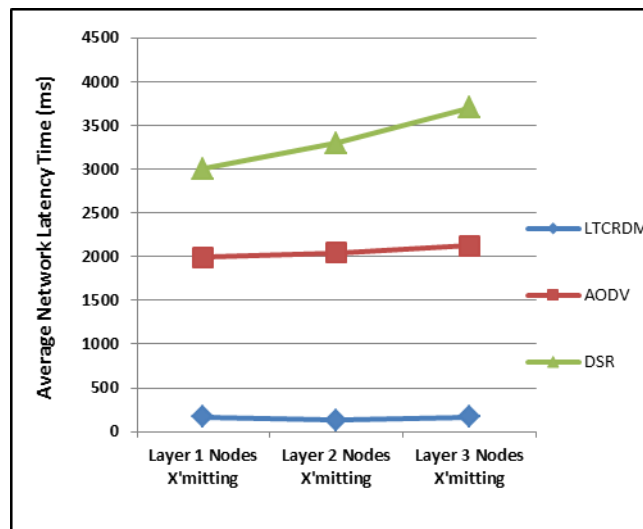


Figure 9. Impact of Layer Mechanism on Network Latency Time (ms)

C. Impact of Number of Nodes on Packet Delivery Ratio

With an increase in the number of nodes in the network, the congestion in the network increases as does the number of hops required for delivering the packet. This has a direct adverse impact on network latency and packet delivery ratio. Simulation tests are run on scenarios where 20, 50 or 70 nodes are deployed in a random manner over an area of 30 m x 30 m thus creating a fairly dense deployment scenario. 100 packets of sensed information are transmitted by the nodes in each experiment. The worst case scenario is assumed i.e. all the nodes try and send data simultaneously and at same sampling rate. A

maximum T_{NLT} of 500 ms is considered for LTCRDM and the packets received after this time delay are ignored at the sink and do not contribute towards the calculation of average Effective Packet Delivery Ratio. Figure 10 presents the comparative performance of the three mechanisms viz LTCRDM, AODV & DSR in terms of the number of nodes and the Effective Packet Delivery Ratio. As expected, the effective packet delivery ratio is significantly higher for LTCRDM as compared to AODV & DSR. This is because not only does LTCRDM reduce the number of hops by using the layered

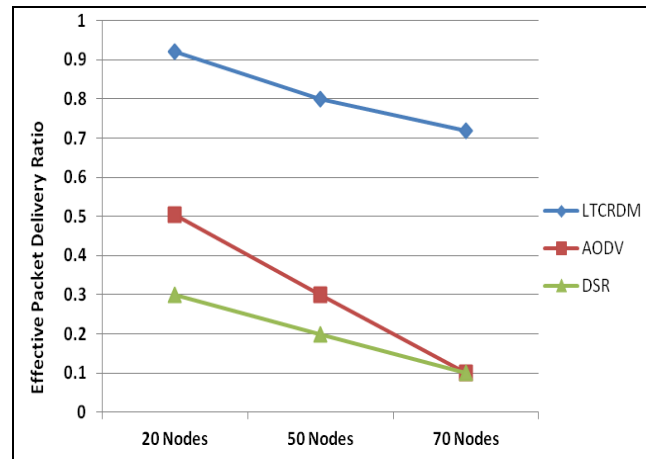


Figure 10. Impact of Traffic on Effective Packet Delivery Ratio (Nodes Transmitting Simultaneously but with fixed periodicity)

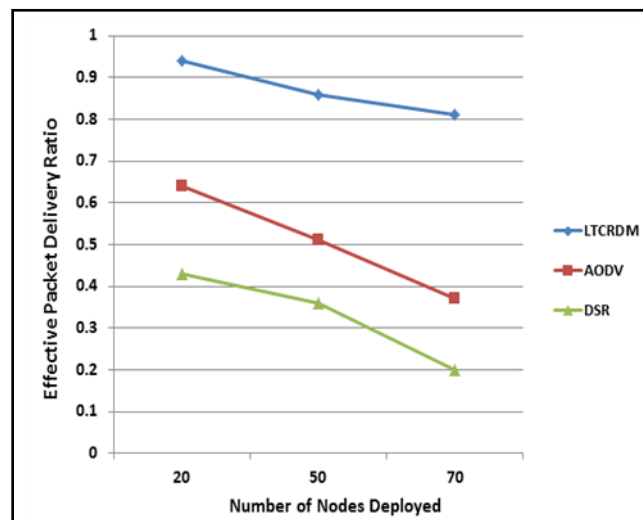


Figure 11. Impact of Traffic on Effective Packet Delivery Ratio (Nodes Transmitting Randomly but with Fixed Periodicity)

neighbor mechanism, thus reducing the network latency time, but also makes best effort to deliver the packet to the destination by using the look-up-table containing information about the prioritized neighbors (successful path). The packet delivery ratio is high in all the three cases when the number of nodes is less i.e. the number of hops to the sink is less. The effective packet delivery ratio starts dropping as the number of nodes is increased to 50 and 70 nodes subsequently. However, the degradation of performance is less pronounced in LTCRDM as compared to standard methodologies like AODV & DSR.

The performance of all three mechanisms improves when the simulation is setup such that all the nodes do not transmit their sampled data packets simultaneously; rather the packets are transmitted with the same periodicity but at random time. Figure 11 presents the comparative performance of the three mechanisms viz LTCRDM, AODV & DSR in terms of the number of nodes and the Effective Packet Delivery Ratio in this case. As expected, the effective delivery ratio improves for all three mechanisms however the effect is more pronounced in AODV as compared to LTCRDM. This is because unlike LTCRDM, AODV does not create multi-path during route search mechanism. Thus on a packet facing rejection because of packet collision, it restarts the process of finding the alternate route thus consuming significant time. As the probability of packet collision reduces, its performance improves.

D. Impact of Node failure on Packet Delivery Ratio

Simulation tests are run on a scenario where 50 nodes are deployed in a random manner over an area of 30 m x 30 m thus creating a fairly dense deployment scenario. Out of these, a total of 20 nodes, spread over 3 layers, are identified which sense and transmit 100 packets each to the sink. The other nodes only re-transmit packets but do not create packets on their own. The worst case scenario is assumed i.e. all the 20 nodes try and send data simultaneously and at same sampling rate. A maximum T_{NLT} of 500 ms is considered and the packets received after this time delay are ignored at the sink and do not contribute towards the calculation of average Effective Packet Delivery Ratio. It is expected that the Effective Packet Delivery Ratio will fall with increase in number of failed nodes all three cases although all three algorithms have built-in mechanism to take care of node failure. However, AODV & DSR are likely to degrade poorly as compared to LTCRDM because their focus is on delivering the packet and not on meeting the latency time criterion. Figure 12 presents the results obtained and as expected it is observed that the LTCRDM degrades gracefully as compared to AODV & DSR with loss of nodes and a reasonable degree of reliability of information delivery is still maintained. However as the percentage of nodes fails, the decline in reliability is more steep. This is again on expected lines as more time will be consumed at each node .

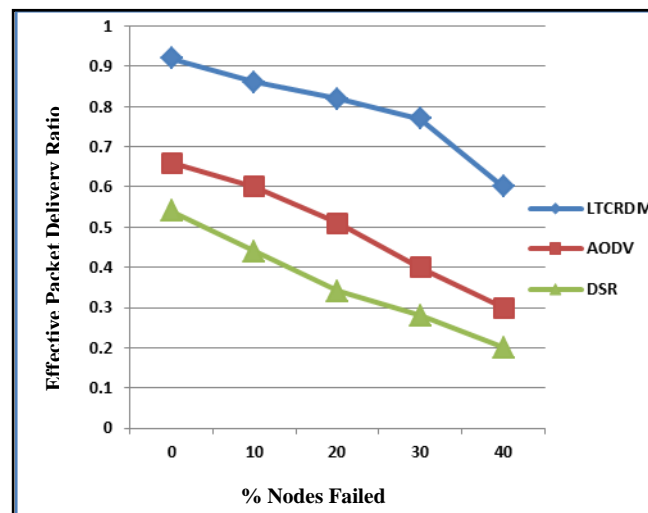


Figure 12. Impact of Node Failure on Effective Packet Delivery Ratio

E. Experimental Validation of LTCRDM

The basic hypothesis of LTCRDM is that by having a layer based mechanism, it is possible to choose adjacent & upstream neighbors, prioritize them and store the information in look up tables at each node. At the time of forwarding a packet the prioritized neighbor will ensure a high probability of successful delivery of packet to the sink with minimal network latency. Further, as LTCRDM creates a multi-path mechanism, a degree of fault tolerance is built into the network thus ensuring a high packet delivery ratio. A test-bed of MEMSIC IRIS XM 2110 Motes was used for testing the basic hypothesis of LTCRDM. The nodes were kept on a plane surface and organized as given in the picture in Figure 4.16 over an area of 7 m x 7 m. Experiments were repeated with varying the number of deployed nodes from 10 to 20. The common setup for LTCRDM-C is as below: Ten nodes were deployed such that they were categorized into three layers. Each node was programmed to transmit 100 packets at interval of 1 packet / s and the total packets received at the base station were measured to calculate the Packet Delivery

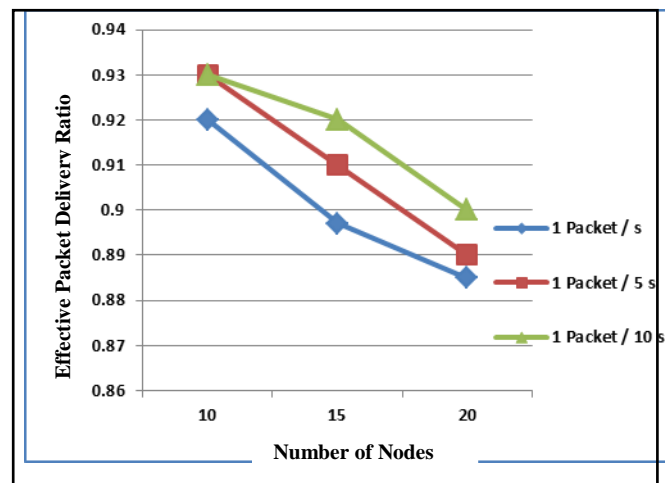


Figure 13. Impact of Number of Nodes on Packet Delivery Ratio

Ratio. The experiment was repeated after deploying 15 and then 20 nodes still divided into three layers. The complete set of experiments above was repeated with the transmit interval changed to 1 packet / 5 s and then 1 packet / 10 s. The Packet Delivery Ratio was measured in each case and the results obtained in each case can be seen in Figure 13.

Experimental readings indicate that the Packet Delivery Ratio obtained was slightly lower than what was obtained during the simulations and can be attributed to the practical considerations including the fact that the experiment was conducted in a room where the reflection was high thus leading to higher degree of interference. The interference increases with increase in number of nodes just because more radio signal sources are present. The drop in the Packet Delivery Ratio is not significant even when the number of nodes is doubled from 10 to 20 as is expected since the LTCRDM algorithm is designed to ensure delivery of packet. The variation in the transmission rate from 1 packet / s to 1 packet / 10 s does bring about an increase in the Packet Delivery Ratio although it is not significant. This is because with a decrease in the transmission rate, the probability of multiple neighbor nodes transmitting together reduces to an extent thus reducing the probability of packet collision which improves the probability of packet delivery without re-transmission.

F. Common Simulation setup for LQDM-C

Varied simulation setup was used to evaluate the different performance parameters of the network. All simulation was carried out using IEEE 802.15.4 PHY & MAC layers. Simulation has been done using QualNet™ Network Simulator. The objective of the simulations is to verify that a query initiated by the sink reaches every node within the network using the LQDM-Centralized mechanism in the layered distribution of the nodes. Further it is to check the time taken by LQDM to disseminate a query originating from a sink to all nodes within the network. The test is

Table 2. Common Simulation Parameters for LQDM-C

Simulation Parameter	Value
PHY Layer	IEEE 802.15.4 PHY
MAC Layer	IEEE 802.15.4 MAC
Data Rate	250 kbps
Antenna Height	0.1 m
Antenna Power	0.0db
Antenna Gain	0.0db
Noise Factor	10.0
CCA Mode	Carrier Sense
Beacon Order	15
MAC Propagation Delay	1 μ s
MAC Retransmission	03
MAC Acknowledgement	On
Node Deployment Area	40 m x 40 m *
Query Sending Rate	1 Query / s
Nodes Deployed	70 / 50 / 20 *
Node Deployment Method	Random
Packet Size	50 bytes

performed by sending 50 queries, at the rate of 1 query/s from the sink and then measuring the time the query reaches every node for the first time. Then an average dissemination time is calculated layer wise. This experiment is repeated thrice, once with 20 nodes, second time with 50 nodes and then with 70 nodes. The number of layers in which the nodes will be distributed is limited to 4 layers in keeping with the assumption made. It is expected that since large number of re-transmissions are being made by nodes of every layer, the query will reach every node in the network. However, as a filter mechanism is in place to ensure that a query is stored only once in a node that automatically leads to only one re-transmission per node per query. This ensures that flooding and implosion does not occur in the network. Further because of the layering mechanism in place, it is expected that the dissemination of the query will be with low network latency.

The observations recorded in Table 3 indicate that the query initiated from Sink, in case of Centralized Decision Making Scenario, takes about 157-269 ms for dissemination to nodes which are spread out in 4 layers. All nodes reported reception of the Query Packet thus confirming the reliability of the query dissemination mechanism. It is observed that with larger number of nodes in place i.e. with 70 nodes, the application criterion for network latency i.e. 500 ms for query dissemination is not met if number of layers is more than 3. For lesser number of nodes, the application criterion is satisfactorily met.

Table 3. Simulation Results for LQDM-C

Sr.	Layer Number	Avg. Time for Dissemination of Query Within Layer		
		70 Nodes	50 Nodes	20 Nodes
1	1	55 ms	44 ms	38 ms
2	2	47 ms	41 ms	33 ms
3	3	51 ms	43 ms	39 ms
Avg. Total Time for Dissemination		153 ms	128 ms	110 ms

10. Conclusion and Future Work

The Layer Based Time Constrained Reliable Data Acquisition Mechanism (LTCRDM) has been proposed with the objective of improving the reliability of process of acquiring data gathered by the deployed sensor nodes with high packet delivery ratio and low network latency. The results obtained from simulations and experiments indicate that the mechanism achieves the objectives satisfactorily.

The results obtained during simulations and experiments indicate that the concept of layers, layer based neighbours, neighbour success rate (Ant Colony based) and usage of explicit and implicit acknowledgements, which form the heart of Layer Based Time Constrained Reliable Data Acquisition Mechanism (LTCRDAM), have a direct positive impact on the successful delivery of packets at the sink within the network latency time constraint T_{NLT} .

This leads to the conclusion that usage of the above techniques does in fact reduce the number of hops and the number of re-transmissions required to deliver a packet successfully to the sink within the constraint of the network latency time T_{NLT} . However, the results also indicate that the effectiveness of the mechanism may be less if the number of hops increases. It is clear that network latency will involve some energy trade-off [92] as the benefit achieved in terms of reduction in Network Latency is because of higher energy cost of communication which goes up because of reduction in number of hops. However this offset to an extent by the comparatively lesser number of re-transmissions required.

LTCRDM-C along with LQDM-C present a composite set of algorithms for reliable collection of information as well as for reliable dissemination of a query in a WSN. In conclusion it is safe to state that the potential of utilization of these, in view of the overall shift towards WSN applications in various fields, is very high. The limitations of the current work along with the improvements required to be made as part of future work are discussed next.

Future work could study the data acquisition process from the perspective of other QoS parameters like jitter, throughput etc. and the effect of maintaining these parameters on the Reliability of Data Acquisition can be studied. Moreover the mobility of the nodes and its impact on the Reliability of Data Acquisition can also be an interesting issue for future work. Future work can also be done in the direction of improving the Energy consumption of the nodes by adding scheduling algorithms.

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