Layer Based Time Constrained Reliable Data Acquisition Mechanism for Wireless Sensor & Actuator Networks

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Abstract

one of the most critical tasks of a Wireless Sensor Network is the ability to sense the parameter or event under consideration and then ensure delivery of sufficient amount of information gathered to the sink for it to be able to re-construct the event reliably. This reliable delivery of information assumes more importance in a Wireless Sensor & Actuator Network 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, for reliable delivery of information sensed periodically by the sensors deployed over a geographical area to a centralized sink where the decisions are taken based on the collected data and then passed on to the actuators for subsequent actions. In view of the reliability and latency requirements of Wireless Sensor & Actuator Network, the mechanism detailed has constraints on the time between sensing at the sensor node and reception of data at the sink besides ensuring relatively low packet loss as compared to standard packet delivery mechanisms. Authors have provided detailed algorithm, results of simulation and observations using IEEE 802.15.4 PHY & MAC as underlying layers. A critical analysis of the results is presented for comparison against the standard methodologies in vogue.

Keywords

Wireless Sensor Networks, Wireless Sensor & Actuator Networks, Reliable Data Acquisition, Network Latency Time, IEEE 802.15.4, Packet Delivery Ratio.

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Introduction

Over the last decade, Wireless Sensor Networks have emerged as an accepted methodology for sensing events and for acquiring data generally spread over a large geographic area[1]. Using low cost, inexpensive and untethered wireless sensor nodes for the purpose of sensing parameters and events has dramatically removed the constraints associated with traditional wired methodologies thus providing a paradigm shift in the approach towards the process of data acquisition. These nodes can be left unattended for long period of time and have the ability to self-organize to form a network and ensure delivery of sensed information or event to each other for collaborative sensing, besides sending the information to a centralized base station. However these nodes are energy constrained, have low computational capability, low accuracy of sensing and are prone to hardware and communication failure. The problem is further augmented by the fact that the wireless medium is itself prone to irregular and unpredictable behaviour because of issues like interference and channel fading. This raises the issue of reliability of these networks to sense the environment effectively and more importantly to deliver the information regarding the sensed phenomenon to the centralized sink. Wireless Sensor Networks use basic standard methodologies to get over these problems including introducing redundancy in the network by deploying large number of sensor nodes than what are actually needed for sensing and eventual estimation and re-construction of the sensed event at the sink[3]. This is introduced to counter the issue of node failure and packet loss during communication besides improving reliability of coverage[2] to ensure detection of event. Moreover network life-time is improved by making the nodes to go into low power sleep mode when not sensing thus conserving battery life. Multiple strategies and methodologies for reducing the packet loss have been proposed which focus on issues like optimized routing algorithms with multiple paths for packet delivery[4–7], energy aware routing algorithms[8], algorithms proposing multiple sinks or mobile sinks[6] in the network to ensure availability of a sink in geographical vicinity of nodes and so on. Use of various protocols including Bluetooth, IEEE 802.11 etc.[9,10] have also been proposed for implementation of Wireless Sensor Network however the IEEE 802.15.4 standard[11] remains the most appropriate standard, available in public domain, for implementation.

However with the evolution of Wireless Sensor & Actuator Networks additional constraints have been thrust upon the data acquisition process of the network since the decisions taken by the Network controller for control of actuating action depends on the data acquired. These constraints[12] include data acquisition latency, low packet loss, response time, integrity of data collected etc.

The authors have proposed a mechanism which focuses on significantly reducing the data acquisition latency and improves the reliability of data acquisition of a WSAN. The algorithm assumes utilization of IEEE 802.15.4 PHY & MAC in the underlying layers. The proposed algorithm presents a reliable data acquisition mechanism which is non-hierarchical in nature but divides the nodes into layers. Transfer of information from nodes of one layer to another Layer is allowed with a focus on making best possible effort for the transfer of information while simultaneously resulting in meeting the time constraint placed on the time between sensing of the phenomenon and delivery of the packet containing the information to the sink. A tabular approach is used for storage of neighbour information but unlike traditional methods places minimum overheads on the memory required since the definition of neighbour nodes is altered. Simulation results are also presented. The remaining paper is organized as follows- Section II presents the problem statement, Section III surveys the Existing Solutions, Section IV lays down the objectives of the solution, Section V contains the definition of measurement of Reliability of Data Acquisition, Section

VI contains the proposed solution, Section VII presents the Simulation results, Section VIII presents the conclusions and Section IX talks about the future work.

Statement of the Problem

Wireless Sensor & Actuator Networks consist of sensor nodes which are assigned the task of collecting the information regarding the parameters under consideration or for detecting the events, and Actuator Nodes which perform the actuation for implementing the control action. The Actuator nodes are expected to have considerable computing and memory resources besides having sufficient battery or line power[12]. In the case of Centralized control action, the sensors pass on the information to a centralized location where the decision regarding the action to be taken by the Actuator nodes is made and the same is passed on to the Actuator nodes (Fig 1(a)). In case of distributed control action, the sensors pass on the information to the corresponding Actuators which collaboratively decide upon the action to be taken (Fig 1(b)). In both scenarios, the decision making process relies upon the information sensed by the sensors and passed on to the decision making entity. This places following constraints on the network:

a) The information should be sensed reliably by the sensors and in case of detection of events; the event should not be missed. The data sampling rate may be periodic, randomly variable or event based. This may require the nodes to have very small or no sleep time which would affect the network life-time adversely.

b) The information sensed by the nodes should be routed to the decision making entity or entities with least possible loss of information in the form of network packet loss.

c) The routing mechanism should be rugged, dynamic and adaptive to withstand temporary or permanent loss of communication with certain neighbours.

d) There should be minimum time lag between the time the information was sensed or the event detected and the time the information is delivered at the decision making entity. This is necessary to ensure that the control action is in tune with the actual circumstances of the environment being reported by the sensors.

e) The delivery of the packets at the decision making entity should be coherent as far as possible.

f) The decision making entity should be able to sift through the data received and be able to identify data from noise and discard noisy data from the decision making process.

Reliable Data acquisition refers to the ability of the Wireless Sensor & Actuator Network to ensure delivery of sufficient amount of the gathered information, by the deployed sensor nodes, in a time-bound and coherent manner to the centralized sink for it to be able to faithfully and successfully re-construct the event and take necessary action in time. Reliability further includes the availability of the data acquisition service being provided by the network for as long as possible without compromising on the ability of the centralized sink to faithfully re-construct the event sensed by it. Reliability also includes the ability of the network to be tolerant to faults, within a limit, without comprising on the basic issue as mentioned above. It is with this definition of reliability in mind the authors have studied the problem at hand and have arrived at the objectives of the proposed solution.

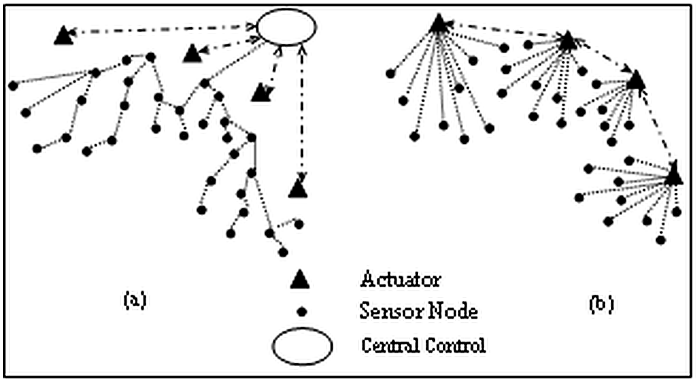

Figure 1. Diagram illustrates the two types of Control Action (a) Centralized Control Action (b) Distributed Control Action with Actuator Co-operation

Related Work

Various techniques have been employed to improve the reliability of the data acquisition process by the deployed sensor nodes. PSFQ[27] focuses on enhancing reliability by ensuring high packet delivery ratio at sink using hop by hop reliability and fetching of lost packets from neighbours, however Network Latency Time is not constrained. ESRT[17] propounds reliability only in form of detection of event and not in readings from nodes and uses a state based approach. (RT)2[18] attempts to achieve reliable and timely event detection with minimum possible energy consumption and no congestion by using a scheduling policy at the buffers to send packets with tight time constraints on priority but indicates possibility of not meeting the time constraint in congested networks..[19] Proposes a multi-path mechanism based on AOMDV which calculates node and path reliability at each node and then chooses the most reliable path, however packet overhead is significant. EAR[20] presents a *routescore* parameter to choose the most optimal path for forwarding of packet at each node and uses the RTS/CTS mechanism to improve reliability.[21] Surveys a bunch of mechanisms proposed for reliable acquisition and clearly indicates the problems associated with each of them. AReIT[22] provides capability for changing of retransmission to overcome changes in event detection or query periodicity and uses spatial knowledge of network to improve reliability. LTRES[24] addresses the reliability issue specifically for event detection applications by using source rate adaptation giving high reliability but at high control overheads and failure to converge if multiple events occur at high rate.[25] Surveys a host of multi-path routing mechanisms to emphasize that reliability can be increased by using the multi-path routing approach although achieving coherence of packets may be a problem.[26] uses the cluster approach to improve reliability, fault tolerance and reduce energy consumption however the reliability reduces significantly with increase in number of nodes.[16,23] discusses algorithms based on swarm intelligence techniques like Ant colony Optimization, Foraging, GA etc. to improve reliability of transfer of information. Literature survey indicates that multi-path approach and cluster based approach generally show good results but the improvement in reliability is at cost of high control overheads or energy.

Objective

Reliable Data acquisition refers to the ability of the Wireless Sensor & Actuator Network to

a) ensure delivery of sufficient amount of the gathered information, by the deployed sensor nodes, to the centralized sink / Actuators for it to be able to faithfully and successfully re-construct or estimate the event and take necessary action in time.

b) ensure delivery of the sensed information by the deployed nodes within the constraint placed on Network Latency Time (T_{NLT}) i.e. time between sensing of information by the nodes and the time of delivery of information at Sink/Actuators, T_{NLT}, must be less than the Actuation Latency Time.

c) ensure delivery of sensed information by the deployed nodes in a coherent manner

d) be tolerant to faults, within a limit, without comprising on the ability of the centralized sink / Actuators to faithfully re-construct the event sensed by it.

e) ensure availability of the data acquisition service being provided by the network for as long as possible without comprising on the basic issue as mentioned above.

The objective therefore is to design a set of algorithm which can deliver efficiently the desired results within the constraints imposed. The set of algorithms meeting all the constraints will span more than one layer of the network stack; however since IEEE 802.15.4 has been chosen as the PHY & MAC layer of choice, the algorithms described in this paper operate within the network layer only with fine tuning of some parameters in the MAC layer.

Measurement of Reliability of Data Acquisition

Assume a fixed area in which an event is to be detected or parameter to be measured using WSAN. Let N be the threshold number of nodes which are required for faithful estimation or re-construction of event (Application Dependent) Due to known constraints of WSAN the actual deployed nodes will be M with $M > N$. Let an event occur at Time T1 which is sensed by K nodes out of M nodes deployed where $N <= K < M$. Let the actual number of information packets delivered at the Centralized sink be X such that

$$X = K * P \tag{1}$$

where

$$\text{Effective Packet Delivery Ratio at Sink} = P = \frac{(T - S)}{K} \tag{2}$$

T = No. of Packets reaching Sink for event detected at T1 by K nodes such that T <= K

S = No. of Packets reaching beyond constraint on Network Latency Threshold Time (T_{NLT}) i.e. where $T_{arrival} > T1 + T_{NLTMAX}$.

then

$$\text{Reliability of Data Acquisition} = \gamma = \frac{X}{N} \tag{3}$$

Substituting

$$\gamma = \frac{(T - S)}{N} \tag{4}$$

Where minimum value of S=0 & maximum value of T=K =N

$$\gamma \propto (T - S) \tag{5}$$

Based on the above mentioned methodology the following conclusions can be obtained which help in refining our objectives:

- Reliability of Data Acquisition & estimation & re-construction at Sink/Actuators will be higher if Effective Packet Delivery Ratio, considering the constraint of Network Latency Time (T_{NLT}), is high and is approaching the maximum value of 1
- Reliability would be reduced if packets arriving at the Sink do not meet the time constraint applied on the Network Latency Time (T_{NLT})
- 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 if the Data Acquisition mechanism can provide high Effective Packet Delivery Ratio i.e. with constraint on T_{NLT}
- This would also increase the overall Network life-time since more number of nodes can remain in sleep mode for longer period of time

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 WSAN. IEEE 802.15.4 standard is used for the PHY & MAC layer. Nodes are assumed to be deployed randomly. Unlike Wireless Sensor 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.

The basic principle of the algorithm is three-fold, firstly the number of hops between the sensor and the sink must be reduced to cut down significantly on the delay between sensing and delivery time thus improving the chances of meeting the time constraint. Secondly, every effort must be made by the network to ensure that the packet transmitted at the sensor actually reaches the sink, within the time-constraint. Thirdly, congested or failed neighbours must be identified and assigned least priority and neighbour with highest probability of transmission-reception success rate must be assigned high priority to reduce delay in forwarding of information and thus improving probability of meeting the constraint on Network Latency Time. Thus multiple delivery paths must be available for the delivery of the packet which can be adapted dynamically without having to start from the originating sensor every time a route fails. The current algorithm has been designed for operating under the situation where the sensor nodes sense the information periodically and then transmit it to the centralized sink. The algorithm is divided into two phases viz the Layer & Neighbour Discovery Phase and the Data Acquisition Phase which are explained hereafter.

Layer & Neighbour Discovery Phases

The objective of the first part of this algorithm is to categorise the sensor nodes, deployed randomly, into layers such that the nodes from one layer will communicate with nodes of the upstream layer. The objective of this approach is to reduce the number of hops that a node will take to transfer the sensed information to the sink. Although having more number of hops does increase the energy consumption of the network, this is balanced by the decrease in the end-to-end delay because of less packet overheads and generation of lesser number of packets.

Each node is assigned a variable $\text{Layer\_no}_{\text{node}}$ initialized to 0 and a myfinaldestination variable initialized to Sink address.. After the network forming phase is over and an IEEE 802.15.4 PAN is formed by the underlying PHY & MAC layer, the algorithm starts functioning. Initially the Sink node transmits a Layer Discovery Packet with the $\text{Layer\_no}_{\text{packet}} = 0$. All the nodes which receive this transmission and satisfy the condition

$$LQI_{recvd} > LQI_{low} \; \&\& \; Layer\_no_{node} == 0 \tag{6}$$

assign a new value to their $\text{Layer\_no}_{\text{node}}$ variable

$$Layer\_no_{node} = Layer\_no_{packet} + 1. \tag{7}$$

All these nodes are now part of Layer 1. A selected set of nodes out of the nodes of this layer with $\text{LQI}_{\text{recvd}} > \text{LQI}_{\text{low}} * 1.2$ now transmit, with random delay in-between, the Layer Discovery Packet with $\text{Layer\_no}_{\text{packet}} = \text{Layer\_no}_{\text{node}}$ i.e. value 1. All the nodes which receive this packet and satisfy the condition at equation (6) assign their $\text{Layer\_no}_{\text{node}}$ variable with value as per equation (7). These nodes now are part of Layer 2. The above mentioned process is repeated till all nodes are segregated into Layers as shown in Fig 2. This completes the Layer forming phase of the algorithm.

It may be argued that the value of LQI is not a very reliable indicator of the distance of the nodes from the Sink or from each other and that better methodologies for ascertaining the position of the nodes vis a vis each other do exist[13–15]. However, in the current case LQI is not being used to exactly ascertain the position of the node but is simply being used as rough marker to categorise the nodes into layers and accuracy of LQI is not a critical requirement for this purpose.

The neighbour discovery phase of the algorithm starts after a brief delay on completion of the Layer forming phase. The objective of this 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 Fig 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

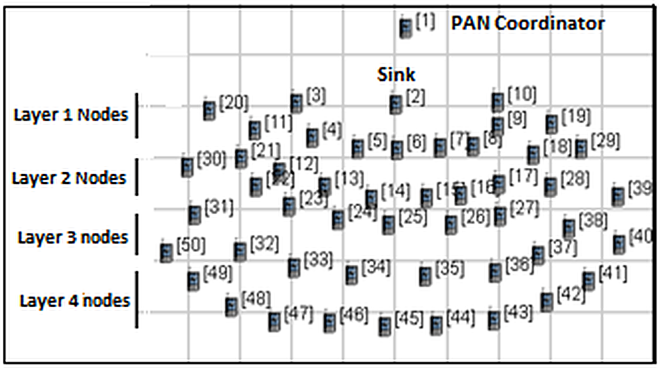

Figure 2. Representative illustration indicating deployed Nodes being categorised into Layers 1-4

Table Structure for Four types of Neighbor Tables

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

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

Neighbour Table contains the information about the nodes in the Down-stream 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 Rate (SR) & Recent Failures (RF) for each of neighbour node entry which are initialized to zero.

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

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

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.

$$\text{Neighbour Priority} = f_n(LQI, \text{Battery Status}) \tag{8}$$

The phase is initiated by some nodes of nodes of Layer 1 which broadcast the Neighbour Discovery Packet Layer 1 once after random delay between their transmissions. These nodes are the ones which are closest to the outer boundary of Layer 1 and satisfy the condition $\text{LQI}_{\text{recvd}} > \text{LQI}_{\text{low}}$ * 1.2. This ensures that flooding of the network does not happen. All nodes of Down-stream layer which receive the packets fill up their Upstream Neighbour Table based on the function at (8) while the same packet information will be used by the nodes within Layer 1 to fill their Adjacent Neighbour Table. The Upstream Neighbour Table of nodes in Layer 1 will consist of only one entry corresponding to the Sink and will have no entry in the Layer By-pass Table. After some delay, the nodes in Layer 2 will initiate transmissions with random delay using the Neighbour Discovery Packet Other Layers type defined in Fig.3. 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. The nodes in the upper-most layer will have no entries in the Down-stream Neighbour Table.

On completion of this phase, each node has complete information regarding all its neighbours in all possible layers and directions i.e. the topology of the network, relevant from each node's perspective, is fully established. It is pertinent to note here that the Node is not storing the topology information about the whole network but only related to its own immediate neighbours. This ensures minimum requirement of memory resource for storing the topology information.

Packet Delivery Mechanism Phases

The algorithm operational in this phase is expected to ensure that the routing & delivery of the packets from the sensor nodes to the sink meets the objectives outlined in IV above i.e. low packet loss and delivery of packet within the time constraint in spite of temporary or permanent loss of communication link between any node and some of its neighbours.

A node could possibly have two situations when it has a packet to send, the first is when it is the originating node i.e. it has sensed some information and needs to forward it to the sink and the second is when it is acting as a Forwarding Node i.e. it has received a packet originating from some other node and its is required to forward the packet towards the sink. The common algorithm for the two cases is given below.

Case –I: Node is Originating Node

The Originating node may have data to send periodically since it sense the information periodically or it may have detected a specific event which it is required to transmit. Either way, when a node senses some information and is ready to send, it looks for the highest priority neighbour in its Upstream Neighbour Table and sends the packet of Data Packet format, as shown in Fig. 5 and starts a timer at the same time. If this neighbour receives the packet it then sends back a packet of ACK Packet format as shown in Fig. 5 confirming the receipt of the packet sent by the originating upstream node. Now the onus of routing the

Table 1. Table illustrates the Layer & Neighbour Discovery Algorithm

Layer & Neighbour Discovery Algorithm
Step 1: On wake up Complete Network Association Process Step 2: Set $Layer\_No_{node}$=0 & myfinaldestination= Address of sink. 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 1broadcast Neighbour Discovery Packet Layer 1 Step 8: if $Layer\_No_{packet}$=$Layer\_No_{node}$ then Insert_ Adjacent_ Layer_Table Update_ Adjacent_ Layer_Table else if $Layer\_No_{packet}$ <$Layer\_No_{node}$ then Insert_ Upstream_ Layer_Table Update_ Upstream_ Layer_Table end if Step 9: for nodes in Layer 2 with $LQI_{recvd} > LQI_{low}$ * 1.2 Prepare list of Downstream neighbours Broadcast Neighbour Discovery Packet Others Step 10: if $Layer\_No_{packet}$=$Layer\_No_{node}$ then Insert_ Adjacent_ Layer_Table Update_ Adjacent_ Layer_Table else if $Layer\_No_{packet}$ >$Layer\_No_{node}$ then Insert_ Downstream_ Layer_Table Update_ Downstream_ Layer_Table else if $Layer\_No_{packet}$ <$Layer\_No_{node}$ then Insert_ Layer_Bypass_Table Update_ Layer_Bypass_Table end if Step 11: Repeat Steps 8, 9 & 10 for all Layers Step 12: Neighbour Discovery phase Completed

packet forward lies on this new neighbour and the originating neighbour has no further role to play, even if the neighbour node is unable to send the packet further.

In case the originating node does not receive the ACK Packet from the neighbour, to which it had sent the packet, in the specific turnaround time T_{ACK}, the originating node assumes failure of communication and searches its Downstream Neighbour Table for 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.

Then the originating node starts looking for neighbours in its Adjacent Neighbour Table i.e. look for neighbours within its own layer. It then sends the packet to its adjacent neighbour with highest priority and waits for the ACK Packet confirming the receipt of the packet at the neighbour within T_{ACK}. In case of non-receipt of the ACK Packet it repeats the process till the time all adjacent neighbour entries in the Adjacent Neighbour Table are exhausted.

Table 2. Packet Delivery Mechanism Algorithm

Packet Delivery Mechanism Algorithm

Step 1: Node wakes up and takes a sample or receives a packet
Step 2: Transmit Data Packet to Priority 1 upstream neighbour node. Initialize i=1
Step 3: while(ACK not received within T_{ACK} && i < MAX[upstreamneighbour])
{ Update SR / RF / Priority
i++;
Transmit Data Packet to upstream neighbour with priority i;}
Step 4: if (ACK received) then
Update SR/RF/Priority
goto Step 1;
else Step 5
Step 5: Transmit Data Packet to Priority 1 Adjacent Neighbour node. Initialize i=1;
Step 6: while(ACK not received within T_{ACK} && i<=MAX[Adjacentneighbor])
{ Update SR / RF / Priority
i++;
Transmit Data Packet to adjacent neighbour with priority i }
Step 7: if (ACK received) then
Update SR/RF/Priority
goto Step 1;
else Step 8
Step 8: Transmit Data Packet to Priority 1 Layer Bypass Neighbor
Step 9: while(ACK not received within T_{ACK})
{ Transmit Data Packet to Layer Bypass neighbor }
Step 10: if (ACK received) then Success else Stop

Format of Data Packet & ACK Packet

Packet Type	Layer No.	Com. + Sq. No.	Data	Source Address

Com bits = 00 for Data Packet & 01 for ACK Packet
Sequence No. = 14 bits i.e. 0 to 16384

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

Once all the neighbours in the Adjacent Neighbour Table are exhausted 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.

This is best explained with an example. As can be seen in Fig6, Node 9 is the originating node with 4, 5, 6 as Upstream Neighbours, 8 as Adjacent Neighbour and 3 as Layer Bypass Neighbour. Similarly Node 8 has 9 as its adjacent neighbour and 6 & 7 as upstream neighbour. Similarly 3 & 1 are upstream neighbours of 5 while 4 is its adjacent neighbour. 2 is upstream neighbour of 6 while 2 and 3 are adjacent neighbours of 1. If 9 is the originating node then the following steps occur for delivering packet from 9 to sink:

$9 \rightarrow 4$, Wait for ACK within T_{ACK}. If YES then stop else
$9 \rightarrow 5$, Wait for ACK within T_{ACK}. If YES then stop else
$9 \rightarrow 6$, Wait for ACK within T_{ACK}. If YES then stop else
$9 \rightarrow 8$, Wait for ACK within T_{ACK}. If YES then stop else
$9 \rightarrow 3$, Wait for ACK within T_{ACK}. If YES then stop else drop packet

The same mechanism is followed at every node till the time the packet reaches the sink.

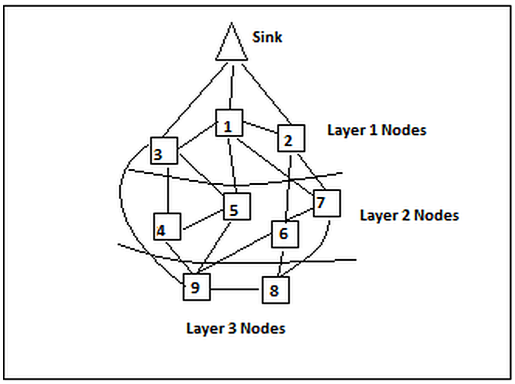

Figure 6. Diagram illustrating the Packet Routing & Delivery Mechanism for a 3 Layer WSAN with 1 Sink & 9 Nodes

Case –II: Node is Forwarding Node

In this scenario, a packet may be received from another node from either the down-stream layer or from the same layer. This is because the node is viewed as a Upstream, Adjacent or By-pass layer neighbour of the node which has sent the packet.

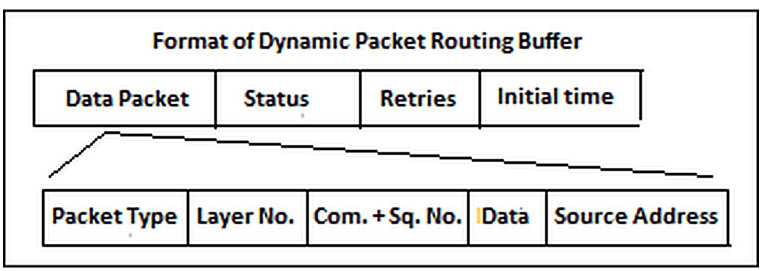

Figure 7. Format of Dynamic Packet Routing Buffer created on every Node

The objective in this case is to simply forward the packet received to its subsequent neighbours thus enabling the packet to eventually reach the sink. The mechanism of forwarding the packet 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.

As can be observed, the focus of the algorithm in the Routing & Delivery Mechanism Phase is to ensure that every effort is made to deliver the packet to the sink to reduce the packet loss. The dynamic Packet Routing Buffer is not memory intensive since it does not store information about the packets that have been successfully transmitted and only the packets under current consideration have an entry here. This ensures that the number of entries in this buffer remain limited.

Congestion, Failure Detection & Priority Reassignment

Non-Receipt of the ACK Packet from the neighbour node is taken as an indicator that the neighbouring node has not received the transmitted data successfully. This could be because of node congestion, node buffer overflow or node failure but the end result is the same. 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 as less time will be wasted in sending data to neighbours which have low probability of receiving information and sending if further.

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. In line with the specifications mentioned in IEEE 802.15.4, the MPDU size, with the current payload of the format of Data Packet (10 bytes) and with no security related overheads is 35 bytes. This translates into a PPDU of 41bytes. The data being sent is assumed to be 2 bytes long and the overall PPDU size could change if the data size is enhanced. 14 bits have been kept for the Sequence number of the packet thus putting a limit of 16385 on the number of packets per node.The following set of equations shows the Upper Bound to 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

$$T_{MAXLAYER1} = (T_{TRANSMIT} + T_{ACK}) * (D_n + A_n) \tag{9}$$

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:

$$T_{MAXPERLAYER2} = (T_{TRANSMIT} + T_{ACK}) * [(D_{n0} + D_{ni} + D_{n2} + .. + D_{nk}) + A_{n0}] + T_{MAXLAYER1} \tag{10}$$

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

$$\begin{aligned} T_{MAXPERLAYER(M)} = (T_{TRANSMIT} + T_{ACK}) * [(D_{n0} + D_{ni} + D_{n2} + .. + D_{nk}) + A_{n0}] \\ + T_{MAXLAYER(M-1)} + \text{.........} + T_{MAXLAYER1} \end{aligned} \tag{11}$$

$T_{TRANSMIT}$ 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.

Simulation Results

This section provides the results of simulation carried out for studying the impact of variation in various parameters on the behaviour and efficacy of the algorithm in meeting its stated objectives. All simulation was carried out using IEEE 802.15.4 PHY & MAC layers. The parameter being changed include node density, number of hops, sampling & transmission rate, deployment pattern and the parameters being monitored are packet loss, delivery time from node to sink and jitter. Comparison has been made against two very popular and standard algorithms namely AODV and DSR. 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 with Binary Tree is used in Zigbee.

b) Both represent the on-demand or dynamic routing mechanism which is expected to be more reliable than Table based approach.

Impact of Layering Mechanism on Network Latency Time

The objective of this test was to establish the impact of using the concept of layers in a given deployment on the Network Latency Time (T_{NLT}). 50 nodes were randomly deployed in a 40 m x 40m area and the average time for reliable delivery of information sensed by a set of nodes was found by selecting set of nodes from each layer. No constraint was however put on T_{NLT} and comparison was made by using AODV & DSR as transport mechanisms for the same deployment.

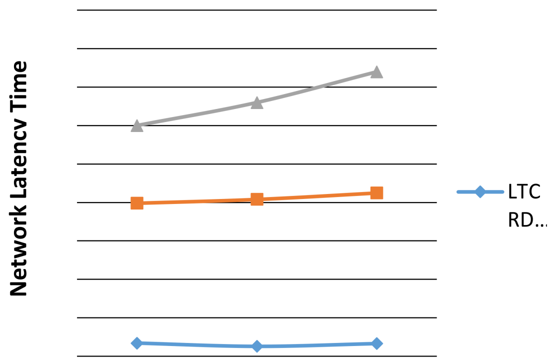

Figure 8. Impact of Layer Mechanism on Network Latency Time (mSec.)

It was observed that there was a significant reduction in the Network Latency Time T_{NLT} if the layer based approach was taken instead of the traditional approach of transmitting information to the nearest neighbour thus justifying the layer based approach.

Impact of number of Nodes on Effective Reliable Packet Delivery Ratio

The objective of this test is to observe the impact of the increase in the number of nodes and the resulting packet traffic on the Effective Reliable Delivery Ratio capability of the network while using LTCRDM. Effective Reliable Delivery Ratio is defined in context with Equation (3) mentioned at Section V above. This indicates that not only should the packets be delivered successfully at the sink but they should also b delivered within the time constraint applied on the Network Latency Time T_{NLT} failing which they would be treated as undelivered packets. As the number of nodes increases, the congestion in the network increases as does the number of hops. It is predicted that this will result in more reliance on alternate paths which will improve reliability of delivery but will reduce effective reliability as the constraint on Network Latency time may not be met. The observations support the reasoning. It is observed that the effective Packet Ratio dropped with an increase in the number of nodes however the effect is much less pronounced as compared to standard methodologies like AODV & DSR.

Impact of Neighbour count on Effective Reliable Packet Delivery in LTCRDM

The objective is to analyse the impact of number of Neighbours i.e. Adjacent & Upstream neighbours on the Effective Packet Delivery Ratio in LTCRDM. For Layer 1 nodes, only the number of Adjacent numbers is changed while for nodes in other layers, both adjacent and upstream neighbours are changed. It is expected that increasing the number of adjacent neighbours will have a positive impact on the Effective Reliability of Packet Delivery but will have a negative impact after a specific number since the constraint on Network Latency Time will not be met. The observations during the simulation support the theory (Fig.10 & Fig.11)

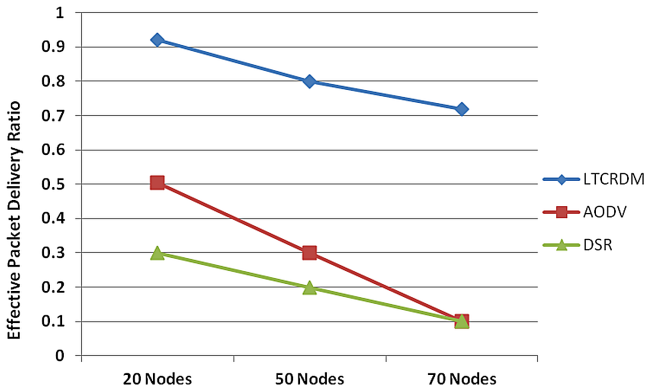

Figure 9. Impact of Traffic on Effective Packet Delivery Ratio

Impact of Node Failure on Effective Reliable Delivery of Information

The objective of this simulation test is to study the impact of failure of nodes on the ability of the network to provide effective reliability of delivery of information to the centralized sink.

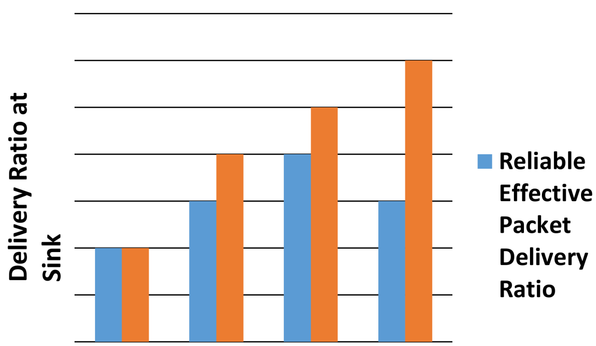

Figure 10. Impact of Number of Adjacent Neighbours on Delivery Ratio

Node failures were introduced within the network indicating permanent failure of nodes and then the effective delivery ratio at sink was monitored. It was observed that the performance of the LTCRDM degraded gracefully with loss of nodes and a reasonable degree of reliability of information delivery was maintained by it (Fig. 12).

Conclusion

A Layer Based Time Constrained Reliable Data Acquisition Mechanism (LTCRDM) has been proposed with the prime objective of ensuring that sufficient amount of information sensed by the deployed nodes

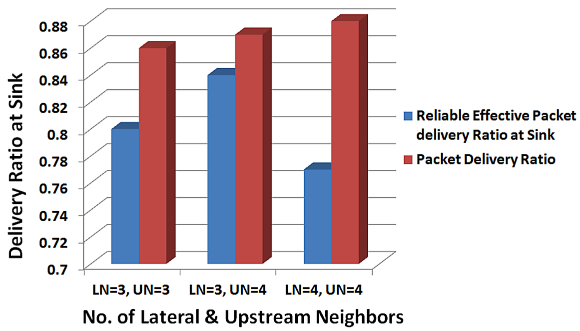

Figure 11. Impact of Adjacent & Upstream Neighbours on Delivery Ratio

is delivered at the sink with a constraint on the Network Latency Time in a purely IEEE 802.15.4 environment. A novel definition of reliability of data acquisition in this context is also provided. Using the simulation results it has also been demonstrated that using the Layer based approach and the new definition of neighbours, as mentioned in LTCRDM, has a significant

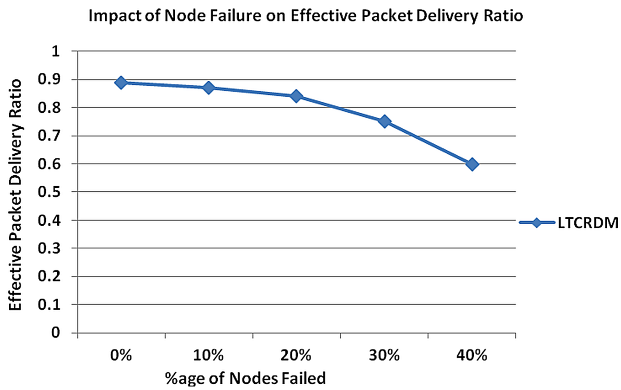

Figure 12. Impact of Node Failure on Effective Packet Delivery Ratio with LTCRDM

impact on the Network Latency Time of the Network orienting it towards the needs of a WSAN where this parameter is critical. Since the algorithm presented does not perform any complex calculations it can be safely concluded that it places no stress on the limited computational capabilities of the node. Similarly since the various tables mentioned in the algorithm are used to store information regarding immediate neighbors only and not the end-to-end path, it meets the constraint of memory resources of the nodes. The results also indicate that the effective reliability of data acquisition is maintained within a reasonable degree with increase in the number of nodes deployed. The fault tolerance capability of the algorithm is also observed based on the simulation results and the graceful de-gradation of performance indicates the reliability of the algorithm. The initial hypothesis that only increasing the number of alternate paths will not improve the effective reliability of data acquisition has also been proven as it has been demonstrated that having larger number of neighbors could actually reduce the effective reliability as the time constraint on T_{NLT} may not be met.

Future Work

The algorithm and mechanism demonstrated are specifically designed for the Centralized Decision making configuration i.e. with Centralized Sink. However the same with modifications could be adapted for the distributed Decision making configuration. The authors intend to study and demonstrate the same in immediate future.

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