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ENERGY AWARE CORONA LEVEL BASED ROUTING APPROACH FOR IEEE 802.15.4 BASED WIRELESS SENSOR NETWORKS

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Abstract

Wireless Sensor Network test-bed consists of miniaturized sensor motes deployed over a monitored environment (indoor/outdoor) and controlled by a remote gateway or sink. These sensor motes are capable of sensing, processing, transmitting/receiving/forwarding payload containing processed data. These motes are programmed to either send burst data upon triggered events or periodically transmit their sensed data. The sensed data are transmitted directly or via multi-hop to the sink for data collection, monitoring and take remedial actions if necessity arises. Since the motes are low power IEEE 802.15.4 battery driven radios, their transmission range is limited and hence multi-hop transmissions become necessary. This work aims to design and implement in real time an energy-aware, multi-hop hierarchical (based on corona levels) routing protocol, using the SENSEnuts platform. In the network setup phase, sink floods a control

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packet to the neighboring nodes and they in turn disseminate/re-broadcast continuously till it reaches the entire network. The nodes identify the levels in which they belong and also choose/sort parent nodes based on link quality to reduce packet drop over multiple hops. This work attempts to reduce the problem due to implosion by using sleep mode to avoid redundant reception during network setup phase. The energy savings achieved through doze mode is calculated based on radio specifications and compared with the existing Level Based Routing protocol implementation available on SENSEnuts [1] protocol stack (developed by Eigen Technologies).

***Keywords*:** Routing; Link Quality; Corona Level ; Doze Mode; Implosion ; Flooding

1 INTRODUCTION

Wireless ad hoc and sensor networks is a core branch of communication networks which lacks a fixed wireline infrastructure. Efficient and seamless inter-communication between wireless (mobile) sensor devices is active research area as it is subjected to resource constraints such as power, bandwidth and memory [2]. Direct communication between any two wireless sensor nodes deployed in the networks may not be possible and the need for multi-hop routing arises. The traditional OSI model layering approach is criticized to apply in wireless networks and the need to exploit any layer information at any level becomes a necessity (cross layer design) for overall network performance [8-9].

To achieve good Quality of Service (QOS) in Wireless Sensor Network, OSI layers have to jointly collaborate to make correct decision due to highly unreliable channel conditions. Shortest path routing strategies will not work in wireless scenarios as choosing a neighbor that lies at the edge of source's transmission range may lead to huge packet loss due to the varying channel conditions. However obtaining the quality of wireless link from the physical layer and use it as routing metric for selecting the next hop neighbor would improve the packet delivery ratio. Another example in case of Transport Layer is the Transmission Control Protocol (TCP).

TCP may conclude the nodes failure as congestion in the network and would reduce the data rate. Hence efficient design and analysis of cross layered frameworks in wireless sensor networks is needed.

WSN applications either send data continuously or sparsely when an event is triggered. Zigbee alliance has designed network layer adhering to IEEE 802.15.4 PHY/MAC layer specifications. This enables to support numerous WSN applications because of its low power, low data rate design such as smart home monitoring, patients care (Health) monitoring, Industrial monitoring control, Environmental, Military, Event Detection etc. WSN consists of sensor nodes which are capable of sensing, computing and communicating via Zigbee RF transceiver and are powered mainly through batteries. To prolong the sensor nodes battery life, design of efficient algorithms which will have less computational complexity and communication cost becomes necessity. Most of the energy consumption happens in the communication module and rest depends on the processing module.

Reporting the position of the sensor node to the sink has been a mandatory requirement in many applications. Inbuilt GPS receivers or Localization Algorithms are used to compute 2D/3D location. The location information is included in the reported data to take appropriate action at the appropriate time and avoid any disaster or service the requirement accordingly. However there is enormous overhead for location estimation using Localization algorithms. The existing GPS driven solutions are power hungry and not suitable for constrained tiny battery driven sensor motes.

This work focuses on to design and implement Layer 3 routing protocol in hardware sensor mote IEEE 802.5.4 radio driven platform named SENSEnuts [3] with the following objectives

- Efficient Routing Tree construction with respect to PAN coordinator to avoid problems of implosion (due to flooding).
- Next Hop (in forward transmission) and Parent selection (in reverse transmission) based on current status of wireless link (link quality computation).
- Incorporation of sleep schedules to avoid unnecessary

redundant reception and achieve energy savings.

- Increase capability of handling dynamic topology changes due to unreliable channel conditions, node failures.
- Enforce load sharing to avoid overloading particular nodes.

The idea of work is to propose a flexible tree based hierarchical networking Solution, reducing human intervention for numerous WSN monitoring and control applications such as low power WSN and IoT solutions, covering larger areas through multi-hop solutions. Wireless Sensor Networks are being used in a wide range of environmental based applications, and most of the time the geographic location of the nodes are not easily accessible. Therefore, this makes it difficult to replenish node batteries, service faulty nodes or to replace dead ones. So nodes lifetime in a network could be critical to ensure coverage of the area being monitored. Hence, extending the life of a sensor mote and thereby the network is essential to increase the efficiency of the network. Our project aims to enhance the existing level based routing implementation in SENSEnuts protocol stack so as to maximize the network coverage and node lifetime by using minimal resources.

2 RELATED WORK

In this section, Routing algorithms proposed in literature are categorized as Pro-active, Re-active (On-Demand) protocols [10-11]. Proactive routing is not applicable for wireless sensor network as it is not scalable and energy efficient. The overall network maintenance of each node tracking all nodes in table by sharing their routing tables adds to the space complexity owing to severe memory constraints of sensor node. Though it minimizes the delay in sending critical data, it fails in other major requirements of WSN

Periodic beaconing consumes more energy as periodic Hello messages is sent to track neighbors in the table. Reactive routing, on the other hand finds a route on-demand and only when need arises to send data. This category of routing is relatively scalable and energy efficient for wireless sensor network applications. Owing to dynamic topology in WSN, on-demand schemes are efficient. However protocols like Ad-hoc On-demand Distance Vector (AODV) and Dynamic Source Routing (DSR) [4-5] floods the network by broadcasting control packets to form an end-end route. This creates additional control overhead and more power consumption. Numerous works are proposed in literature to restrict the flooding by means of Location information [6,15]. Zigbee adopts modified AODV using link quality as the metric and but fails to justify the control overhead and energy consumption in the network [14]. Geographical based beaconless routing protocols which are almost stateless can be a better option [16].

Greedy design technique was the first approach adopted in Geographic routing [7]. Though this has served as the base for all future approaches [15-17], choosing the maximum distance forwarding neighbor always makes it loaded heavily compared to other neighbors. Also link quality is not considered as routing metric which causes packet/energy loss. Geographic routing also faces a problem when no eligible forwarding nodes exists and switches to perimeter/face routing as proposed in literature[7]. Geographical routing solutions ignores the overhead involved in location computation.

Najet Boughanmi [14] tuned the Zigbee modified AODV to prolong the life time of the network. The residual energy of the sensor node and the bounded end-end delay were the new proposed metrics to achieve load balancing in the network. However the control overhead due to periodic beaconing, route setup maintenance are the issues found.

Adel Ali Ahmed [13] uses geographical information of nodes and restricts number of forwarding neighbor nodes reply by estimating quadrant dynamically and allowing only nodes in that region to reply. Though multipath routing and dynamic power control mechanism is proposed, the computational complexity is severe in this design.

3 ALGORITHM DESIGN

A. Existing Level Based Routing (LBR)

The Existing Implementation in SENSEnuts Level Based Routing can be used when destination is PAN Coordinator (Sink). The protocol initiates with an assumption that the MAC layer will take some time to setup throughout the network. The routing process initiates when the timer expires for which the task is added to be executed after the time assumed for the setup.

1. When the timer expires, PAN Coordinator sends a packet in the network with its level (hop) set to '0'.
2. All the nodes which are in range of PAN coordinator receives the packet and set their level to '1' after which, they rebroadcast the packet
3. The next hop now may receive the packets from multiple nodes in level '1'.
4. Each node saves the information of four nodes (at max) and set their level as '2'
5. They do a rebroadcast only for the first packet received from level '1'. This is how each node gets a level and saves the information about the nodes in previous level.
6. Now to send a data packet to the previous level, the node follows the Round Robin principle between the nodes in the previous level whose information is saved in its memory (which can be four at max).
7. This may help in saving the battery and hence increase the network lifetime

B. Enhancements in existing LBR Corona Based Level Based Energy Aware Hierarchical Routing Protocol Design

1. Existing LBR is a pure flooding process for creating the routing tree where every node has to rebroadcast and associate to their corresponding level

- It would create implosion
- Nodes at Level 'i' would get multiples copies of packets from multiple parents at Level "i-1"
- Nodes at Level 'i' would also receive multiple copies of packets from the next level "i+1" unnecessarily

2. Radio module specification (of SENSEnuts) specifies Rx current 17mA (current drawn when receiver is on) and Tx current 15mA ;

   - Since the nodes are always ON ; this would consume more energy at Layer 3 (for receiving packets / transmitting packets depending on time taken to transmit/receive)
   - **Solution incorporated in Corona Level Mechanism:** Nodes are explicitly made put to sleep (doze) mode for fixed configurable value of time units once they rebroadcast packet to avoid unnecessary receptions.

3. Round Robin Fashion of Parent Selection would distribute the Load but can lead to packet loss due to poor link quality

   - Solution incorporated in Corona Level Mechanism: Hence Parent Selection can be based on Link Quality (mapped based on Received Signal Strength Indicator) sorting of entries in descending order based on Link Quality

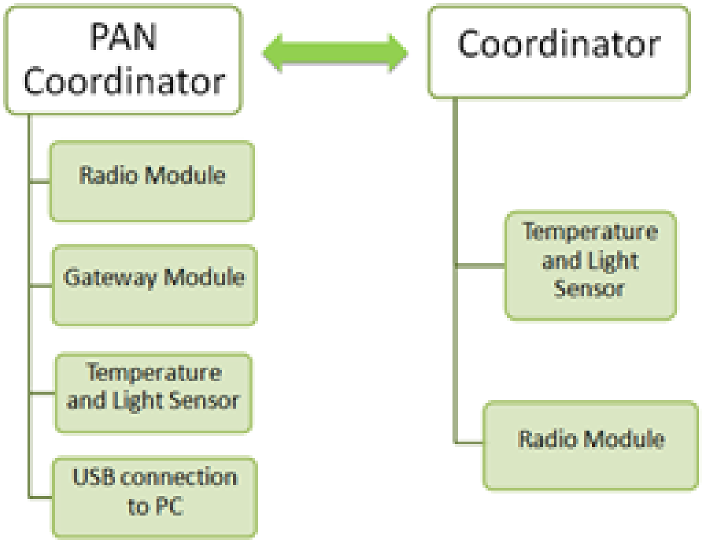

Fig 1: Hardware Modules Used

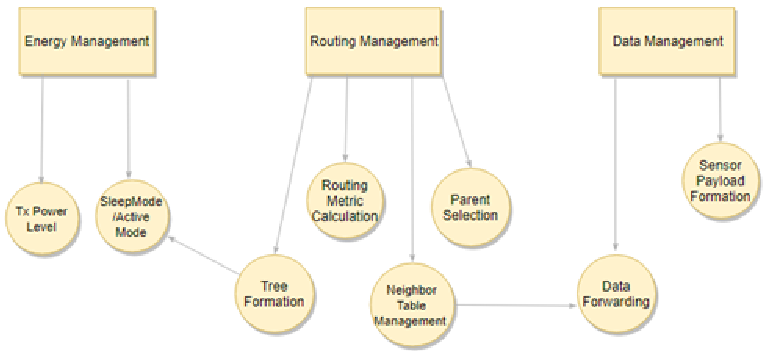

Fig 2: Management Modules

C. Parent Selection

Corona Level represents the concentric circle of uniform width with respect to the sink. The relative distance of any node w.r.to sink is based on transmission range 'r' for selected Optimal Transmit Power Level multiplied by level at which node resides.

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Selection of a parent node in a level higher than the current coordinator is being done by comparing the link quality of the available paths and choosing the highest link quality among them. When the network is being set up, every coordinator saves up to four node IDs of coordinators in the higher level and their corresponding link qualities. Every time a node has to relay data, it compares the stored link quality values and chooses the highest of them. This happens at every node a data packet arrives at, eventually finding an optimal path to the PAN Coordinator. SENSEnuts radio module can transmit at four power levels available (-32dBm, -20dBm, -9dBm, 0dBm). Range testing has been done for all the four power levels and this information has been used to decide optimum distance of separation between the nodes and static placement and deployment. Link Quality between two nodes can affect the packet delivery, where poor link quality could lead to packet drop and hence unnecessary consumption of energy. Link Quality is inversely proportional to distance between the nodes. During parent selection, the nodes in the upper level that are closer to the node that is transmitting data would have better link quality. Unwanted battery consumption occurs when idle nodes are constantly scanning the network for data transmissions. This can be avoided by switching the nodes to low power/sleep mode. After broadcasting the setup packet, the nodes in the upper levels can switch to sleep mode for a minimum time duration, during which no data meant for that particular node could be received. They are then brought back to normal mode of operation. These fixed periods of sleep help extend battery life.

The Coordinator records the temperature and light data from the surroundings and embeds them into packets, which are then sent to the PAN Coordinator. It also relays the setup packet to the lower levels during network formation and data packet to the upper levels.

D. Sleep Implementation

During set-up broadcasts, every node re-broadcasts the set-up packet, after incrementing level information to, the next levels. The problem of implosion occurs, wherein neighboring nodes or

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previous level nodes overhear packets unnecessarily and begin processing the same thereby using up energy that can otherwise be saved up. So the clock frequencies of the intermediary nodes are reduced to their minimum 1MHz in an attempt to save energy at every node. The normal operating clock frequency of a SENSEnuts node is 16MHz and it consumes 500mA current when processing data. In the low-power mode (1MHz frequency mode); only 1.7mA is consumed.

E. Technical Specifications

SENSEnuts Radio Module: The JN516x is an IEEE802.15.4 wireless microcontroller that provides an integrated solution for applications using the IEEE802.15.4 standard in the 2.4 - 2.5GHz ISM frequency band. The SENSEnuts Radio Module has the following specifications

- 32 bit microcontroller with up to 32 MHz clock speed. (1, 2, 4, 8, 16, 32)
- 256KB flash, 32KB RAM, 4KB EEPROM.
- Up to 20 Digital inputs/outputs available.
- 10-bit 4-input ADC for Analog to Digital conversion.
- UARTs, 1 SPI (with 3 selects), 1 I2C port and 5 PWM.
- 128-bit AES security processor.
- Dynamic controllable transmission power (-32dBm to 0 dBm).
- Low TX current(15.3 mA) and RX current(17 mA)

Gateway Module

- Connects the network and data collection system via USB.
- Also used to program the nodes.
- Usually connected to PAN Coordinator during data collection process.

- Data Transfer rate of 115200 baud.
- Disconnects battery and provides power to node if both battery and gateway are connected to the node.

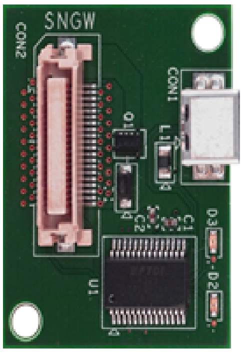

Fig 3 : Gateway Module

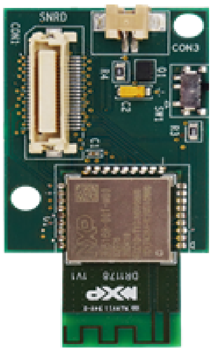

Fig 4 : Radio Module

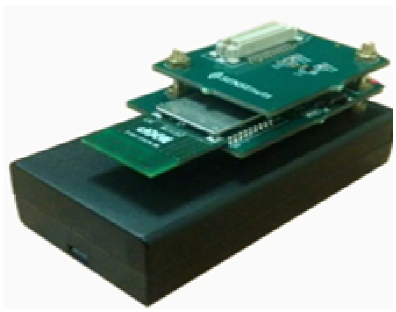

Fig 5: SENSEnuts Platform

4 IMPLEMENTATION ANALYSIS

The implementation of the Energy Aware Hierarchical Routing Protocol has been observed to exhibit the following outcomes

A. Range Testing

The maximum transmission range has been tested for all the four available transmit power levels.

Fig 6: Range Testing

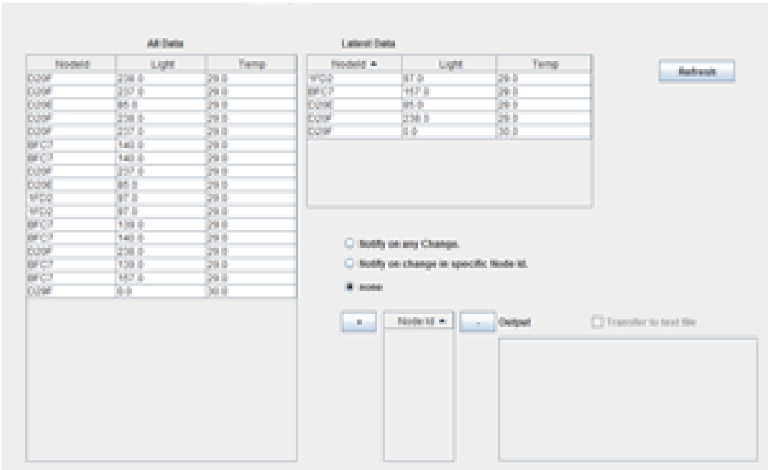

Fig 7 : SenseNuts Live Data Results

Table 1: Transmission Range

Transmit Power Level	Maximum Range
-32dBm	1.5 ± 0.2m
-20dBm	6 ± 1.2m
-9dBm	20 ± 5 m
0dBm	60 ± 10 m

B. Multi-hop Live Data Testbed setup

When coordinators were placed beyond the transmission range of another node, they communicated via multi hops.

Fig 8: Multi-hop Testing

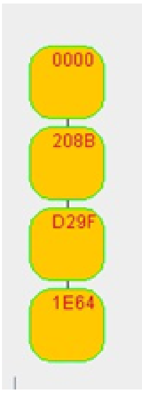

Fig 9 : Multi-hop Topology in SENSEnuts GUI

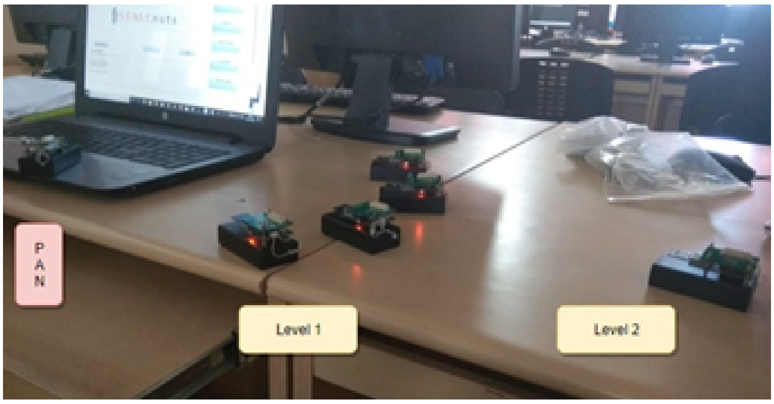

Fig 10 : Multi-Corona Level Deployment for lowest -32dbm Tx Power Level

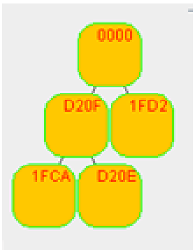

Fig 11 : Network Topology in SENSEnuts GUI

C. Energy Consumption Analysis

Node 1 is source which transmits the packets. The packets transmitted by node 1 are received by node 2 and node 3. So node 1 acts as the transmitter, whereas, node 2 and node 3 acts as the receiver.

E_T: Energy consumed by node 1 during transmission from node 1 to node 2 and node 3
E_{R21}: Energy consumed by node 2 during reception from node 1
E_{R31}: Energy consumed by node 3 during reception from node 1

Assumptions: During the times when a node is neither transmitting nor receiving (idle mode), the CPU in SENSENUTs nodes are in low-power mode which consumes approximately 1.7mA current. When CPU is on its active mode, it consumes nearly 4.5mA current. These values of currents will always be present and the results that would be obtained would include the energy consumed because of these currents. These values would be added to the voltage level calculations for transmitter during transmission and for the receivers during reception. The PAN Coordinator transmits a set-up packet every 8 seconds; this brings up. Due to random micro-delays, there is an assumption made that a maximum of 15 data packets are sent per minute.

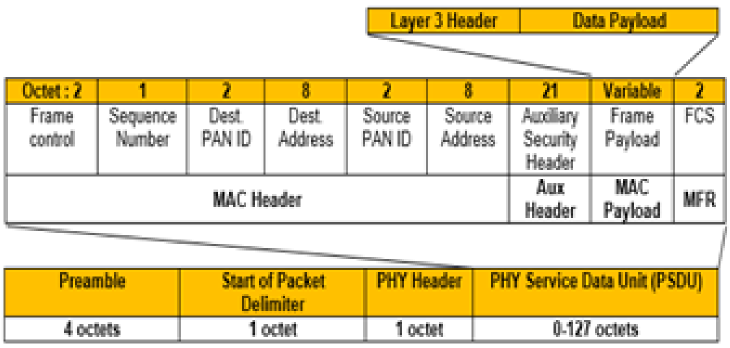

Fig 12 : IEEE 802.15.4 Frame Format Header(s)

Data Frame size and period

- Physical Layer payload = 6 bytes
- MAC Layer header = 23 bytes
- Payload (sensor data) = 6 bytes
- Payload (set-up packet) = 2 bytes
- 23+6+2 = 31 bytes for Set-up Packets
- 23+6+6 = 35 bytes for Data Packets
- Data rate = 250 kbps
- Data frame transmission period = (6+23+6) * 8/250 = 1.12ms per data frame

- Set-up frame transmission period = (6+23+2) * 8/250 = 0.992ms per set-up frame
- Total Bits Transmitted = (45*35*8) + (21*31*8) = 17808bits
- Packet Rate = 22 packets per minute
- Total time = 180 seconds
- Number of Packets for Analysis : 7 set-up + 15 data = 22 packets per minute

Charge during Low Power (Doze) mode
Total current used when clock is at 16MHz Clock cycle = 500mA
Total current used when clock is at 1MHz Clock Cycle = 1.7mA
Transmitter Node
Total transmission time for 66 frames = (1.12ms *45) + (0.992ms *21) = 71.232ms
Current consumed during transmission = 15.3mA
Total time in doze mode = 21000ms (1 second after every set-up broadcast)
Current consumed during doze mode = 1.7mA
Charge consumed during transmission (Q1) = 15.3mA *71.232ms = 1.089mC
Charge consumed during doze mode (Q2) = 1.7mA *21000ms= 35.7mC
Average voltage of node = 3V
Average power consumed by the source (transmitter) = 3*204.38μ= 0.613mW
Average energy needed (ET) = 0.613mW*180 = 0.110 J
(ET)per bit = 0.110/17808 = 6.177μJ per bit
Total Charge consumed = Q1 + Q2 = 36.789mC
Average current consumed =
Total Charge Consumed/ Total Time =36.789mC /180s = 204.38μA
When node is not in doze mode, charge consumed during that time
= 15.3mA *21s = 0.321C
Average current consumed = 0.322/180 =1.789mA
Average power consumed = 3*1.789m = 5.367mW
Average energy needed (ET) = 0.966 J

(E_T)per bit = 0.966/17808 = 54.245μJ per bit
Energy Savings at the transmitter = 54.245μ - 6.177μ = 48.068μJ/bit
Receiver Node
Total Reception Time = Total Transmission Time
= (1.12ms *45) + (0.992ms *21) = 71.232ms
Total processing time = 1ms
Total propagation delay (at -32dBm power level) = 1.5m/3*108mps = 5ns
(Propagation delay is thereby negligent.)
Total time at receiver = 71.232 + 1 = 72.232ms
Total time in doze mode = 21000ms (1 second after every set-up broadcast)
Current consumed during reception = 17mA
Current consumed in doze mode = 1.7mA
Charge consumed in reception = 17mA *72.232ms = 0.463mC
Charge consumed in doze = 1.7mA * 21000ms = 35.7mC
Total Charge = 36.163mC
Average current consumed =
Total Charge Consumed/ Total Time = 36.163mC/180s = 0.201mA
Average voltage of receiver = 3V
Average power = 0.201mA *3V = 0.603mW
(Energy Consumed) node 2= ER21= 0.603mW *180= 0.109J
E_{R21}per bit = E_{R21}/ total bits received = 0.109/17808= 6.129μJ/bit
Average Energy at Receiver Node (ER) = 6.209μJ/bit

When node is not in doze mode, charge consumed during that time
= 15.3mA *21s = 0.321C Average current consumed = 0.322/180 =1.789mA
Average power consumed = 3*1.789m = 5.367mW
Average energy needed (ET) = 0.966 J
(ET)per bit = 0.966/17808 = 54.245μJ per bit
Energy Savings at the receiver = 54.245μ - 6.209μ = 48.036μJ/bit
Therefore, as analysed, the energy savings are visibly significant even though doze mode comprises of 11.67% of total time.

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