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Abstract

Many applications of Wireless Sensor Networks such as Airborne Ad-hoc Networks (AANETs) or Underwater Wireless Sensor Networks (UWSNs) require the network architecture to be three-dimensional. In this paper, we present a terrestrial three-dimensional network architecture as well as protocol stack deployment for static sensor nodes placed at varying heights. A Dynamic Cluster-Based TDMA MAC (DCB-TDMA MAC) protocol has been developed for this network and simulated using Cooja platform. Cluster-Head nodes are rotated based on residual energy in order to maximize the lifetime of the network. Detailed working of protocol involving Time Synchronization, MAC, Cluster-Head rotation, Dynamic Routing is provided in this paper along with simulation results and analysis.

Keywords: Three-Dimensional Wireless Sensor Networks; Time Synchronization; TDMA MAC Protocol; Cluster Head Rotation.

1. Introduction

A Wireless Sensor Network (WSN) is comprised of large number of sensor nodes, densely deployed in an ad-hoc manner. Sensor nodes are equipped with sensing, processing and communication capabilities. They are also supported by limited stand-alone source of power making them suitable for random field deployment. Because of their versatility, WSNs are opted for different scenarios varying from critical applications such as military surveillance, health-care monitoring to non-critical applications such as environment monitoring, structural health monitoring and precision agriculture.

In most application scenarios, WSN is deployed in a two dimensional (2D) pattern, taking into account the \( x \) and \( y \) co-ordinates alone but ignoring the depth/ height (\( z \)) co-ordinate since the network is considered to operate at ground level. But the additional dimension (that is deployment along depth/ height) cannot be neglected when the application scenarios include underwater/ airborne deployment of network where it plays a vital role. Addition of the third dimension opens a door of opportunities for different application scenarios such as ocean monitoring, weather forecasting, climate monitoring and mine monitoring. Deployment along the height/ depth also introduces additional challenges which generally are not addressed in the protocol stack development of 2D networks. Nodes in 3D networks are scattered in the area resulting in much lower density than that of 2D networks. AANETs and UWSNs cover most
of the 3D WSN space and they are equipped with limited power sources. Replenishment of power source for individual node is not possible because of the difficulty in accessing the nodes. In this way, 3D networks are bound by stringent energy consumption requirements to prolong network lifetime.

In this paper, we have developed a protocol stack for three dimensional (3D) WSN. Protocol stack’s development in WSN is application specific since it is defined by the environmental conditions and constraints of the application scenario. Network topology also creates a large impact on overall protocol stack design and energy consumption. Here, we are assuming that static 3D architecture of the network is deployed at various heights in the form of clusters. Such a design can be useful for health monitoring of structures such as bridges or buildings. It can also be utilized for long-term pollution monitoring in the target 3D field. We have assumed that nodes provide full network coverage and are aware of their location using GPS.

Among various layers of the protocol stack of WSN, Medium Access Control (MAC) protocols play a pivotal role in avoiding collisions in the network, sharing communication medium in fair and efficient manner and increasing the energy efficiency of the network resulting in prolonged network lifespan. MAC protocols for WSNs can be broadly classified into two categories: Contention based and Schedule based protocols.

Contention based MAC protocols are based on Carrier Sense Multiple Access (CSMA). They have advantages in terms of adaptability to variation in node density, traffic load and changes in topology. Disadvantages are that, they are non-deterministic in nature, waste energy in idle listening, contention resolution and over-hearing. Variations of CSMA based protocols such as PAMAS, B-MAC, WISEMAC, Sift use various topology-control integrated with CSMA or CSMA/CA to reduce the energy consumption in the network.

Among various schedule based protocols such as FDMA, CDMA, TDMA based protocols, TDMA based MAC protocols can exploit advantages in terms of simplicity, fairness and energy efficiency. Collisions, idle listening and over-hearing can be avoided in these protocols. Hidden node problem is easily solved without using an extra message overhead because neighbouring nodes transmit at different time slots. Channel utilization can be significantly improved if parallelism in communication is allowed. These concurrent transmission schemes can be exploited using proper channel reuse concept already available in cellular mobile networks. Slots can be reserved for future expansion and can be allocated on dynamic basis to address the scalability issue. If we assume structured deployment and deterministic scheduling scheme with known traffic patterns, then any simple or energy efficient time synchronization can suffice in TDMA MAC protocol, since it will provide an upper bound on the propagation delay in the network.

Our network takes into account 3D hierarchical topology of the network comprised of N layers. Each layer consists of certain fixed number of nodes initially, with one of the nodes acting as a Cluster-Head node. Each node is allotted a time slot of constant duration in order to transmit or receive the data. Certain time slots are kept idle (or vacant during initialization phase of network), which can be utilized to expand the network in future with addition of new nodes. As the time progresses, nodes dissipate energy, while maximum energy is consumed by Cluster-Head nodes. In order to balance the energy consumption, we have implemented a Cluster-Head rotation policy based on energy consumption of nodes.

To simulate our proposed 3D WSN, we have used Cooja software platform which is provided by Contiki. Unlike other network simulation tools which recreate the operation or behaviour of the WSN but may not necessarily abide by all of the rules of the network being simulated, Cooja is an emulation tool capable of emulating Tmote Sky/ Telos-B and many other nodes in the network. Cooja allows device level and network level simulation.

Paper is organized as follows: In section 2, we provide a brief description of the proposed lightweight time synchronization protocol, since time-synchronization is essential for TDMA based MAC protocol. In section 3, we describe the architecture of proposed 3D terrestrial WSN. Section 4, gives detailed implementation of proposed protocol, which includes Dynamic Cluster-Based TDMA MAC (DCB-TDMA) protocol, Cluster-Head rotation and Dynamic Routing. In section 5, we provide the simulation results and analysis of this protocol using Cooja platform. Section 6 provides conclusions.

2. Time Synchronization

The purpose of time synchronization protocol is to maintain a common time base within a certain tolerance in the network. The precision of the synchronized clock depends on the requirement of the application. Time synchronization
includes three primary techniques. Type I technique relies on fixed time servers for synchronization of the network in which all the nodes are directly synchronized with servers having precise time values. Type II technique takes translating the time throughout the network into account where time synchronization is achieved in hop by hop manner in the network and in the Type III technique, the nodes do not rely on dedicated time servers. Temporary master nodes are elected to synchronize the nodes in the network. Commonly used time synchronization protocols in WSN include, Network Time Protocol (NTP), Timing-sync Protocol for Sensor Networks (TPSN), H-sensor Broadcast Synchronization (HBS), Time Synchronization for High Latency (TSHL), Reference-Broadcast Synchronization (RBS), Adaptive Clock Synchronization, Time-Diffusion Synchronization Protocol (TDP) and Adaptive-Rate Synchronization Protocol (ARSP).

In our protocol stack, we have implemented Multihop Tri-Message Time synchronization protocol for time synchronization. This protocol is suitable for hierarchical cluster based networks. Single Tri-Message synchronization process involves the least amount of message transfer in any given time synchronization protocol scheme, leading to increased energy efficiency of the network. Multi-hop-Tri-Message Time synchronization is a coarse grained time synchronization protocol which was originally developed for high latency network such as Underwater Acoustic Sensor Network (UASN). For better accuracy in our protocol, tri-message protocol can be replaced with fine grained time synchronization protocols. In Tri-Message synchronization there are two nodes, Node $N_1$ and Node $N_2$. $N_1$ is considered to be the originator of Tri-Message synchronization and assumed to have synchronization with the global clock. In the first Tri-Message synchronization phase, $N_1$ transmits first message to $N_2$ at time $T_1$. $N_2$ receives this message at time $T_2$. In the second phase, $N_2$ sends the message back to $N_1$ at time $T_3$, which is received by $N_1$ at time $T_4$. Finally in the third phase, $N_1$ transmits the third message at time $T_5$. In this message $N_1$ includes the time stamp $T_4$ and $T_5$. $N_2$ receives this message from $N_1$ at time $T_6$, which completes the Tri-Message synchronization process. After the completion of this process, $N_2$ has all six timestamps available with it. Time gap between $T_2$ and $T_3$ is considered to be processing time for $N_2$. Similarly, equal duration gap between $T_4$ and $T_5$ is the processing time for $N_1$. Figure 1 shows Tri-Message synchronization between two nodes Node $N_1$ and Node $N_2$. Clock skew ($\beta$) and offset ($\alpha$) in the Tri-Message synchronization protocol can be calculated with following equations:

$$\beta = \frac{T_6 - T_2}{T_5 - T_1}$$  \hspace{1cm} (1)

$$\alpha = \frac{(T_2 + T_3)}{2} - \frac{\beta(T_2 + T_3)}{2}$$  \hspace{1cm} (2)

At the end of Tri-Message synchronization, $N_2$ transmits fourth message to $N_1$ which includes clock skew and offset parameters calculated from earlier equations. Overall time synchronizing one node involves exchanges of four messages inclusive of two transmit and two receive messages by each node. Once the destination node, $N_2$ has got time synchronized, it can further synchronize another node situated one hop away, effectively providing Multihop Tri-Message time synchronization.

3. Proposed Network Architecture

In our scenario, we have implemented 3D WSN architecture with static node positions arranged in the form of multiple clusters. As shown in Fig. 2, this topology encompasses a cylindrical space with the height of 600 m.
and diameter of 50 m. At every 200 m height, a cluster of nodes is deployed consisting of ten nodes including a Cluster-Head node. At the very bottom of this topology, we have a Base-Station node (BS) which is connected to power source. Overall, we can categorize the nodes in this topology into three categories namely.

1. Base-Station node (BS node)
2. Cluster-Head node (CH node)
3. Cluster-member nodes or simply Cluster-nodes (CN)

Responsibilities of these nodes are as follows

1. **Base-Station node** – Base Station (BS) is the sink node and also the originator for time synchronization. This node sends control messages to the CH node immediately above it. Control message includes time synchronization message, topology update message (node addition/deletion) etc. On the reverse link BS collects the data information from the CH above it.

2. **Cluster-Head node** – This node receives the control information from the CH node below it in the hierarchy (or from the BS in case of first CH node). After receiving the control information from the CH below it, the current CH node sends the control information to CH above it in topology. Also, the control information is percolated to all the cluster-nodes of its own cluster. On the reverse link, CH collects data information from all its cluster-member nodes and forwards this data to CH below it after appending and aggregating its own data.

3. **Cluster-member nodes** – These nodes receive the control information from the respective CH node of its cluster on the forward link. On the reverse link these nodes send the data to the CH node in their respective time slots.

In the architecture shown in Fig. 2, we have implemented 3 clusters at height of 200m each from ground. Each cluster consists of 10 nodes inclusive of CH node. Additional nodes can be dynamically added to this topology. The Base Station (BS) is termed as $N000$. The nodes in the cluster 1 are termed as $N100, N101, N102$ and so on till $N109$, wherein $N100$ is initially acting as CH of Cluster 1 i.e. CH1 node. Nodes in Cluster 2 are termed as $N200, N201, N202$
and so on till N209, while N200 is initially appointed as CH for Cluster 2 i.e. CH2 node. Similarly nodes in Cluster 3 are termed as N300, N301, N302 and so on till N309, with node N300 acting as CH3 in the cluster. Each cluster has provision to accommodate additional maximum five nodes at a time. Each node is assumed to be a Telos-B mote with an AA battery. It is possible to control power levels of Telos-B motes in order to transmit (or restrict transmission) to a particular range. Here we have chosen two different power levels for each node which can be dynamically changed at run-time. Using power level $P_l$, a node can transmit up to 25 meter distance and using power level $P_h$, it can transmit up to 200 meter distance.

4. Proposed Protocol Implementation

We have implemented Dynamic Cluster-based TDMA MAC (DCB-TDMA MAC) protocol on 3D wireless sensor network. This protocol is implemented by dividing the common period into cycles (Master cycles), which repeat at regular interval of time. Each master cycle consists of three phases,

1. Control cycle phase
2. Data Cycle phase
3. Sleep phase

Each node has a bidirectional communication link. Master cycle starts with control cycle phase, wherein BS first transmits the control message (For example, time synchronization message) to the CH1 node. Here, a Tri-Message time synchronization is implemented as described in section 2. Synchronizing CH1 node will consist of transmission and reception of two messages each, totally consuming 4 time slots. After getting time-synchronized with BS, CH1 node synchronizes Node CH2. Node CH2 further synchronizes Node CH3. This chain of nodes starting from BS-CH1-CH2-CH3 is termed as backbone link of the network. Since the distance between the nodes on this vertical link is about 200 meters, nodes have to transmit these control messages using power level $P_h$.

Once the CH nodes are time synchronized, these nodes start the synchronization process with respective cluster-member nodes one-by-one in sequence. While synchronizing node at a horizontal distance of 25 meters, CH node utilizes a power level $P_l$ for transmission. Utilizing a lower power level effectively reduces the level of interference with the nodes in other adjacent clusters. This means, that when a CH1 node (N100) is synchronizing the first CN node in its cluster (N101), during same period CH2 node (N200) can synchronize the first CN node (N201) in its cluster, and CH3 node (N300) can synchronize the first CN node (N301) in its cluster. This parallel transmission scheme is possible because of effective interference management, which can be compared with the concept of cellular communication in the mobile communication field. Here, after synchronizing the first node, each CH will synchronize sequentially next node in the cluster, till all nodes are synchronized.

After completing the time-synchronization, control cycle ends and data cycle begins. Each node now sends the sensor values collected over sensing interval. Nodes are allowed to only transmit in their respective time-slot. Each cluster-member node has to transmit data only to its CH node at horizontal distance of 25 m. By using lower power level $P_l$, nodes of various clusters can transmit their data in parallel to respective CH node. For example, when Node N101 is transmitting data to CH1 Node N100, Node N201 can transmit data to CH2 Node N200, Node N301 can transmit data to CH3 Node N300. In this way, data will be collected from all nodes of each cluster at respective CH nodes. After collecting data at CH nodes, a backbone link of the network can be utilized to send data towards BS on reverse link. That is, collected data can be transmitted using link CH3-CH2-CH1-BS. Each CH can append its data or perform aggregation on the collected data. In the simulation, we are simply averaging the values, so as to keep the data packet size same throughout the simulation for the sake of simplicity.

It is obvious that the backbone link is very important for the working of this protocol and failure of the link owing to poor channel conditions, hardware issues might lead to the complete breakdown. We can overcome this problem by utilizing proper recovery procedure in case any node along the backbone link is non-responsive. Generally, every control cycle starts with the time synchronization, which essentially is a message exchange between two nodes. If the CH node is not responding to the time synchronization, multiple attempts are made. After certain fixed number of attempts, BS can appoint a new CH for the current and subsequent cycles. New CH node can be chosen run time based on the available energy with the node.
4.1 Additional Features of DCB-TDMA MAC

In a Control cycle, distinct types of control information can be transmitted as per the requirement of the network. Various types are – a) Node addition information, b) Cluster-Head rotation information.

Node addition – In our protocol stack, every node has predefined time slot for time synchronization and for data transmit/receive. In Master Cycle, after control cycle phase we have kept a margin of time duration equivalent to time synchronization period for 5 extra nodes. Similarly, 5 extra vacant slots are available in the data phase. If the new node is not added, then this duration is sleep duration. When a new node is added, it occupies the required time slots from available vacant slots. In this way up to five nodes can be added in dynamic manner. Node addition is controlled and initiated with the help of BS. When a node has to be added in a cluster, BS sends the addition information to the Cluster-Head nodes during the control cycle. Cluster Head nodes forward this information to the corresponding nodes in the cluster. In this manner, nodes can be concurrently added in different clusters in the network.

Cluster-Head rotation – During every fifth control cycle, the nodes forward their data along with depleted energy information to their respective Cluster-Head nodes which can select the new Cluster Head for it’s cluster. The Cluster Head then forwards this information to the CH below in the topology. In the sixth control cycle, CH sends the ID of new CH of above clusters to rest of the nodes in it’s cluster. From seventh cycle onwards, the new CH takes effect in the network.

4.2 Calculation of time slot duration and energy consumption

Duration of the time slot can be calculated based on Packet Delivery Time (PDT) and achievable accuracy of the time synchronization. PDT can be obtained from Packet Transmission Time (PTT) and Propagation Time (PRT).

Packet Transmission Time (PTT) can be calculated as a ratio of Packet Size (PS) to Bit Rate (BR), where PS is in terms of bits and Bit Rate (BR) is in terms of bits/sec.

\[ PTT = \frac{PS}{BR} \]  

(3)

Propagation Time (PRT) is the ratio of Distance (D) and Speed (S).

\[ PRT = \frac{D}{S} \]  

(4)

Packet Delivery Time (PDT) is composed of PTT and PRT.

\[ PDT = PTT + PRT \]  

(5)

We can calculate the energy consumption of a node in the network by calculating the energy consumption in transmission and reception by a node. Energy consumption in transmission and reception of one packet having packet size PS (in bits) and BR (in bits/sec) is as follows

Energy consumed in transmission at power level \( P_l \)

\[ E_{TX}(P_l) = \frac{PS}{BR} * V * I_{TX}(P_l) \]  

(6)

Energy consumed in transmission at power level \( P_h \)

\[ E_{TX}(P_h) = \frac{PS}{BR} * V * I_{TX}(P_h) \]  

(7)

Here, \( I_{TX} \) stands for current drawn by the Telos-B mote while transmitting with power level \( P_h \) and \( P_l \) respectively. Energy consumed in reception

\[ E_{RX} = \frac{PS}{BR} * V * I_{RX} \]  

(8)

Here, \( I_{RX} \) stands for current drawn by the Telos-B mote while receiving.
Table 1. Various types of packets used in the network.

<table>
<thead>
<tr>
<th>Packet type</th>
<th>Link type</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Sync</td>
<td>Vertical</td>
<td>27 Bytes</td>
</tr>
<tr>
<td>Time Sync</td>
<td>Horizontal</td>
<td>29 Bytes</td>
</tr>
<tr>
<td>Data</td>
<td>Vertical</td>
<td>23 Bytes</td>
</tr>
<tr>
<td>Data</td>
<td>Horizontal</td>
<td>23 Bytes</td>
</tr>
<tr>
<td>Data + Energy</td>
<td>Vertical</td>
<td>24 Bytes</td>
</tr>
<tr>
<td>Data + Energy</td>
<td>Horizontal</td>
<td>27 Bytes</td>
</tr>
</tbody>
</table>

5. Result and Analysis

As mentioned in section 3, we have simulated a 3D WSN comprising 3 clusters of 10 nodes each. One node among these cluster nodes is appointed as CH in the initialization phase itself. Each node has predefined time slot. Protocol execution consists of repetitive master cycles, each master cycle is broken up into two parts: Wake Period and Sleep Period. Wake period is further divided into Control Cycle phase and Data Cycle phase. While the Nodes sleep during the Sleep period, all the nodes can sleep after scheduled transmission or reception in their pre-defined time slots. In the master cycle simulation, first phase is control cycle phase, in which all the nodes of the cluster are synchronized. After this control cycle phase, data is collected by the sink node (BS node) from all the nodes. We have added three more nodes in each cluster in the third master cycle and two more nodes in each cluster in fifth master cycle. Also, for the Cluster-Head rotation algorithm, we collect the energy information from all the cluster nodes in every fifth cycle. All nodes append the residual energy values along with the data in the data cycle phase. In the next master cycle, information about new CH nodes is percolated to all nodes in network. New CH takes effect from subsequent cycle. In this way, we have packets of variable sizes depending on the type of messages, such as regular time synchronization information, regular data packets, aggregated data packets and data packets piggybacked with energy information (Data+energy). Table 1 provides the list of packets with their type and respective sizes.

Bit Rate used for simulation is 20 kbits/sec. Considering the maximum distance of 200 m, maximum packet size of 29 Bytes, we can calculate PTT, PRT and PDT by using equations 3, 4 and 5.

\[
PTT = \frac{29 \times 8}{20 \times 10^8} = 0.01 \text{ sec}
\]

\[
PRT = \frac{200}{5 \times 10^8} = 0.67 \mu \text{sec}
\]

\[
PDT = 0.01 \text{ sec} + 0.67 \mu \text{sec} = 0.01 \text{ sec}
\]

Time slot duration for simulation is kept as 20 ms, since the time synchronization used is coarse-grained and it is assumed that data collection intervals are separated over large time intervals. We have used power levels 5 and 23 as power levels $P_l$ and $P_h$ respectively. These power levels have been selected based on the range of communication. With power level 5, a Telos-B mote can communicate till 50m distance while with power level 23, range of communication can be extended till 200 m. Based on the Telos-B data sheet\(^{21}\), current drawn during transmission ($I_{TX}$) at these two power levels is as follows

\[
I_{TX(P_l)} = 9.2 \text{ mA}
\]

\[
I_{TX(P_h)} = 15.2 \text{ mA}
\]

Current required for receiving the data ($I_{RX}$)

\[
I_{RX} = 19.7 \text{ mA}
\]

Telos-B mote operates on 3V batteries. Therefore, using equations 6, 7 and 8 energy consumed during transmission and reception can be calculated.
Table 2. Information of Cycle 1.

<table>
<thead>
<tr>
<th>Type of Node</th>
<th>CH1</th>
<th>CH2</th>
<th>CH3</th>
<th>CN1</th>
<th>CN2</th>
<th>CN3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node ID</td>
<td>N100</td>
<td>N200</td>
<td>N300</td>
<td>N105</td>
<td>N205</td>
<td>N305</td>
</tr>
<tr>
<td>No. of Packets Transmitted</td>
<td>23</td>
<td>23</td>
<td>21</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>No. of Packets Received</td>
<td>32</td>
<td>32</td>
<td>29</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Energy consumed in Transmission</td>
<td>8.152</td>
<td>8.152</td>
<td>7.16</td>
<td>0.894</td>
<td>0.894</td>
<td>0.894</td>
</tr>
<tr>
<td>Energy consumed in Reception</td>
<td>20.33</td>
<td>20.33</td>
<td>18.51</td>
<td>1.371</td>
<td>1.371</td>
<td>1.371</td>
</tr>
<tr>
<td>Total Energy Consumed</td>
<td>28.482</td>
<td>28.482</td>
<td>25.677</td>
<td>2.265</td>
<td>2.265</td>
<td>2.265</td>
</tr>
</tbody>
</table>

Table 3. Information of Cycle 5.

<table>
<thead>
<tr>
<th>Type of Node</th>
<th>CH1</th>
<th>CH2</th>
<th>CH3</th>
<th>CN1</th>
<th>CN2</th>
<th>CN3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node ID</td>
<td>N100</td>
<td>N200</td>
<td>N300</td>
<td>N105</td>
<td>N205</td>
<td>N305</td>
</tr>
<tr>
<td>No. of Packets Transmitted</td>
<td>33</td>
<td>33</td>
<td>31</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>No. of Packets Received</td>
<td>47</td>
<td>47</td>
<td>44</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Energy consumed in Transmission</td>
<td>11.372</td>
<td>11.372</td>
<td>10.387</td>
<td>0.938</td>
<td>0.938</td>
<td>0.938</td>
</tr>
<tr>
<td>Energy consumed in Reception</td>
<td>31.252</td>
<td>31.252</td>
<td>29.408</td>
<td>1.371</td>
<td>1.371</td>
<td>1.371</td>
</tr>
<tr>
<td>Total Energy Consumed</td>
<td>42.624</td>
<td>42.624</td>
<td>39.795</td>
<td>2.309</td>
<td>2.309</td>
<td>2.309</td>
</tr>
</tbody>
</table>

Table 2 provides the information about number of packets transmitted and received by nodes CH1 (N100), CH2 (N200), CH3 (N300), N105, N205, N305 in cycle 1. We have chosen one node from each cluster to illustrate the difference of number of packet exchanges compared to CH nodes. For all other cluster member nodes, the values remain same, since these nodes have the same functionalities. [Here, we denote node numbers N105, N205, N305 as representative cluster member nodes of cluster 1, cluster 2 and cluster 3 respectively.]

From column 2 of Table 2, it can be observed that number of packets transmitted and received by CH1 is 23 and 32 respectively. In control cycle phase of first cycle, CH1 has been time-synchronized by BS which involves transmitting 2 time-sync packets and receiving 2 time-sync packets in total utilizing 4 time slots. Later, CH1 node has time-synchronized CH2 node, occupying 4 time slots, 2 time-sync packet transmissions and 2 time-sync packet receptions. Each time-sync packet on the vertical link is of 27 bytes. CH1 has then performed time-synchronization for all 9 nodes on the horizontal layer consisting of total 18 packet transmission and 18 packet reception, each packet of the size 29 bytes. In data cycle, it first collects (receives) data packets from all 9 cluster member nodes, each packet of size of 23 bytes. CH1 later receives the data packet on the vertical link from CH2, having a packet size of 23 bytes. One aggregated data packet of size 23 bytes is then transmitted to the BS. Overall, in cycle 1, CH1 has transmitted 23 packets and received 32 packets, which consists of packets of different types and hence different sizes. Also, different power levels $P_t$ and $P_l$ have been adapted by CH1 to communicate at vertical and horizontal levels. By using formulae 6, 7 and 8, total energy consumed is calculated as 28.48 mJ.

Similarly, to illustrate the energy consumption of any other node (for example N105) in cluster 1 in first cycle, we can use values provided in column 5 of Table 2. Node N105, has received 2 time-sync packets from CH1, of size 29 bytes consuming 1.37 mJ of energy. The node transmits 2 time-sync packets to CH1, each of size 29 bytes, consuming 0.64 mJ energy. It also transmits 1 data packet in data cycle phase to the CH1 node, of size 23 bytes consuming 0.25 mJ energy. In totality, this node consumes 2.26 mJ energy.

In cycle 3, three nodes were added in each cluster. Additional two nodes were added in cycle 5 in each cluster. In Table 3, values for cycle 5 are given. Also in cycle 5 energy information is being sent, all nodes append energy information with the data packets in data cycle phase of cycle 5. Size of data+energy packet on horizontal level is 27 bytes and at vertical level it is 24 bytes as mentioned in Table 1.

In cycle 7, node number N113 becomes the new CH node for cluster 1, similarly for cluster 2 and cluster 3, new CH nodes are N213 and N313. Table 4 provides the information of cycle 7, wherein new CH nodes have been appointed. Table 5 provides the information of all first 10 cycles collectively. Here we have shown the energy consumption information of nodes N100, N200, and N300, which had been Cluster-Head nodes till cycle 6. From cycle 7 onwards, these nodes participate in cluster only as cluster-member nodes consuming only 2.26 mJ energy in these cycles.
Table 4. Information of Cycle 7.

<table>
<thead>
<tr>
<th>Type of Node</th>
<th>CH1</th>
<th>CH2</th>
<th>CH3</th>
<th>CN1</th>
<th>CN2</th>
<th>CN3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node ID</td>
<td>N113</td>
<td>N213</td>
<td>N313</td>
<td>N105</td>
<td>N205</td>
<td>N305</td>
</tr>
<tr>
<td>No. of Packets Transmitted</td>
<td>33</td>
<td>33</td>
<td>31</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>No. of Packets Received</td>
<td>47</td>
<td>47</td>
<td>44</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Energy consumed in Transmission</td>
<td>11.353</td>
<td>11.353</td>
<td>10.368</td>
<td>0.894</td>
<td>0.894</td>
<td>0.894</td>
</tr>
<tr>
<td>Energy consumed in Reception</td>
<td>29.904</td>
<td>29.904</td>
<td>28.084</td>
<td>1.371</td>
<td>1.371</td>
<td>1.371</td>
</tr>
<tr>
<td>Total Energy Consumed</td>
<td>41.258</td>
<td>41.258</td>
<td>38.452</td>
<td>2.265</td>
<td>2.265</td>
<td>2.265</td>
</tr>
</tbody>
</table>

Table 5. Information of first 10 Cycles.

<table>
<thead>
<tr>
<th>Type of Node</th>
<th>CH1</th>
<th>CH2</th>
<th>CH3</th>
<th>CN1</th>
<th>CN2</th>
<th>CN3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node ID</td>
<td>N100</td>
<td>N200</td>
<td>N300</td>
<td>N105</td>
<td>N205</td>
<td>N305</td>
</tr>
<tr>
<td>No. of Packets Transmitted</td>
<td>182</td>
<td>182</td>
<td>170</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>No. of Packets Received</td>
<td>248</td>
<td>248</td>
<td>230</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Energy consumed in Transmission</td>
<td>62.798</td>
<td>62.798</td>
<td>57.873</td>
<td>9.03</td>
<td>9.03</td>
<td>9.03</td>
</tr>
<tr>
<td>Energy consumed in Reception</td>
<td>159.451</td>
<td>159.451</td>
<td>149.783</td>
<td>13.711</td>
<td>13.711</td>
<td>13.711</td>
</tr>
<tr>
<td>Total Energy Consumed</td>
<td>222.25</td>
<td>222.25</td>
<td>207.656</td>
<td>22.741</td>
<td>22.741</td>
<td>22.741</td>
</tr>
</tbody>
</table>

Overall, nodes N100, N200, N300 have consumed 222.25 mJ, 222.25 mJ and 207.66 mJ energy respectively. Without rotation of Cluster-Head nodes, (and assuming absence of energy collection in 5th cycle), these nodes would have consumed 376.81 mJ, 376.81 mJ, and 348.76 mJ respectively.

Cluster-Head rotation algorithm is used for effective energy balancing between the network nodes. New Cluster-Head node is selected from the remaining cluster-member node. A node having highest residual energy is selected as CH node. In simulation, we added 2 nodes in cycle 5, one among these nodes can be selected as new CH. Among the nodes having highest residual energy, we have chosen CH node based on sequential ID number. Rotation of CH node also requires exchange of time slots between old and new CH node, since CH node is integral part of the backbone link and thus precede in control cycle phase. Similarly, old CH node needs a time slot for time-synchronization as well as to transmit one data packet to the new CH node. Rotation also requires a new CH node to dynamically adapt to the power levels while communicating at vertical and horizontal levels. Along with these requirements, more importantly, rotation of Cluster-Head node leads to adoption of new route at run-time. All the control message exchanges and data packet collection is done at new CH node. Whenever a Cluster-Head node rotates, a new route is established from nodes to the sink of network, leading to a dynamic routing protocol in our network.

6. Conclusions

In this paper, we have developed a network architecture and protocol stack for 3D wireless sensor network. This protocol stack consists of time synchronization, TDMA-based MAC, Cluster-Head rotation as well as Dynamic routing. In the proposed Dynamic Cluster-Based TDMA MAC (DCB-TDMA MAC) protocol, newer nodes can be added to different clusters making the network scalable. After a fixed number of cycles, base-station receives energy values of the nodes in network and rotates the Cluster-Head node accordingly, increasing a life-time of a network. Nodes also utilize requisite power level depending on the range of communication, which not only helps in effective energy utilization but also increases channel utilization by allowing channel reuse with the help of parallel communication in multiple clusters with proper interference avoidance. Energy is further saved in DCB-TDMA MAC protocol, since nodes can sleep after the communication in their respective predefined time slots. Duration of sleep phase can be tuned based on sensing interval required by the application. In simulation using Cooja, the packet delivery ratio is observed to be 100% since ideal channel and clock conditions were assumed. In the future work, we plan to port the code on actual Telos-B motes to relate simulation result with outcome of the practical scenario.
References