Energy-Efficient Multi-hop Medical Sensor Networking

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ABSTRACT

Wireless sensor networks represent a key technology enabler for enhanced health care and assisted living systems. Recent standardization efforts to ensure compatibility among sensor network systems sold by different vendors have produced the IEEE 802.15.4 standard, which specifies the MAC and physical layer behavior. This standard has certain drawbacks: it supports only single-hop communication; it does not mitigate the hidden terminal problem; and it does not coordinate node sleeping patterns. The IEEE 802.15.4 standard design philosophy assumes that higher layer mechanisms will take care of any added functionality. Building on IEEE 802.15.4, this paper proposes TImezone COordinated Sleep Scheduling (TICOSS), a mechanism inspired by MERLIN [2] that provides multi-hop support over 802.15.4 through the division of the network into timezones. TICOSS is cross-layer in nature, as it closely coordinates MAC and routing layer behavior. The main contributions of TICOSS are threefold: (1) it allows nodes to alternate periods of activity and periods of inactivity to save energy; (2) it mitigates packet collisions due to hidden terminals belonging to nearby star networks; (3) it provides shortest path routing for packets from a node to the closest gateway. Simulation experiments confirm that augmenting IEEE 802.15.4 networks with TICOSS doubles the operational lifetime for high traffic scenarios. TICOSS has also been implemented on the Phillips AquisGrain modules for testing and eventual deployment in assisted living systems.

Categories and Subject Descriptors: [Wireless, communication, wireless, sensor, scheduling, networking, networks, routing, 802.15.4, ZigBee]: Miscellaneous

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1. INTRODUCTION

The ageing population in many developed countries highlights the importance of novel technology-driven enhancements to current health care practices. Recent technological developments in the fields of sensing, actuation, processing, wireless communication, and information management have fueled increased interest in technology-enhanced health care. For example, a wireless network of sensor and actuator nodes can be deployed in an elderly person's home (with the person's consent) to assist the person in living independently for as long as possible. Another example is the use of wireless sensor networks to monitor hospital patient vital signs to allow the patient's greater freedom of movement.

A major enabling technology of enhanced health care systems is wireless sensor networks (WSNs). The large scale adoption of WSN technology for health care systems will depend on the Quality-of-Service (QoS) provided by these networks, namely the reliability, latency, and efficiency. QoS provision in WSN's is tightly coupled with the medium access control (MAC) protocol. The MAC layer is responsible for coordinating channel access, such as transmission scheduling to maximize throughput and to avoid packet collisions. To ensure network longevity and acceptable end-to-end packet delay, MAC protocols for sensor networks target a balance between energy efficiency and end-to-end packet delay at the expense of data throughput.

Recent studies have highlighted the critical requirements of sensor network MAC protocols:

- Coordinated sleep states: recent studies revealed that the transceiver activity (transmitting and receiving) is one of the main sources of node energy consumption; therefore, alternating periods of activity (radio on) to periods of inactivity (sleeping) can lead to significant reductions in energy consumption reduction. However, communication between neighboring nodes necessitates simultaneous node activity, so coordinated sleeping is necessary.

- Multi-hop communication: in order for a transmitter and receiver pair to communicate, the required transmitting power Pt changes exponentially with the distance D. Significant energy saving can be achieved by reducing the sensor transmitting power and by enabling multihop communication.

- Hidden node avoidance: Sensor network MAC protocols should provide mechanisms to avoid the hidden terminal problem (**HTP**) that is characteristic of distributed wireless communication networks.

The recent IEEE 802.15.4 standard developed for energy-efficient WSNs assumes that higher layers will handle the above requirements. The IEEE 802.15.4 standard only supports a single star-topology network, in which several child nodes communicate with a designated coordinator node. The communication performance seriously degrades when the system scales to a larger network which includes several nearby star-networks in the same area. The IEEE 802.15.4 also cannot control the channel access within a multiple-star topology network, leaving the resolution of multi-hop routing for higher layer protocols. Furthermore, the 802.15.4 standard does not provide any mechanism to avoid the HTP or to coordinate sleeping patterns in multi-hop peer-to-peer networks.

Building on the IEEE 802.15.4 standard, this paper proposes a mechanism called TImezone COordinated Sleep Scheduling (TICOSS) that provides multi-hop support, HTP mitigation, and coordinated sleeping through the division of the network into time zones. The time zone concept adopted from the recent developed MERLIN [2] mitigates the HTP by ensuring that nodes in neighboring zones do not transmit simultaneously. The time zones also provides coordinated sleeping, through the V-table scheduling, and shortest path multi-hop routing. The adoption of MERLIN is due to its earlier comprehensive evaluation in [2] that presented a superior energy/delay performance than existing protocols for WSNs.

The remainder of the paper is organized as follows. Section 2 motivates the design of TICOSS through a patient monitoring application. Section 3 introduces the basics of IEEE 802.15.4. Building on the standard, Section 4 describes the operational details of TICOSS, which is evaluated through simulations in Section 5. Section 6 concludes the paper.

2. A MOTIVATING APPLICATION: PATIENT MONITORING

An interesting application for TICOSS is wireless in-situ patient monitoring, which includes two network types: (1) body area networks consisting of small body sensor (**BS**) nodes that are attached to patients' bodies to continuously monitor their vital signs; and (2) ambient sensor (AS) nodes placed throughout the site, for instance an hospital. The two networks collaborate to relay data from and to patients.

BS's are responsible for collecting data from the patient that is wearing them. A designated BS, called body-gateway (**BG**) collects the data from the BAN and relays it to the surrounding AS nodes. Rather than relaying all data from the body area network, the BG should perform data aggregation, pruning data gathered from all BS's to relay only useful information. The BG then transmits the aggregated data to one or more AS nodes in the vicinity of the patient. The data is subsequently forwarded to the base station which stores information related to all patient conditions for analysis by a doctor.

The motivating application above exposes the requirements of supporting protocols for medical-based sensor networks. As the data in the network traverses multiple hops before reaching the user, the underlying protocols must support multi-hop communication. Inherent to multi-hop wireless networks is the need to avoid hidden terminals. Finally, the BAN nodes run on very small batteries or through scavenging energy from body heat and movement. The sparse energy resources requires nodes to sleep for most of the time, raising the need for a coordinated sleeping strategy. Coordination between activity and inactivity time periods ensures that nodes are awake at the correct time to receive and forward their data.

The next section identifies the drawbacks of the IEEE 802.15.4 standard when it is used in a multiple-hop topology network.

3. OVERVIEW OF IEEE 802.15.4

The IEEE 802.15.4 standard [5] provides MAC and PHY layer specifications for low data-rate and energy-efficient wireless networks. The standard does not provide any routing support,which need to be built separately. An example of a system with networking capabilities over IEEE 802.15.4 is ZigBee [4] which builds on the recent AODV [10] routing algorithm for low-speed ad-hoc networks. In IEEE 802.15.4, devices can be of 3 types: (1) Personal area network (PAN) coordinator that can act as a gateway to interface the network with the user; (2) Full Functional Devices (FFDs) that are sensor devices with routing capability; (3) Reduced Functional Devices (RFDs) that are end devices that can be part of the network by associating them with one FFD and allowing only communication with that FFD. Although the IEEE 802.15.4 standard mentions peer-to-peer network formation, the main network topology is a one-hop star topology network. The standard leaves the resolution of issues related to more complex topologies for higher layers.

3.1 Star topology

The star network consists of one central PAN coordinator surrounded by several FFDs and RFDs. Communication between the PAN coordinator and devices may be regulated by periodical beacon transmission referred to as a beacon-enabled network. Alternatively nodes can communicate in nonbeacon-enabled mode.

In beacon-enabled mode, periodical beacons indicate the beginning and the end of a transmission frame referred to as a superframe structure. As illustrated in Figure 1, the superframe is divided in two parts: (1) A Contention Access Period (CAP) in which nodes that need to communicate, compete for the channel through the Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism but without the RTS/CTS handshake mechanism to avoid HTPs; (2) A Guaranteed Time Slot (GTS) in which some nodes have a reserved contention free slot, for example for high priority packets.

In nonbeacon-enabled mode, no beacons are broadcast, so there is no coordination for the GTS allocation. As a result, IEEE802.15.4 reduces to plain CSMA-CA. Nonbeacon-enabled mode does not support both the GTS functionality and handshake mechanism to prevent collisions due to HTPs.

3.2 Multihop topology

As an example of large-scale IEEE 802.15.4 multihop topology network, Figure 2 illustrates a mesh of clustered networks. This network topology, discussed in the standard documentation [5], consists of one PAN coordinator, several FFDs and some RFDs as tree leaves. Figure 2 shows the networks divided in clusters with one cluster head (CLH) elected in each tree. The figure does not show the transmission coverage clusters, which are likely to partially overlap. The standard does not provide any methodology for coordi-

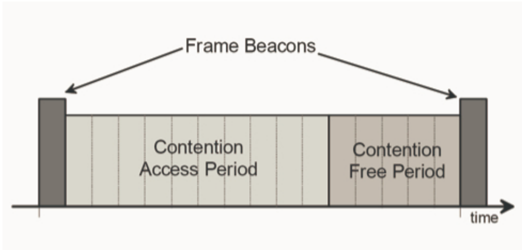

Figure 1: Superframe structure in 802.15.4

nation between clusters. This means that the nodes in the overlapping area may experience heavy interference and packet collisions due to transmission of nodes that belong to different clusters and are within each others' transmission range. Figure 3 shows a situation where a transmitting

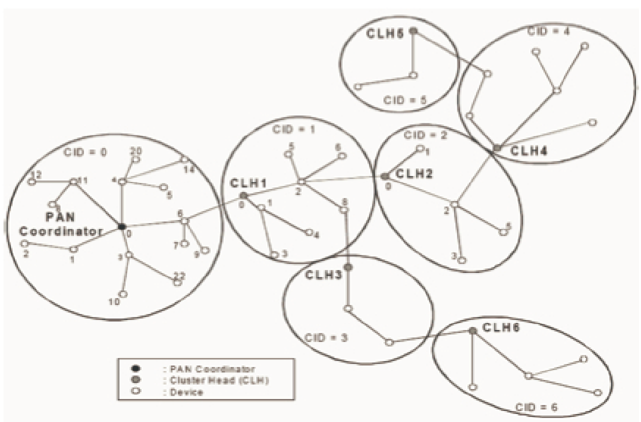

Figure 2: Cluster tree network

FFD interferes with a receiving RFD from a nearby cluster. In this case, network performance worsens with the use of beacon-enabled mode. In fact, beacons are especially weak because they are transmitted directly without using the CSMA-CA mechanism for medium clearance sensing. Finally, IEEE 802.15.4 does not provide any energy saving coordination for FFDs, such as coordinated sleeping. Most of the nodes are FFDs acting both as coordinators for RFDs and as routers to the PAN coordinator. As a result, FFDs need to be active much longer than RFDs thereby causing significant imbalance of energy consumption in the network.

The above discussion motivates the following design choices for TICOSS mechanism that enhances IEEE 802.15.4: adopt the non-beacon mode; give full functional capabilities to all nodes in the multihop network; and implement a coordinated sleep policy to save energy among nodes. The subsequent section describes the design details of TICOSS.

4. TICOSS: TIMEZONES COORDINATED SLEEPING SCHEDULING

The basic idea of TICOSS is inspired from the routing functions of MERLIN [2], which is an integration of MAC and routing into the same architecture. TICOSS adopts the concept of the division of the network into timezones,

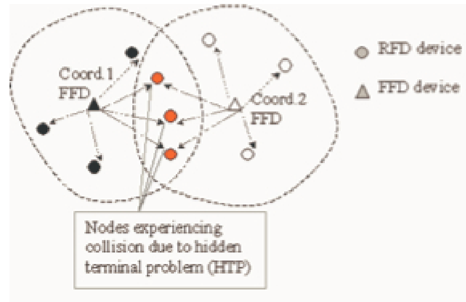

Figure 3: An example of hidden terminal problem in 802.15.4 due to concurrent transmission of nodes, which belongs to different clusters, that are too far apart to sense each other transmission

by means of the V-table for transmission scheduling and the implementation of three FIFO buffers for: (1) upstream packets destined to the gateway; (2) downstream packets, destined to the network; (3) packets for local broadcast. The main task of V-table scheduling is to divide the time into slots that are then used for transmitting the packets from the buffers. We extend the V-Table to combine coordinated sleep scheduling and basic routing functionality for IEEE-802.15.4. We now describe the association phase of 802.15.4, the meaning of timezones, how they are set up and used in the network.

4.1 802.15.4 Association phase for TICOSS

This section describes the steps of the network association phase in which the coordinator provides a short MAC address to new nodes that join the network. IEEE 802.15.4 initially assigns a unique extended ID of 64 bits to each node. Including the extended ID in each transmitted packet produces significant communication overhead, causing an increase of the energy consumption. TICOSS mitigates the overhead by issuing a short ID of 16 bits to associated nodes in the network.

Figure 4 shows the steps of the association phase in IEEE 802.15.4 as captured by a packet sniffer, with each row corresponding to one step in the process. To join the network, a node starts broadcasting a "Beacon Request" (BR) packet. Should the PAN coordinator receive a BR, it responds with a packet containing the PAN ID, superframe specification and GTS fields. The superframe specification contains the length of the frame defined by the macSuperframeOrder (SO) and and the macBeaconOrder (BO) [5]. The PAN coordinator then broadcasts the "Association Request" (AR) that contains its extended ID and parameters related to its state. When the node receives an AR, it sends a "Data Request" (DR) packet to the PAN coordinator using the extended PAN coordinator ID. The DR packet contains the extended ID of the associating node. After reception, the PAN coordinator issues a short ID to the new node that can successfully join the network. In order to avoid high data overhead, the short ID is the one adopted by the MAC for packet communication. The node can now acquire the parameters for the sleep scheduling. In order to allow a peer-to-peer communication, the standard has been set to allow any node that joins the network to become an associated

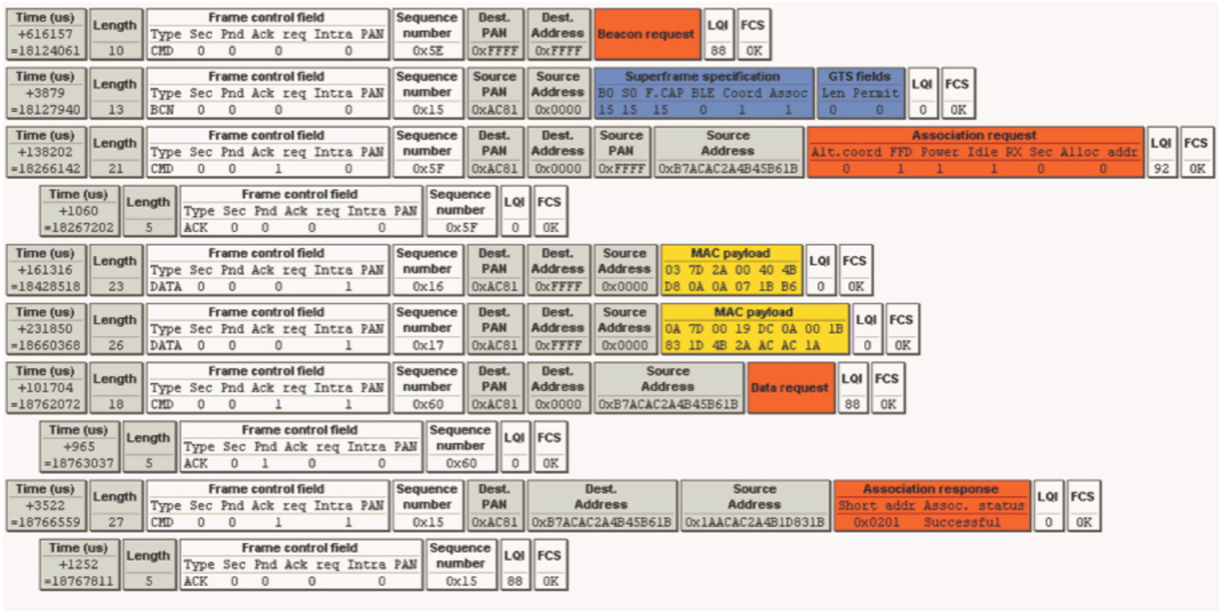

Figure 4: A screen shot of the association steps by the CC2420 packet sniffer device

coordinator. The associated coordinator status enables the issuing of short MAC addresses for other nodes to associate to the network. In order to avoid ID conflicts, short IDs are locally unique among neighboring nodes.

4.2 Timezone definition and setup

Once all nodes associate into the network, the algorithm proceeds with a division of the network in timezones. The timezone of a node is the minimum number of hops required for its packets to reach the PAN coordinator. For instance, the packets of nodes within the 3^{rd} timezone need to be forwarded at least three times to get to the PAN coordinator. The timezone division and synchronization occur during network initialization as follows: the PAN coordinator sends an initial zone message to neighbouring nodes. The message contains the zone of the transmitter (TxZone) which is zero in case of the PAN coordinator and timing information. Receiving nodes can then set their timezone as TxZone+1, update their internal clock and send a new zone message, which contains TxZone+1 as transmitter zone and new timing info. The process is repeated by further receiving nodes as shown by Figure 5.

MAC channel contention can cause nodes to delay the forwarding of its timezone message. As a result nodes in higher timezones may receive a zone message from an alternative path that is longer than the shortest path. The reception of the zone message from the shorter path rectifies this situation, which does not prevent a node from communicating with its neighborhood. The node then places itself in the appropriate timezone and notifies farther nodes by broadcasting the updated timezone downstream.

In order to cope with network changes such as node depletion, replacement and mobility, a node's timezone has a preset expiration time. A node's timezone expires if the node does not receive a zone update message, which all nodes send periodically. Nodes store updates in a table together with a timestamp and the sending node ID to identify and discard stale zone messages. Timestamps also serve the purpose of identifying stale entries, such as entries that are present in the table for more than a given time interval. Upon reception of a packet, the table update mechanism checks whether the packet is from a node that is already in the list and updates it accordingly. The mechanism also periodically scans and deletes stale items in the table. In order to prevent the formation of gaps in the table due to the removal of items, nodes delete stale entries by overwriting them with the last element of the table.

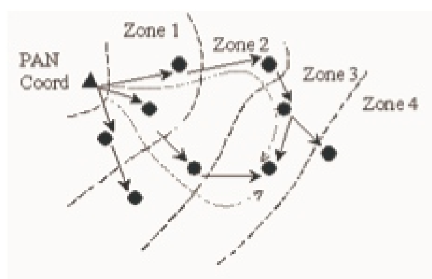

Figure 5: The initial timezone setup by flooding and different path generation

4.3 V-scheduling

The scheduling table allocates timeslots to nodes in order to assign periods of node activity and inactivity. This allows neighboring nodes to transmit and receive during the same interval. Nodes that are neither transmitting nor receiving enter a sleep mode. In TICOSS, nodes in the same timezone use the same time-slot to transmit. The table shown in Figure 6 is named a V-table (due to its V-shape communication flow) and supports 3 types of transmission:

- **Upstream transmission** in which a node transmits to another node located closer to the personal area network (PAN) coordinator, i.e. to a node in a lower timezone node;
- **Downstream transmission** in which a node transmits to another node which has longer distance to the PAN coordinator, i.e. to a node in a higher timezone;
- **Local broadcast** in which a node sends to all the neighboring nodes simultaneously (for example for the time synchronization procedure).

The V-scheduling table is either transmitted by the gateway during the initialisation phase or stored in the nodes during code uploading. Currently, the nodes statically store the table; however, an interesting direction for future investigation is the investigation of of dynamically injecting different tables into the network as function of the application requirements. The length of the table in Figure 6 is equal to the length of a single frame and each small rectangle represents a time slot. This V-table supports consecutive transmission of 4 timezones and therefore it consists of $4 \times 2 + 1$ timeslots: 4 timeslots for upstream transmission, 4 timeslots for downstream transmission, and 1 timeslot for local broadcast. In general, the allocation of upstream, downstream, and local broadcast transmissions in a symmetric network of N zones requires $N \times 2 + 1$ timeslots per frame.

When TICOSS allocates a timeslot for transmission to a particular timezone, the adjacent zone owns the slot for reception while nodes in further timezones are in sleep mode. The V-table performs fast upstream and downstream transmission by forwarding a packet to 4 timezones towards the PAN coordinator or in the opposite direction within the same frame. Appending the same table yields the scheduling of further zones. This means that appending the same table N times produces the scheduling table for $N \times 4$ zones. The scheduling for further frames is obtained by flanking the same table. In other words the scheduling for further frames is obtained by a round robin procedure on the same table. The 4-zone V-table allows potential parallel transmissions between nodes that are located 4 zones apart. Appending the scheduling table for further zone transmissions shows that an increase of the number of zones in a table results in fewer parallel timezone transmissions. Therefore, a table with fewer zones theoretically results in a more efficient usage of the medium. However, a table with only 2 zones, and 5 timeslots, causes continuous packet collisions when further tables are appended. Furthermore, simulated results have shown that a 3-zone table still produces a significant number of collisions at the zone in between parallel transmissions when further tables are appended. Such collisions are due to the random node locations and transmission range irregularities. Empirical results in [2] proved the 4-zone V-Table to be the most advantageous number that supports a high number of parallel transmissions together with a minimum number of collisions.

The last column of timeslots in the V-table is dedicated to local broadcast packets. However, simultaneous local broadcast of nodes either in adjacent timezones or 2 timezones apart results in packet collisions. Simultaneous local broadcasts in TICOSS should be at least 3 zones apart (local broadcasts at zones 1 and 4 followed by zones 2 and 5 and so forth). To further ensure inter-zone collision avoidance, TICOSS uses simultaneous local broadcast separation of 4 timezones. The following formula applies:

$$Mod(frameN, NFRAME) = Mod(myZONE, NSLOT)$$

Where $frameN$ is the frame counter, $NFRAME$ is the number of frames of the V-table, $myZONE$ is the node timezone and $NSLOT$ is the slot number in the V-table. In the V-table in Figure 6, $NFRAME$ is equal to 9 and $NSLOT$ is equal to 4, so nodes in the same timezone can contend the slot for local broadcast only once each 4 frame times. When a zone is scheduled for local broadcast, the nodes within the same zone and adjacent ones enter the listening mode.

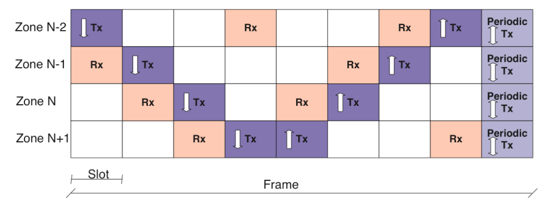

Figure 6: The table of scheduling with periodic local broadcast

4.4 Timezone-based Medical Sensor Networks

Returning to the motivating example in Section 2, this section revisits the benefits of TICOSS applied to medical sensor networks. Figures 7 and 8 show how nodes in both the body network and the ambient network self-organize in timezones. Although nodes within the body might form a one-hop network due to their vicinity, some preliminary experiments with Philips nodes showed lack of communications between nodes located on the chest and other nodes located on the back of the patient. This was accentuated when the transmission power was put to a minimum for energy saving reasons. For the BAN, the BG starts transmitting a zone-msg message to neighbouring BSs that subsequently update their timezone and forward the packet. In case an AS receives a zone-msg message from any BS which is not a BG, then the AS discards the zone-msg. The ambient network BS also starts the same procedure for all AS nodes. The division of the network into time zones allows the body to freely move and yet be able to communicate with ambient nodes that are spread in the environment to relay the information to the closest BS.

5. SIMULATIONS

An initial performance evaluation of the network lifetime benefits of TICOSS uses the OmNet++ simulator [12] for 5 random topology scenarios of 49 nodes and 1 gateway each, using 10 different seeds to generate each topology. The simulations use the CC2420 transceiver specifications to model the physical layer communication [11].

Figure 9 compares the lifetime, expressed in minutes per Joule, for a network running IEEE 802.15.4 with a network that runs TICOSS on top of IEEE 802.15.4 as the inter-packet generation time varies. The left side of the figure corresponds to higher traffic scenarios, i.e. when the packet generation frequency is high, and the right side corresponds

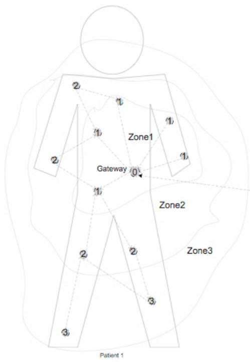

Figure 7: Timezone formation on the patient

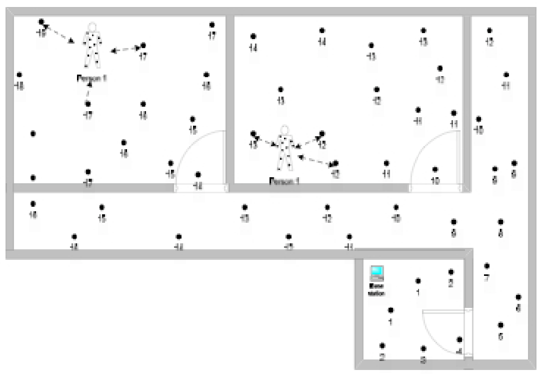

Figure 8: Timezone formation on the environment

to low traffic scenarios. TICOSS clearly exhibits longer network lifetime for the entire range of considered traffic scenarios. Another observation on Figure 9 is that the lifetime of plain 802.15.4 is shorter for higher traffic cases, whereas the traffic load has little effect on the lifetime of the TICOSS-enhanced network. In the case of 802.15.4, the dominant cause of energy depletion is packet transmission and reception, which explains the shorter lifetime for high traffic scenarios. In TICOSS, idle listening, which is a function of the frame length, dominates the energy consumption profile of a node, yielding similar performance for high and low traffic scenarios. Thus, TICOSS provides more stable and deterministic performance in IEEE 802.15.4 networks. For the whole set of simulations, we experienced of MERLIN-802.15.4 delivery rate of over 92% which was slightly higher than the delivery rate 802.15.4 solely. This was mainly due to the positive effect of the timezones that scheduled the traffic so that nodes in nearby timezones did not transmit simultaneously. Therefore, TICOSS maintained the same delivery rate with significant energy benefits.

6. CONCLUSION

The application of sensor networking in a field as crucial as the medical fields requires the use of reliable and well-established standard protocols and mechanisms. While the IEEE 802.15.4 standard aims to provide one-hop communication between powerful sensor nodes, it leaves most of the

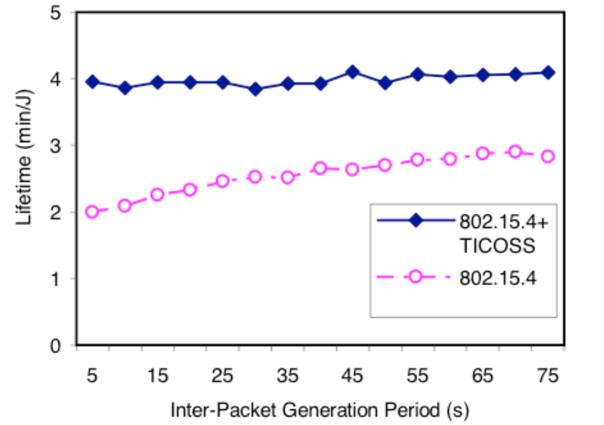

Figure 9: A comparison of the network lifetime between 802.15.4 with and without TICOSS

specification of more complex issues to upper layers. This paper has described improvements to the IEEE 802.15.4 standard by setting all nodes to FFDs then imposing a timezone coordinated sleeping mechanism named TICOSS to (1) save energy; (2) mitigate hidden terminal collisions through V-table scheduling; (3) provide configurable shortest path routing to the PAN coordinator. The performance evaluation of TICOSS confirms that the mechanism extends IEEE 802.15.4 to support multi-hop networks, and doubles the operational lifetime for high traffic scenarios.

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