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An Improved MAC Protocol for Wireless Sensor Networks in Medical Application

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Abstract. Wireless Sensor Networks (WSNs) provide a valuable capability to autonomously monitor remote activities. Their limited resources challenge WSN medium access control (MAC) layer designers to adequately support network services while conserving limited battery power. We expect sensor networks to be deployed in an ad hoc fashion, with individual nodes remaining largely inactive for long periods of time, but then becoming suddenly active when something is detected. These characteristics of sensor networks and applications motivate a MAC that is different from traditional wireless MACs such as IEEE 802.11 in almost every way: energy conservation and self-configuration are primary goals. This paper proposes M-MAC, a medium access control protocol designed for medical wireless sensor networks. M-MAC's centre management function offers significant energy savings by wiping off contention and keeping nodes sleeping all the time except awaking to send its Data package. All Slave Node(SN) need only communicate with a specific Master Node(MN) in a group and due to close range, routing is unnecessary. The MN acts as scheduler and when receives a Data package from a SN, it will indicate the SN how long it should be asleep and what it should do after awaking. Period is introduced as the time windows and it is divided into Frame Time. Every MN occupies a unique Frame Time and this is decided by its MAC address. Then the Frame Time separates into smaller Slot Time and it is the atomic time span for SN exchanging data with MN. Practice has proved that the M-MAC protocol is effective in our medical application and it can extend the lifetime of SN greatly.

Introduction

Wireless sensor networking is an emerging technology that has a wide range of potential applications including environment monitoring, smart spaces, medical systems and robotic exploration. Such a network normally consists of a large number of distributed nodes that organize themselves into a multi-hop wireless network. Each node has one or more sensors, embedded processors and low-power radios, and is normally battery operated. Typically, these nodes coordinate to perform a common task.

Communication in wireless sensor networks can, like most network communication, be divided into several layers. One of those is the Medium Access Control (MAC) layer. This layer is described by a MAC protocol, which tries to ensure that no two nodes are interfering with each other's transmissions, and deals with the situation when they do.

Since wireless sensor networks (WSNs) operate in a broadcast medium, these networks require a medium access control layer to resolve contention in a random, multi-access environment. In efforts to make inexpensive sensors ubiquitous, these sensor platforms tend to have limited processor capability, memory capacity, and battery life. In dynamic ad hoc network environments, WSNs have the additional challenge of self-adapting to changes in topology, traffic loads, and existing battery conditions.

An improved MAC, Master MAC (M-MAC) protocol is described in this paper, which is adapted to our special medical application. In M-MAC, the time spent on idle, sending and receiving mode is minimized greatly. The detailed implementation method will be described in following part.

Main energy consumption

WSN MAC protocols extend network lifetimes by reducing the activity of the highest energy-demanding component of the sensor platform-radio. Trading off network throughput and latency (delay), energy-efficient MAC protocols synchronize network communication to create opportunities for radios to sleep with active duty cycles as low as 2.5% under minimal traffic conditions. Typical sources of energy loss in WSNs include idle listening, frame collisions, protocol overhead, and message overhearing.

Idle listening: Idle listening occurs when a device listens to an inactive medium. Contention-based WSN MAC protocols attempt to synchronize network traffic so that transmissions begin only in predetermined time slots. Once all network transmissions are complete for a particular cycle or time frame, the protocols allow nodes to return to sleep until the next transmission period. Contention-free WSN MAC protocols reduce idle listening by scheduling transmission slots and allowing nodes not actively exchanging messages to sleep.

Frame collisions: A frame collision occurs when a node sends a message which collides or overlaps intime with another message. Single-channel radios cannot simultaneously receive while in transmit mode. Therefore, the message sender's only indication of a collision is the failure of the receiver to return an acknowledgement (ACK) for the message. Protocol designers reduce frame collisions by employing contention-free scheduling protocols or contentionbased backoff algorithms to minimize the probability of collisions.

Message overhearing: Receiving and discarding messages intended for other nodes, or message overhearing, is commonly employed in non-energy constrained networks to increase throughput and decrease latency. Message overhearing is costly in WSNs since all of the nodes expend energy receiving a message intended for just one node. Early rejection and network allocation vector (NAV) sleep are energyefficient methods which reduce message overhearing. Early rejection allows a sensor node to turn off its radio once it has read a different destination field for an incoming message. NAV sleep allows nodes to schedule a sleep period during the overheard request-to send / clear-to send (RTS-CTS) handshake sequence by noting the message duration field and scheduling a NAV table interrupt [7][8].

Related Work

Many MAC protocols have been designed for WSNs. Below we present a selection of protocols that have relevance to our new protocol.

Current MAC design for wireless sensor networks can be broadly divided into contention-based and TDMA protocols. The standardized IEEE 802.11 distributed coordination function (DCF) [1] is an example of the contention-based protocol, and is mainly built on the research protocol MACAW [2]. It is widely used in ad hoc wireless networks because of its simplicity and robustness to the hidden terminal problem. However, recent work [3] has shown that the energy consumption using this MAC is very high when nodes are in idle mode. This is mainly due to the idle listening.

Sensor MAC (S-MAC) [4] and Timeout MAC (T-MAC) [5] are contention-based protocols focused on reducing idle radio listening by concentrating the network's data transmissions into a smaller active period and then transitioning to sleep for the remainder of the cycle. SMAC establishes a fixed active cycle (i.e. 10% active), and T-MAC allows the traffic to adjust the duration of the active period dynamically by transitioning nodes to sleep only after listening to an idle channel for a timeout period equivalent to a transmitting node's worst-case contention backoff. Concentrating the transmissions into a smaller active period reduces idle listening, but it also increases the probability of collisions, thus wasting precious bandwidth and energy. Berkeley-MAC (B-MAC) [7] is another contention-based protocol that saves energy by having radios periodically wake up to sample the medium. Transmitting nodes extend the duration of message preambles to cover the entire range of the wakeup period to ensure all nodes receive the preamble and remain awake to accept the message. This protocol loses efficiency as network traffic increases because all nodes remain awake throughout the entire packet transmission and a portion of the extended preamble. However, B-MAC is an efficient protocol in low network traffic conditions since nodes will spend most of the time sleeping.

Several TDMA protocols have also been developed. A good example is the LMAC protocol. Contrary to many other TDMA protocols, the LMAC protocol uses a completely distributed slot assignment mechanism. Each slot owner sends at least a packet header in the slot the node owns. Neighboring nodes listen to the start of each slot, and detect which slots are free. However, for a TDMA protocol it is required that a slot is not reused within a two-hop neighborhood. The LMAC protocol therefore includes a bitmap with all the slots assigned to a node's neighbors in the header. By combining the bitmaps of all neighbors, a node can determine which slots are free within a two-hop neighborhood. Pattern MAC [7], or PMAC, also divides time into frames. Each frame consists of two parts: the Pattern Repeat part and the Pattern Exchange part. Both parts are divided into slots. During the Pattern Repeat part, nodes follow the sleep/wake pattern they have advertised. Nodes also wake up when a neighbor for which they have a packet to send has advertised it will be awake during a particular slot. Nodes advertise their chosen patterns during the Pattern Exchange part. Each slot in the Pattern Exchange part is long enough to send a node's pattern information and nodes have to contend for these slots. To enable all nodes to send their pattern information, the Pattern Exchange part has as many slots as the maximum number of neighbors a node is expected to have. The sleep/wake patterns are adapted to the traffic going through a node, to achieve maximal energy savings.

The Crankshaft protocol, whose basic principle is that nodes are only awake to receive messages at fixed offsets from the start of a frame. This is analogous to an internal combustion engine where the moment a piston fires is a fixed offset from the start of the rotation of the crankshaft. Allowing different nodes to wake up for reception at different offsets from the start of the frame means that there are fewer nodes overhearing messages and spreads out the communication between unrelated receivers[9].

Master MAC protocol design

M-MAC is targeted to our special application scene, and it provides effective network control mechanisms to maximize sleep durations, minimize idle listening, and wipe off cluster control.

Application Background

It is well known that oxygen inhalation is a very direct and valid method to improve blood oxygen concentration, so we apply oxygen machine on chronic pulmonary disease in order to improve their blood oxygen concentration. On the other hand, we need to get the blood oxygen concentration data of patient and the status parameter of oxygen machine. Basing on these data, we can estimate the effect of oxygen inhalation and find some quantitative rules.

We place maximum four sets of oxygen machines in one room and equip five to eight neighboring rooms as the diagnosis and treatment area. In every room, once the oxygen machine is working, the status parameter and the blood oxygen concentration of patient will converge into the doctor work station through WSN. Because all oxygen machines and the doctor work station is at close range in a room, routing is unnecessary It seems that the only most important thing is finding some scheduling strategy to avoid idle listening , frame collisions and message overhearing so that the lifetime of nodes can be extended. Figure 1 shows a possible layout of equipments in a consulting room.

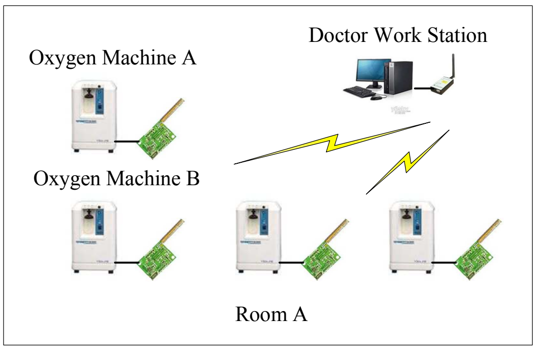

Figure 1. Layout of equipment in a consulting room

Hareware Design

We design two types of wireless data transmit-receive modules in order to achieve different goals. One is powered by common AA battery, named Slave Node(SN), which is composed mainly by a low consumption MCU-MSP430 2132 and a 2.4G transceiver chip CC2500. SN communicates with oxygen machine through TTL-232 and exchanges information with other SNs by 2400-2483.5 MHz ISM. The other, named Master Node(MN), communicates with PC through USB and is powered by USB at the same time. The MN is composed mainly by Stellaris-3634, which is an ARM Cortex-M3 processor with USB interface, and a 2.4G transceiver chip CC2500. Because the MN needn't sleep and acts as the scheduler of network, its computing power is critical. The appearence of MN and SN is displayed in Figure 2.

Figure 2. Appearence of MN and SN

M-MAC Protocol

In this case, all of SNs in a consulting room need only to communicate with given MN and SN needn't exchange data to other SNs or MNs, so it can sleep all the while until the moment is arriving to send its data. Our M-MAC Protocol is designed basing on above judgment. The main sources of energy loss in WSNs include idle listening, frame collisions, protocol overhead, and message overhearing can all be overcame in the M-MAC Protocol.

The basic principle of the protocol is that nodes are only awake to receive messages at fixed offsets from the start of a frame. Allowing different nodes to wake up for reception at different offsets from the start of the frame means that there are no nodes overhearing messages and only one node spreads out the communication between unrelated receiver. Below we detail the working of the M-MAC protocol.

The M-MAC protocol divides timeline into time windows, which can also be regarded as period. Period is the basic scheduling unit in actual application. In more detailed, period is divided into frame, and each frame is divided into slot . There are two types of slot in M-MAC protocol: broadcast slot and unicast slot . During a broadcast slot all MNs is ready to listen for an incoming message. Every frame starts with a broadcast slot, followed by the unicast slot.

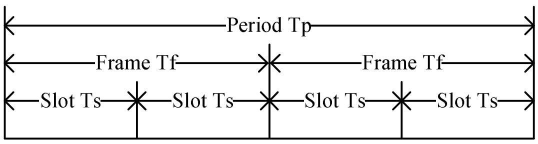

Figure 3. Different time span division in a peiod

Broadcast is applied between MNs to exchange synchronization information and it needn't ack. Unicast uses a Data/Ack sequence and the slot time length is such that it is long enough for the maximum-length package. If the SN does not receive an acknowledgement from the MN, the protocol is set to retry at once. Though contention maybe occurs, enough long slot time and enough short actual sending span make it difficult for collision.

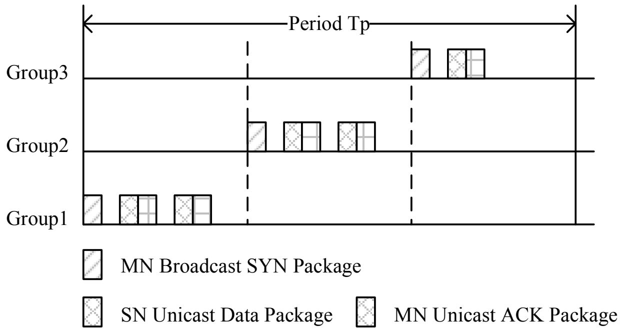

Figure 4. A possible scheduling process

The Data package is made up of specific service content, such as the status parameter of oxygen machine or the configure information of SN. The Ack package is composed by response or indication information to SN, such as sleep span or reporting signal intensity.

Although many complicated methods of frame assignment are possible, we have chosen to use a simple mechanism to limit the amount of processing power required. Each period has n frames, and the frame assignment is performed by calculating MAC address modulo n. Using a static frame assignment like this may result in above two MNs maybe being assigned the same frame. In this case ,we assign the MN whose MAC address is smaller occupying the frame, the bigger will select a spare frame randomly. Because there are most n MNs in a period, it is sure that every MN will have a unique frame at last.

Once frame is set, slot is very easy to fix. We divide the span of frame into several smaller span and bind it to certain SN. The ruler can accord with the MAC address of SN, or the moment of whose first package arriving.

Clearly, using frames requires that MNs are synchronized. Synchronization can be achieved both through a reference node, or through a distributed algorithm like GSA. In M-MAC protocol, the former is adopted because it is easy to realize and a relative synchronization is enough. Every MN sends a package with synchronized clock at the beginning of its frame or, in broadcast slot, other MNs receive this package will adjust its own clock to be consistent with the public clock if its self address is bigger than the sending MN. All MNs will keep consistent with the MN whose address is smallest finally. If a new MN joins or an existed MN leaves, synchronization will carry on again.

MN acts as the scheduler in WSN and calculates the sleep time for SNs dynamically. For example, if we set the period Tp equal 10s, the Tf equal 2s and Ts equal 100ms. It means that there are maximum five groups of equipment and maximum nineteen oxygen machines in a group working together. The SN awakes and sends Data to MN, then sleeps as long as time indicated in Ack under normal conditions.

Experimentation

The main goal of the experimentation described here is to measure the energy consumption of the radio for using each of the MAC modules we have implemented and prove that if M-MAC chould work correctly.

In actual situation, blood oxygen concentration changes slowly and it is enough that the SN exchange information with MN once a minute. The total length of the package is 36 bytes including oxygen pressure, oxygen flow rate, patient blood oxygen concentration and warning etc.

We use 3 rooms as our experiment zoon and there are 3 oxygen machines in every consulting room. We set the period equal 60s, Tf equal 10s and Ts equal 1s. All the nodes keep working all along for a week and all the packages are recorded by a sniffer. A protocol analysis software is used to check the validity of M-MAC. The result shows that all captured packages are in correct order and the synchronization is consistent.

On the other hand, a high-accuracy ammeter is applied to measure the current when SN works in different mode. We can find that the current is about 43mA on transmitting, 35mA on receiving and 3μA on idle. Basing on this fact, a pair of common AA battery can support it for working almost more than 12 months.

Conclusion and further work

The M-MAC protocol introduced in this paper establishes a centralized scheduling mechanism which eliminates cluster-wide idle listening, frame collisions and message overhearing, so energy consumption is reduced greatly. In M-MAC, period is divided into frame time and slot time, which ensures that the channel is spare whenevery any node sends its data package. M-MAC belongs to TDMA mode essentially, but the scheduling and synchronization are realized in a simple and direct way. However it turns out that M-MAC works well in our medical application and extends SN's lifetime more longer. Future work in M-MAC protocols includes creating a message priority quality of service (QOS) system and optimizing the schedule by multiple messages sending etc.

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