MAC Protocol for Low-Power Real-Time Wireless Sensing and Actuation

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Abstract— **This paper presents LPRT, a new medium access control (MAC) protocol for wireless sensing and actuation systems. Some of the characteristics of the proposed protocol are low power consumption, support for real-time and loss intolerant traffic through contention-free operation and a retransmission scheme, flexibility, and high throughput efficiency. The LPRT protocol was implemented it in the MICAz motes, a platform for the development of wireless sensor networks. We also briefly describe a wireless hydrotherapy application that benefits from the use of the proposed protocol. This paper also provides experimental results and comparison of the proposed protocol with the CSMA/CA protocol of IEEE 802.15.4.**

I. Introduction

Due to its strict requirements in terms of delay and loss, the traffic of distributed data acquisition and control systems is normally supported by specific cabled networks which are known generically by the term fieldbus [1]. In this context, the replacement of conventional cabled networks by a wireless network can introduce several advantages derived from the elimination of the cables. The freedom from cables enables the mobility of the stations, opening a whole new range of potential applications; however, the power consumption becomes an issue. The range of applications for reliable low-power real-time wireless sensing and actuation systems is huge, ranging from industrial process control to biomedical applications.

The IEEE 802.15.4 [2] is a wireless personal area network (WPAN) designed to be used in wireless sensor network applications. The IEEE 802.15.4 MAC protocol uses a contention based CSMA/CA algorithm which is unable to provide the quality of service required by real-time applications. The IEEE 802.15.4 standard also provides a guaranteed time slot (GTS) scheme in order to support devices requiring dedicated bandwidth or low latency transmission. However, only 7 GTS allocations per superframe are supported with this scheme, and the granularity of transmission time allocation is coarse since each superframe is composed by just 16 slots.

Most research on MAC protocols for wireless sensor networks [3][4][5][6] consider a multihop ad-hoc network topology, where usually the latency and throughput efficiency are sacrificed in exchange for multihop operation. We instead consider an infrastructure based star topology, where the stations communicate directly with the base station. If required by the application, the range can be extended with the use of more than one base station, like in a cellular network. This topology brings some advantages in the design of the protocol, which can be used to enhance the performance of the system. Firstly, the base station, being mains powered, can take most of the burden of power consumption and channel coordination. Secondly, there is no overhead related with topology discovery and multihop communication.

In order to satisfy the requirements of low-power real-time wireless sensing and actuation applications, we conceived the LPRT protocol and implemented it in the MICAz [7] platform. MICAz motes are originally supplied with the basic CSMA/CA functionalities of the IEEE 802.15.4 standard, but not with the GTS scheme. The proposed protocol is more flexible in the allocation of bandwidth and allows a higher number of active real-time stations than the GTS scheme.

Next section presents a description of LPTR protocol. Section III briefly describers a wireless hydrotherapy application that benefits from the use of the proposed protocol. Experimental results for both the standard IEEE 802.15.4 CSMA/CA protocol and the LPRT protocol are presented in section IV. Finally, the conclusions are presented in section V.

II. Proposed Protocol

The LPRT protocol is a hybrid schedule based dynamic TDMA protocol and contention based CSMA/CA protocol. It defines a superframe structure presented in Fig. 1. Each

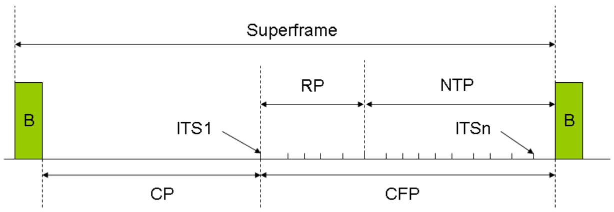

Figure 1. Superframe structure for the LPRT protocol.

superframe is divided in a fixed number of mini-slots (1024, in the current implementation), and starts with the transmission, by the base station, of the respective beacon frame (B), which is followed by the Contention Period (CP). During the CP any station can transmit using the rules of a CSMA/CA protocol. The CP allows the stations to associate with the base station and to request mini-slots for transmission during the Contention Free Period (CFP). It is also used to convey non-real-time asynchronous traffic. Stations must not initiate a CSMA/CA transaction if it cannot be completed before the beginning of the CFP.

The Contention Free Period is placed after the CP. Transmissions during the CFP are determined by the base station using resource grant (RG) information announced previously in the beacon frame of the current superframe. Since the transmissions during the CFP are scheduled by the base station, they are not affected by the hidden station problem, unlike protocols that rely on carrier sensing like the IEEE 802.15.4 CSMA/CA protocol.

The CFP is composed by an optional retransmission period (RP) and a normal transmission period (NTP). The rationale of placing the RP before the NTP is to allow a station to retransmit data corrupted by channel errors before new data is supposed to be transmitted, in order to allow fast data retransmission and to minimize the jitter. This division is not mandatory, however, as retransmissions can be mixed with regular transmissions during the entire CFP period. The retransmission procedure helps to increase the reliability of the protocol, which is fundamental in applications with low loss tolerance.

Fig. 2 shows the structure of the payload of the beacon frame. The superframe duration field gives the duration of the current superframe in multiples of a minimum superframe duration time. It is followed by a list of resource grant (RG) fields, whose quantity is expressed by the RG list length (RLL) field. Each RG is composed by a transmission direction (TD) bit, the association ID (AID) field and an initial transmission slot (ITS) field. The RG allows the scheduling of data transmissions either to or from the station identified by the AID, depending of the value of the TD bit: "0" for downlink and "1" for uplink direction. More than one RG can be granted to a station in the same superframe. The total transmission period granted by a given RG goes from the beginning of respective ITS until before the beginning of the ITS of the next RG on the list. The uplink data can include piggybacked information for alteration of resource allocation parameters, if desired. Other fields may be

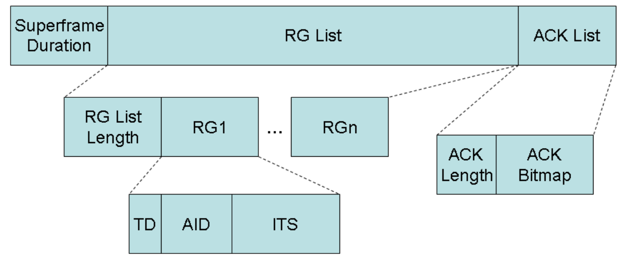

Figure 2. Structure of the beacon frame payload.

included in the payload of the beacon frame; however, the discussion of their functions is out the scope of this paper.

For downlink transmissions the ACK frame follows the data transmission, while for uplink transmissions the acknowledgment is made using the ACK list of the next beacon frame. The piggybacking of acknowledgments in the beacon frame eliminates the power consumption and overhead associated with the reception of individual ACK frames for each uplink data frame. The ACK list is composed by an ACK length (AL) field and an ACK bitmap field containing one bit for each uplink RG of the previous superframe. A successful transmission is indicated by a "1" in the respective bitmap position, while a lost or corrupted transmission is indicated by a "0".

III. Wireless Hydrotherapy Application

The proposed protocol is being tested in a wireless hydrotherapy application composed by a base station and several wireless smart suits. The base station is connected to a computer for data storage and system operator (the therapist) input. Each smart suit contains several sensors that monitor individual biometric data, such as heart rate, respiratory frequency and posture, through the monitoring of the main articulations of the human body (shoulders, spine and hips), as the patient does exercises in the pool.

The wireless network module is placed in a floating device attached to the suit (Fig. 3). To have a convenient signal of the patient activity a minimum sampling rate in the order of 5 Hz is needed. Due to the large number of data being monitored (about 26 sensors) the payload per suit is around 40 bytes per sample. The need for power efficiency, in order to reduce the frequency of replacement of the batteries is a requirement of the system.

IV. Experimental Results

The evaluation scenario is composed by a base station and four stations. Each station collects 36 byte samples periodically, with a sampling rate of 5 Hz, which corresponds to a packet inter-arrival time of 200 ms. We measured the current consumption of the MICAz motes as a function of time, which include both the consumption of the transceiver and of the microcontroller, for the IEEE 802.15.4 CSMA/CA protocol and for the LPRT protocol. Using these charts, we can identify five transceiver operation states: transmitting, receiving, listening, idle (not listening) and sleeping. In all states, except for the sleeping state, the

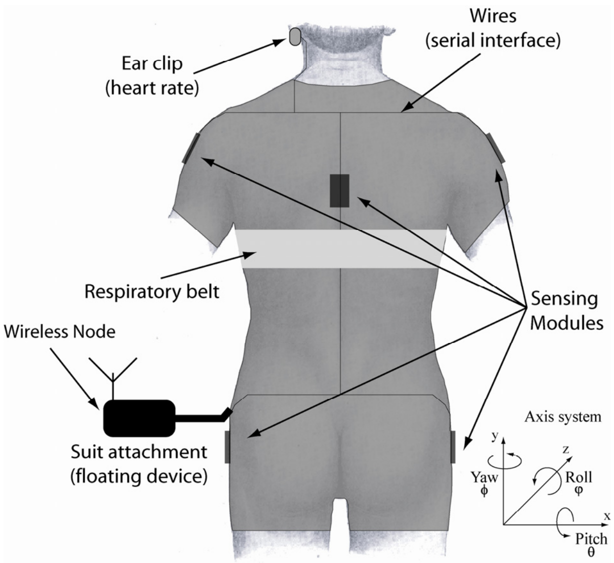

Figure 3. Location of the wireless network module and the sensing modules in the suit.

transceiver consumes approximately the same current. These measurements also allow the identification of the different phases of the communication process.

During the measurements, we noticed that the current consumption of the CSMA/CA using the protocol software supplied with the MICAz motes was almost constant. That means the transceiver was consuming a significant amount of current even when it was idle. We made a modification in the supplied software in order to put the device into the sleeping state instead of the idle state during the periods of inactivity.

Fig. 4 presents the current consumption of the CSMA/CA protocol as a function of time for the beaconless mode using the sleeping state when inactive. It shows the sleeping period before the beginning of the transmission attempt procedure, the backoff period, the data transmission, the reception of the acknowledgment frame and the return to the sleeping state. The current consumption of the device during the inactive state (8 mA) is mostly due to the microcontroller (it was 26 mA before the modification from the idle state to the sleeping state in the software). The

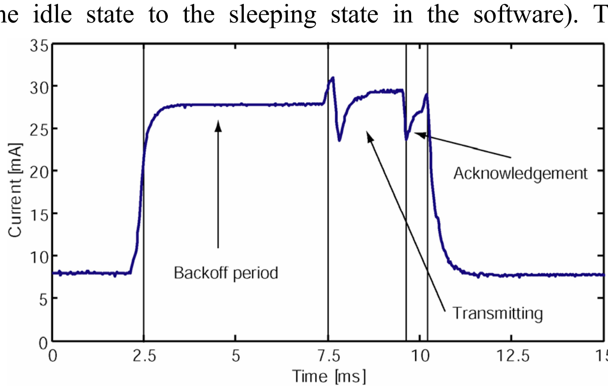

Figure 4. Current consumption of the CSMA/CA protocol as a function of time.

current consumption during the active periods (transmitting, receiving or listening) is much higher, so the minimization of the transceiver activity is paramount to the energy efficiency of the system.

The next results are from the evaluation of the LPRT protocol with four stations in the RG list. The superframe size (200 ms) was chosen to be equal to the packet inter-arrival time. Fig. 5 shows the current consumption for one of the devices for a time range spanning more than a superframe. We can see a first beacon being received by the station, which is used by the base station to announce the allocation of resources in the current superframe and also when the next superframe will start. After receiving the beacon, the station sleeps until the moment scheduled for its transmission. After the transmission, it returns to the sleeping state, waking up again in the next superframe to receive a new beacon containing the acknowledgement of the previous transmission and new allocations.

Fig. 6 presents a closer look to the current consumption charts of the four stations in the RG list, superimposed, where the transmission of each station and the reception of the beacon of the next superframe can be seen. Each superframe is divided in 1024 mini-slots. For a 200 ms superframe, the duration of a mini-slot is around 0.2 ms, allowing a high level of granularity in the allocation of transmission time to the stations. We allocated 16 mini-slots, or 3.125 ms, for each station to make its transmission. This time includes a guard period to avoid the superposition of adjacent transmissions. Transmission position for the first station that associates with the base station is closer to the end of the CFP, and so on, in order to minimize the jitter when a new station associates.

With the evaluation parameters, the proposed protocol allows more than 60 stations per superframe (disregarding a minimum CP period). The data throughput of each station is 1.44 kbps, so the maximum effective throughput for this scenario is more than 84.6 kbps.

Fig. 7 shows the effect of collisions on the performance of the CSMA/CA protocol. The packet inter-arrival time

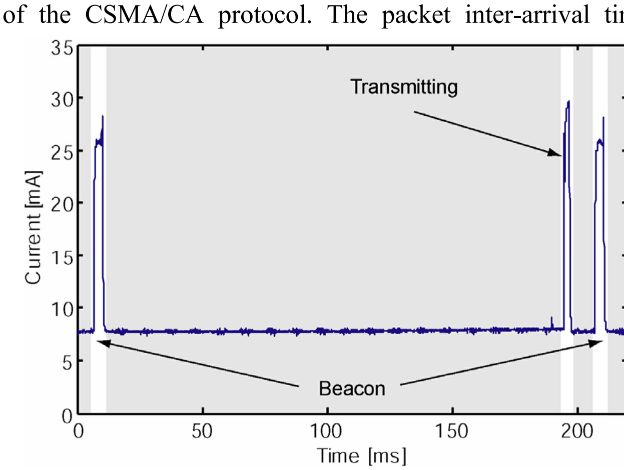

Figure 5. Current consumption of the LPRT protocol as a function of time for one particular station.

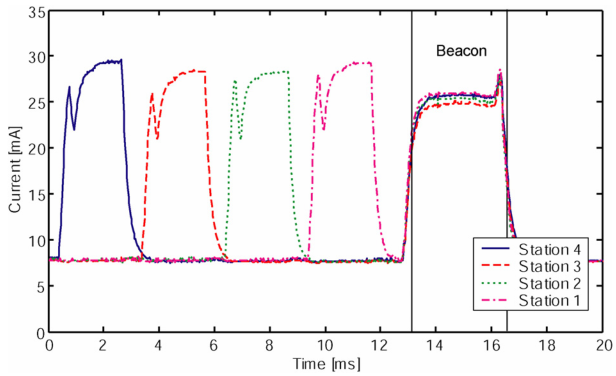

Figure 6. Current consumption of the LPRT protocol as a function of time for the four stations.

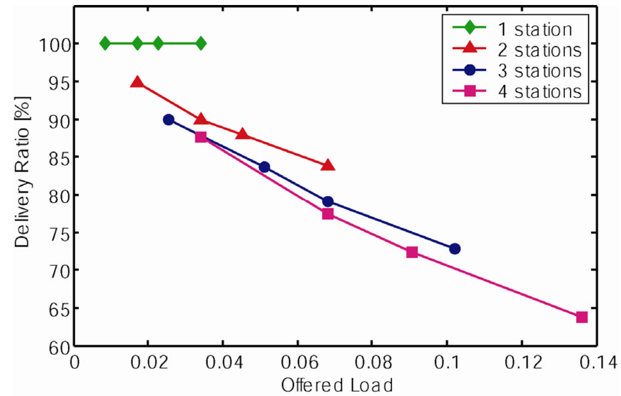

Figure 7. Delivery ratio of the CSMA/CA protocol as a function of the offered load and the number of stations.

was randomly generated from an exponential distribution. For each curve, the offered load increases as the mean inter-arrival time decreases from 200 ms to 100 ms, 75 ms and 50 ms. Even with low loads (below 15 %) and a small number of stations, a great number of frames are lost, which represents a deep impact in the reliability of the protocol. On the other side, since the operation of the LPRT protocol is contention-free, it achieves a 100 % delivery ratio, even with high loads and with a very large number of active stations.

V. Conclusions

This paper presented LPRT, a new protocol for low-power real-time wireless sensing and actuation systems. This protocol enables low power consumption by the terminal stations because they only have to switch on the transceiver to listen to the beacon, which contains allocation information and also acknowledgment feedback, and during the transmission or reception of data. It provides low latency because the scheduled transmissions are contention-free and don't have to follow multiple hops. It is flexible because resources can be reallocated at each superframe, with a high level of granularity, to a large number of stations, according to the demand and the scheduling policy. Also, non-real time traffic can be transmitted using the contention period.

The LPRT protocol provides reliability by the acknowledgement of all data frames and the provision of a fast retransmission mechanism. Since there are no collisions during the CFP, all capacity of the channel can be used for data transmission, except for the small guard periods between the frames, the beacon and the minimum period reserved for the CP at each superframe, which allows the protocol to reach high throughput efficiency.

The comparison of the proposed protocol with the IEEE 802.15.4 CSMA/CA protocol shows that the former is much better suited for handle loss intolerant traffic, especially with high load conditions.

The retransmission procedure is currently being tested in order to evaluate the improvement in reliability that can be achieved with this protocol under channel error scenarios.

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