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Communications protocol for RF-based indoor wireless localization systems

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ABSTRACT

A novel application-specific communications scheme for RF-based indoor wireless localization networks is proposed. In such a system wireless *badges,* attached to people or objects, report positions to wireless *router* units. Badges have very limited communication, energy, and processing capabilities. Routers are responsible for propagating collected badge information hop-by-hop toward one *central unit* of the system and are significantly less constrained by battery than the badges. Each unit can radiate a special sequence of bits at selected frequencies, so that any router in the wireless neighborhood can sense, store, aggregate and forward Received Signal Strength Indicator (RSSI) information. Once the central unit receives RSSI from routers, it calculates the overall relative position of each unit in the system. This new scheme has been developed based on the Chipcon CC1010 Evaluation Module with limited communication capabilities. The implemented protocol rules allow scalability of numerous system parameters. The feasibility of the proposed protocol is simulated on a typical floor – 2-dimensional topology where routers are deployed in a grid fashion. Results show that assuming normal operation and a maximum of thousand badges the system can periodically report about every five seconds. Different scenarios are compared, and the proposed scheme is demonstrated to meet strict reliability requirements while providing energy-efficient badges and an acceptable level of latency.

Keywords: wireless sensor networks, wireless communications and localization

1. INTRODUCTION

Advances in microelectronics and communication technologies have enabled the use of small-scale and cost-effective wireless sensor network (WSN) systems to support numerous applications. However, these tiny sensor devices have strict limitations on communication capability, energy, processing and storage capacity. Hence, the application needs are subject to these limitations.

This paper presents a trade-off protocol solution for communications in an RF-based wireless indoor localization system. The *wireless positioning task* is to localize nodes (badges) attached to people or objects within a certain area. GPS can not operate inside buildings or closed areas. Therefore, there is a need for more sophisticated methods for special-purpose indoor localization WSNs. In this hierarchical system, there are three types of communicating entities: i. *Badges (sources)*: report location information periodically; ii. *Routers*: collect information from badges within a certain area; iii. *Central Monitoring/Management Station (CMS) (sink)*: receives, stores and processes incoming data, providing an interface for an external observer.

Each unit periodically sends out signals at multiple frequencies to its router neighbors. Routers can not only detect the existence of a unit, but they can also measure, store and calculate incoming signal strength information (RSSI bits). A router has three major functionalities. First, it collects information from badges within its antenna range. Second, it receives communication frames from other router(s). Third, it forwards the aggregated data toward the CMS. The CMS is responsible for processing incoming data and calculating unit positions based on the received signal strength values; it also provides network management functions. Badges are expected to move frequently, while routers are assumed not to change their positions. However, the network must also handle emergency monitoring situations where routers are

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deployed one-by-one in a quick manner. Badge-router (B-R interface) and router-router (R-R) communications must be coordinated in order that radiated signals do not interfere. Furthermore, each router should know which neighbor to route information to.

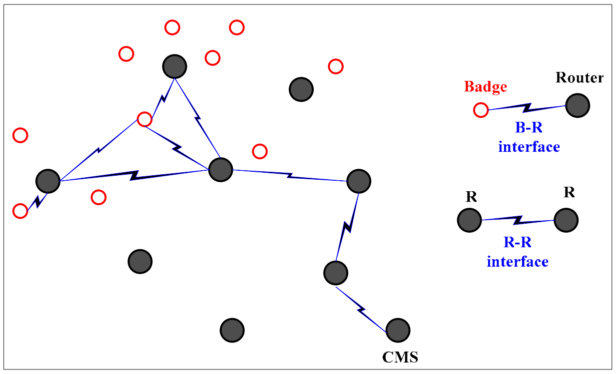

Figure 1: Wireless Indoor Localization Network

Figure 2: Chipcon CC1010EM with Antenna

In this paper, a new Wireless Indoor Localization System Protocol (WILSP) is introduced, detailed, analyzed, simulated and scaled. This WILSP is an application-specific routing and communication protocol for the RF-based wireless indoor localization system. The badge and router communications are constrained by the Chipcon CC1010EM capabilities. The antenna can operate in the 300MHz-1000MHz frequency range, its typical center frequency being in the 900 MHz ISM band. Its range is 10-15 meters (indoor), and its raw data bit rate is 76.8 Kbps[1]. For storing the program code, only the 32 KB of flash memory is used. The code contains two main functional parts: 1. the handling of RSSI bytes for the localization algorithm, and 2. the code needed for communication, e.g. information transfer/routing purposes. Localization consumes about half of the available memory of the chips. Therefore, communication protocol code at routers should be simple enough to fit into 16 Kbytes.

Reliability represents the major requirement; furthermore, the protocol should adapt well to emergency situations. The existence of a reliable localization algorithm is assumed, such that based on the received signal strength data from routers, CMS can calculate relative and absolute positions of every unit at a desired level of accuracy.

This paper is organized as follows. After the introduction, the second section classifies related research activity. Considering trade-offs, an FDMA/TDMA-based medium access protocol is proposed for badge-router (B-R) and router-router (R-R) communications for the presented application-specific system. Section 3 characterizes the system including normal mode and emergency operations, and the unique data collection requirements. The following section introduces scenarios and scheduling of unit operations. Section 5 analyzes WILSP efficiency, overall capabilities and local and global limitations as well. In order to evaluate the features of the new scheme, the OPNET[2] network simulator environment is used. Validation results of grid network scenarios reflect theoretical implications. In closing, section 7 summarizes the conclusions and research experience and envisions future work.

2. RELATED RESEARCH

Langendoen and Halkes[3] classify wireless sensor network MAC protocols using three factors: the number of physical channels used, the degree of organization (or independence) between nodes, and the way in which a node is notified of an incoming message.

Considering the number of physical channels used, most protocol investigations assume a single radio for each unit and propose a code division (CDMA in PicoRadio[4]), time division (TDMA in S-MAC[5], T-MAC[3], SS-TDMA[6]) or frequency division (FDMA) technique or the combined use of them (FDMA/TDMA in SMACS[7]). Since Chipcon capabilities are limited and CDMA-like solutions require an extended level of computational power, FDMA and TDMA are supposed to be used in a Chipcon-based application-specific system. In general, the use of TDMA has several advantages including energy-awareness, predictability and testability; but one has to deal with complicated synchronization, slot distribution and management issues. As it is presented in SMACS[7], over a basic TDMA, the number of available node-to-node links can be increased by the use of different allocated frequency channels (FDMA). FDMA provides an excellent opportunity to prevent collisions when two or more hierarchical levels exist in the system under development.

Data transfer can be non-organized (random or carrier-sense protocols), or organized into time slots (DMAC[8], GANGS[9]) or frames (LEACH[10], LMAC[11]). In general, low implementation complexity, ad-hoc nature, and flexibility represent the major advantages of random access protocols. On the contrary, a frame-based TDMA is more reliable, and - due to the lower number of expected collisions, overhearing, and idle-listening - it is more *energy-efficient*. In slot-based investigations nodes agree on a common slot structure, allowing them to implement an energy-efficient duty cycle regime: nodes are awake in the first part of each slot and go to sleep in the second part. TDMA has to handle dynamic allocation rules and synchronization issues. In scheduled (contention-free) notifications the transfer is scheduled ahead of time. This is important for energy-efficient systems, so that receivers know when to turn on their radios. The opposite of this method is when there is no coordination in the system; the receivers should listen all the time (for example at CSMA).

Overall, the new protocol should follow FDMA/TDMA rules. In order to provide reliability in both normal and emergency levels, TDMA must be contention-free: frame-based in general and preferably slotted at badges. For the optimal mixed use of TDMA and FDMA in a hierarchical system, one has to take application-specific features including hardware characteristics into account. Additionally, the protocol design should consider possible application-oriented specifics such as deployment scenario, required flexibility/adaptability, algorithmic complexity and latency requirements.

3. CHARACTERIZATION OF AN APPLICATION-SPECIFIC WIRELESS INDOOR LOCALIZATION SYSTEM

3.1. Description of the System

The first section envisioned and partially introduced a concept of a routing protocol for the RF-based wireless indoor localization system. In a typical scenario, router functionalities can be integrated into smoke detectors of buildings, or manually attached to walls. Badges can be attached to people or objects. When a badge detects short and periodical broadcast (beacon) signals of routers it begins to periodically send out special RSSI byte sequences at multiple frequencies. The packet containing RSSI bytes at multiple frequencies is identified as a *MultiRSSI packet*. Upon reception of an incoming RSSI sequence, the router unit measures the received signal strength values for each frequency. It keeps the two strongest RSSI values and their corresponding frequencies. Finally, the router creates a *Badge Entry* and stores the information collected about the badge. A Badge Entry contains four fields: badge identifier (ID), detector router ID, time stamp and RSSI information (strongest and second strongest RSSI values measured). Regardless of its functionality, each unit (including CMS) has its own, unique ID in the system. IDs are allocated either by software or by pre-programming the hardware.

If more routers show up in one badge's wireless neighborhood, the badge sends out MultiRSSI packets periodically to all of them or to a selected set of routers. Therefore, badges are expected to generate data to be forwarded to routers in the wireless neighborhood. Data generation patterns follow application-specific rules. This *data collection requirement* makes this application-specific system *unique* among wireless localization networks.

Routers communicate with each other and propagate Badge Entry information toward a CMS. The CMS is a powerful computer located at a specific position in the building, for example in an observer or security office. Data packets are forwarded router-by-router in a *multi-hop fashion*. CMS stores and processes the incoming data. It calculates the position of units by knowing relative router locations and incoming RSSI data[†]. The more routers provide data about a badge, the more accurate the localization of that badge. CMS also runs applications that show the map of badge and router positions for external observers. (Note that from this point the theoretical model is being introduced for a two-dimensional system. Analogically the network can operate as a three-dimensional system as well.)

[†] For the calculation of unit locations based on relative router positions and RSSI values, a patented technology by SuperiorMethods Inc. is applied.

3.2. Normal (Stationary) and Emergency Modes

The system is flexible and adaptive. In emergency situations when routers are distributed in a quick manner - in a building on fire for example– routers are capable of reliably communicating badges' information. Badges and routers have the same communication properties, except that routers are expected to have higher sources of energy.

There are two major modes of operations in the proposed system. *Stationary mode* is normal operation of in-building wireless surveillance and monitoring of badges. It is expected that badges show up on the "edges" of the network – particularly at the entrances of a building – and then routers track and periodically report badges' RSSI information. In stationary mode, communications' performance can be improved if a router sends new RSSI data when the sender unit's RSSI is *significantly different* from the previous measurement results. For example, if a person works on a computer station for hours and her/his position does not change this information does not to be transmitted since RSSI does not change. Neighboring routers should not necessarily send the full and very similar RSSI data over and over again. Only the *delta*s e.g. significant differences should be sent. Furthermore, theoretical traffic pattern models can be determined in order to improve network efficiency by prediction of possible future positions. Routers are to be stuck to walls or ceilings in rooms and corridors. An obvious solution is to integrate cheap router functionality, including antennas, into smoke detectors.

In the case of *emergency (ad-hoc) mode*, people walk or run around in a building and stick router units one-by-one to walls or obstacles. In this situation, routers form a fast-changing ad-hoc network and collect information about surrounding badges. In this scenario, a new router should be quickly recognized by its neighbors so that the overall reaction time of the system would be reduced compared to that of stationary mode operation. *Reliability* of the system in both modes of operation is the most important issue; while *energy-efficiency* represents a secondary issue.

4. WIRELESS INDOOR LOCALIZATION SYSTEM PROTOCOL (WILSP)

4.1. Router Scheduling

For router communications let us consider the mixed use of TDMA and FDMA in the following scheduling (Figure 3). Each router in the system has a fixed length time frame (called time *epoch*) when it can send and receive. The fixed length time epoch contains three major sequential phases. At communication frequency f_M, Management Time (T_M) is reserved for radiation of scheduling and frame synchronization information including uplink and downlink management data transfer. It always starts with a fixed size EPOCH START broadcast frame so that units listening to frequency f_M in the wireless neighborhood can synchronize to possible future transmissions. Every unit knows frequency f_M in the system.

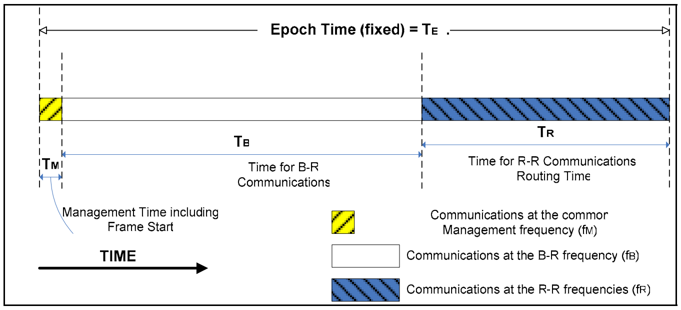

Figure 3: Fixed Time Epoch – Router Scheduling

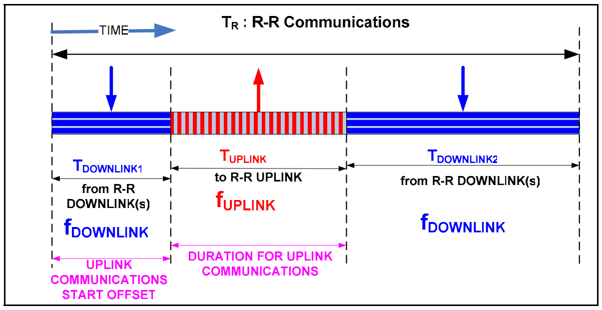

Figure 4: R-R UPLINK and DOWNLINK Communications, Durations and Frequencies

Time for Badge-Router (B-R) communications (T_B) is reserved for badge RSSI information when badges report their MultiRSSI data to the router(s). Badges in this phase send a MultiRSSI packet and upon successful reception, the router stores RSSI information and immediately bounces back a short acknowledge (ACK). During T_B, only badges are allowed to initiate communications. The router switches to the base frequency f_B and listens to MultiRSSI packet starts. MultiRSSI packet transmission takes place at multiple pre-assigned frequencies from the frequency set F_{RSSI}. In order to meet accuracy requirements, our assumption is that bytes for RSSI calculations are sent repeatedly at 10 different frequencies. Communications during T_B follow an ALOHA-like protocol.

Time for Router-Router (R-R) communications (T_R) is reserved for communicating with other router units. When the router is initialized and allowed to store and forward data, its initialization packet from CMS contains its individual UPLINK and DOWNLINK frequencies (f_{UPLINK} and $f_{DOWNLINK}$) and additionally the time assigned to communicate with its only UPLINK neighbor. When the assigned time comes, the router reports all of its data to UPLINK by the use of data packets. Each packet is positively acknowledged by the UPLINK node (router). During the remaining time of T_R, the router listens to its DOWNLINK frequency ($f_{DOWNLINK}$) and collects information from DOWNLINK connections (if any).

At the end of the R-R phase, a new time epoch starts with the radiation of the beacon scheduling start information of T_M. During normal and active operation of a router, the time epoch is repeated until new CMS management message arrives. From the communication point of view, CMS is also considered as a router in the system: the destination sink unit of all collected badge data.

4.2. Badge Operations

When a badge starts working, it first listens to the medium at frequency f_M and looks for router EPOCH START broadcast frame containing the source ID. Upon detection of the frame, the badge checks whether the originator router ID is already in the *associated routers' table*. A router is *associated* to a badge if and only if the badge periodically and successfully can report its MultiRSSI data to that router unit. When the badge finds router ID in the table, it synchronizes to the EPOCH START frame and goes back to listening. In case the router ID is not in the table, it goes into a *time slot exploration cycle* and waits until T_B starts in the detected routers' schedule. From a badge's point of view, T_B time assigned for B-R communications is divided into equal-length time slots. Badges know in advance how many time slots T_B contains (note that T_M, T_B and T_R are expected to be constant values in the system). When T_B begins, the badge starts listening at frequency f_B, and if traffic of other badges or routers is detected, it recognizes the corresponding time slot as occupied. At the end of T_B the badge picks one and only one of the set of available free time slots, and sets the router ID as associated to the selected time slot. (Time slot selection is random by default or can follow a strategy for different occupation patterns. Note that for simulations only the random selection is investigated.) Furthermore, it sets a timer when it periodically radiates its MultiRSSI packet in the selected time slot of the associated routers schedule (periodic time is epoch time T_E). MultiRSSI packet contains the destination router ID. The transmission is determined to be successful if the badge receives a positive acknowledgment from the destined router before the time slot's time expires. In case no acknowledgement arrives, the badge sets the time slot as unavailable and picks another slot out of the set of available time slots and retries sending in that newly selected slot. The badge continues this process until it receives positive acknowledgement from the destination unit. In case the router stops radiating broadcast EPOCH START frames, the badge gives up further attempts.

One badge is expected to send MultiRSSI periodically to more than one of its router neighbors. Obviously, as different routers' schedule starts and loads differ, the badge has different MultiRSSI sending times. For example, if the number of associated routers is three, the badge sends its RSSI bytes three times within one epoch time, one for each associated router.

Several routers may show up in a badge's wireless range. In order to avoid the over-occupation of the B-R interface with the signals of the badge, the possible number of associated routers must be limited. On the other hand this limitation may decrease the accuracy of the localization method. Considering the trade-offs, accuracy expectations and possible normal operation scenarios, this limit was set to four. This means that a badge is allowed to be associated with up to four routers.

4.3. System initialization

System initialization is rooted in and fully controlled by the CMS unit. During initialization, it is assumed that CMS can calculate system elements' positions with certain accuracy based on the incoming RSSI information relative to each units wireless neighbor routers. Having location data, CMS sets up an internal map of the system elements throughout the network and is able to present data directly to users or other applications.

Each router in the system first shows up as a badge and communicates its MultiRSSI exactly the same way as it is described in badge operations. CMS receives RSSI data of a unit, and by checking the ID of the unit CMS can determine whether it is a badge or a router. If router is detected, the CMS calculates an *optimal tree routing* for the system, considering traffic patterns, router connections, delay requirements, routing change costs and reliability issues. In order to avoid major collisions during T_M, the wireless neighboring routers' T_M schedule must not overlap; and for each router, the wireless two-hop neighborhood routers' T_M schedule must not overlap – because of the *hidden terminal problem* effects.

Optimal tree routing assumes that every router (except CMS itself) has one and only one UPLINK connection toward CMS. Once the optimal routing tree is calculated, CMS breaks down the global result to individual routers, and for each router unit it determines UPLINK neighbor ID, epoch schedule start offset relatively to UPLINK (or reference) neighbor, UPLINK communications start and duration in T_R and UPLINK and DOWNLINK frequencies (f_{UPLINK}, $f_{DOWNLINK}$) in T_R.

Acting as a badge, a router still listens to its router neighbors' T_M schedule and waits for authorization in a management packet originated from CMS. Upon reception, it starts operating in router mode using the parameters received. At the beginning CMS is the only router element in the system. When it detects units with router IDs in the neighborhood, it calculates routing and offsets and disseminates management information during its T_M.

4.4. Scenarios for Scheduling Time Epoch Offsets

If more router units are within the wireless range of each other, collision will occur when both radiates at the same time and at the same frequency. For the B-R interface, the slotted ALOHA-like protocol ensures that even if collisions occur, the communication would converge to a collision-free stable state. Routers send acknowledgments in time slots when they successfully receive packets from badges. For the R-R interface wise collision-free time and frequency band arrangements optimized by the CMS ensures the avoidance of collisions. However, during T_M time interval in a router schedule, no communication at f_M is allowed in its wireless 1-hop router neighborhood, and no initialization of communication is allowed by the routers in its wireless 2-hop neighborhood.

Simple Scenario for Scheduling Time Epoch Offsets

A base case with one CMS, one router (R1) and three badges (B1, B2 and B3) is investigated as depicted in Figure 5.

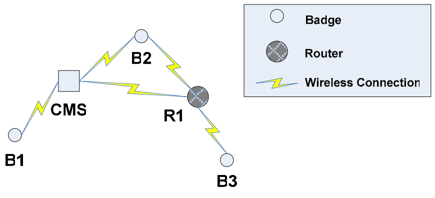

Figure 5: Simple Scenario – CMS, One Router and Three Badges

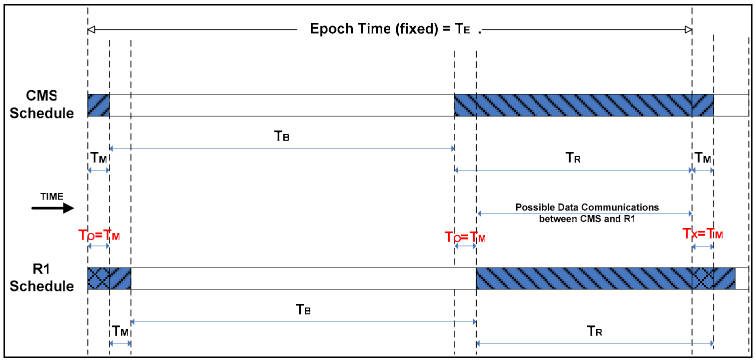

Figure 6: Simple Scenario – Time Offset Setting

CMS and R1 should start their time epochs at different times, because their T_M times are not allowed to overlap. It also means that the difference (Time Offset or T_O) between the schedules should be at least T_M.

The ultimate question here is that what should be the optimal T_O for router R1 in order to achieve an optimal schedule for communications. T_M must not be greater than T_O. If T_O is greater than T_M, then for a T_O-T_M duration CMS should be able to calculate and schedule R-R communications. This would split up TR time interval of the downlink unit and would be more difficult to handle. Additionally, the longer TO is, the less time can be allocated for CMS – R1 R-R communications. Therefore, it is a good strategy to set TO=TM (Figure 6).

Grid Structure Scenario

Figure 7 shows a typical scenario setting when on one floor of a building routers have been placed into a grid structure around CMS.

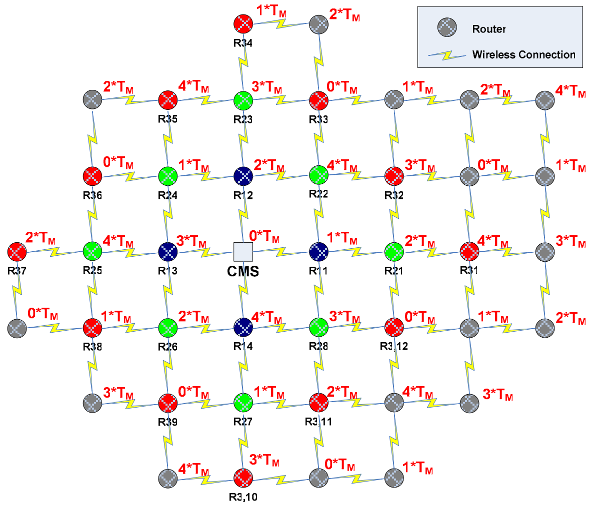

Figure 7: Grid Structure Scenario – Topology and Offset Assignment

In Figure 7, routers are differentiated by two index numbers. The first indicates how many hops away the router is from CMS. For example, R23 is the third router in the two-hop neighborhood. CMS starts its schedule and R11 should have an offset of TO=TM as it was discussed previously. During the TM time R11 radiates its management information, R12 is not allowed to send or receive at fM, therefore, R12's offset time should be set to 2 * TM. Similarly, offset of R13 should be set to 3 * TM, and offset time of R14 should be set to 4 * TM. The number of possible offset values should be as small as possible. Considering that CMS has zero offset, in this scenario there are five offset values altogether: 0 * TM, 1 * TM, 2 * TM, 3 * TM, 4 * TM.

Starting from CMS, one can incrementally assign one by one the offset values to the remaining router units so that their TM durations would not overlap at any points of the communications pane. Figure 7 shows one possible way of assignment. Indicated offset values are relative to CMS's schedule. For the 3-hop wireless neighborhood of CMS it is allowed to re-use the original offset of CMS (TO=0).

5. ANALYSIS ON WILSP IN A CHIPCON-BASED SYSTEM

5.1. Uplink and Downlink Frequency Channels

Based on the considerations of Chipcon documentation[1] for a 2-level FSK encoding, independent frequency channels can be used in every 0.5 MHz. In the 26 MHz-wide 902 MHz-928 MHz ISM band, roughly 26/0.5=52 frequency sub-bands can be allocated. Therefore the number of the available frequency channels for the system used is 52.

For the R-R communications phase, each router unit has one UPLINK and one DOWNLINK frequency assigned by CMS upon authorization. The decision about the values of these frequencies at CMS is a simple process. CMS assigns frequency channels by choosing frequencies out of the available frequency set so that it takes one channel that has not been used before or takes the one that is different from the frequency channels of one-hop and two-hop wireless neighbors of the particular router unit as depicted in Figure 8. CMS can control and organize the structure of active routers so that frequencies for UPLINK and DOWNLINK communications would not overlap. Moreover, in both normal and emergency situations, it is very unlikely that tens of routers show up within a 20-30 m diameter region. It has to be noted that frequency channels can be re-used if necessary in larger networks.

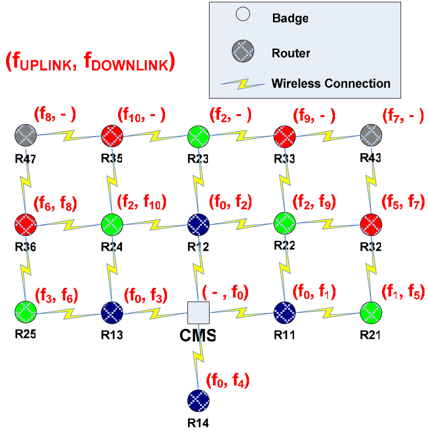

Figure 8: (UPLINK, DOWNLINK) frequencies

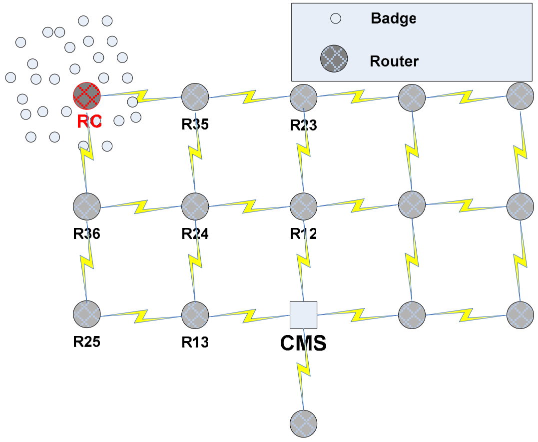

Figure 9: Cafeteria Problem – Router R_C is Heavily Loaded

Figure 8 presents one possible way of frequency channel assignments in a grid topology. CMS does not have UPLINK. For the edge leaf nodes of the router topology graph, CMS may (R_{14}) or may not (R_{23}) assign a DOWNLINK frequency in advance, because in case of stationary mode, no DOWLINK traffic is expected. Edge routers can go to processing or sleeping mode during R-R DOWNLINK communications times. However, if a new router shows up in one of the neighborhood of a leaf router, CMS needs time to let the leaf node know about its assigned R-R DOWNLINK frequency. In emergency mode, CMS always assigns DOWNLINK frequency when authorizing routers.

5.2. Local Limitations

Let t_{ts} denote slot time. The upper bound on the number of badges that can be associated to the given router unit is:

$$\frac{T_B}{t_{ts}} = N_{MAX} = N \cdot$$

Assuming an errorless wireless channel with no propagation delay, the minimum time for sending a MultiRSSI and receiving an ACK is:

$$t_{\min} = \frac{Size(Multi\_RSSI) + Size(ACK)}{r} = \frac{199bytes + 22bytes}{76800bps} \approx 0.023\, s \cdot$$

Considering propagation delays and expected guard times, the proposed value for t_{ts} is set to 0.025 seconds or 25 milliseconds. For normal operations, no more than 100 - 150 slots per router is expected. Note that the larger this value is the more time is allocated for T_B in every epoch in the system. For 120 time slots, T_B results in 3 seconds. Hence by setting T_B to 3s, one router can collect RSSI data for up to 120 badges locally.

Cafeteria Problem

A special scenario is the so-called "*Cafeteria*" *problem*, when only one or some small number of routers collect RSSI information from a big number of badges[‡]. In this case, badges are concentrated and expected to show up at one specific area of the network (Figure 9). Therefore, badge distribution density increases. In the Cafeteria problem, local constraints also limit the number of units the overloaded router (Rc on Figure 9) can handle. Note that if more routers are deployed in the cafeteria area, the system can collect data about more badges than the set number specified by the local limit. However, one badge should not have more than four routers associated. With it, even if router density is high, the amount of RSSI data traffic generated by one badge is limited to four Badge Entries.

[‡] Cafeteria problem represents the phenomenon when people come together in a cafeteria area and having chats at tables or bars. Density of attached badges is expected to increase and routers of the area collect more information.

5.3. R-R Communications – System-wide Limitations

As depicted in Figure 4 at the R-R interface, data to be forwarded to UPLINK consists of two components data received from DOWNLINK and data collected from badges locally.

For CMS, $T_{UPLINK} = 0$. At a non-CMS router unit, when no local badge traffic is detected, ideally T_{UPLINK} should be equal to $T_{DOWNLINK}$, because approximately the same amount of time is necessary to forward the incoming information. The router acts as a simple relay of incoming data. Bottlenecks for R-R communications may appear basically at any routers of the system, depending on the configuration, R-R load and collected local data. Considering 8 byte-long Badge Entries and that one R-R Data Frame can carry up to 30 Badge Entries. For one data frame, the size can be calculated as:

$$Data\_Frame\_size = 23\ bytes + N_{BE} * 8$$

where N_{BE} denotes the number of Badge Entries. For more than 30 Entries, a second data frame is needed. The number of frames needed to transmit N_{BE} Badge Entries is calculated as:

$$N_{FRAMES} = \left\lceil \frac{N_{BE}}{30} \right\rceil = CEILING\left(\frac{N_{BE}}{30} \right)$$

Each Data Frame packet has to be positively acknowledged by a 22-byte-long ACK. Assuming an errorless wireless channel with no propagation delay, the time needed to send N_{BE} Badge Entries is:

$$T_{NBE} = \frac{\left(\left\lceil \frac{N_{BE}}{30} \right\rceil \right) * (23bytes + 22bytes) + N_{BE} * 8bytes}{r}$$

The following table shows the values for some typical Badge Entry numbers.

N_{BE}	Time to Communicate R-R Data (T_{NBE}, sec)
120	0.119
200	0.200
600	0.594

The increase of about 100 badges results in a linear increase of R-R time to send of about 0.1 seconds.

5.4. Duration of Management Phase (T_M)

At the start of each Management Phase, an EPOCH START fixed size packet is sent indicating the start of the epoch of the router unit. Since EPOCH START is a broadcast packet, no acknowledge is sent by the receiving party upon reception. Neighboring units take synchronization information and set or modify their schedules if necessary.

If further management information frame is sent during T_M, then depending on the value of the Destination Unit Schedule Information, its size is between 32 bytes and 270 bytes. Each management information frame is to be positively acknowledged. When the frame is sent, a timer is set and if no ACK comes from the other party at frequency f_M until the timer expires, the frame is retransmitted and the timer is reset. In case duration T_M ends and no ACK has arrived yet, the frame is retransmitted in the next epochs Management Phase. Under normal circumstances, no management frame is allowed to be lost. In case one or more routers of the network should go down, CMS will know about it because of missing incoming data from the damaged region of the system. In this case, CMS would be able to re-calculate routes and assign a more optimal way of receiving and forwarding data at routers. The Management Phase is the most protected out of the three phases in WILSP. That is why a unique frequency and time slot are assigned for management, signaling and control operations. For an errorless wireless channel with no propagation delay:

$$T_M = \frac{size\_of(EPOCH\_START) + \sum_{i=1}^{n} \left[\exp ected\_size\_of(MAN_i) + size\_of(ACK) \right]}{r},$$

where n is the expected maximum number of management packets to be propagated in the Management Phase. For n=5, assuming that the average expected size of management packet is 38 bytes (containing 6 bytes of HOP_ID_SEQUENCEs on average), the throughput factor is $\alpha = 75\%$ [12]:

$$T_M = \frac{22bytes + 5 * (38bytes + 22bytes)}{\alpha * r} \approx 0.045 \sec$$

Additionally, taking guard times and propagation delays into account, the proposed value for T_M results in at least 0.05 seconds.

5.5. Building a Routing Tree

CMS is responsible for building a routing tree rooted by itself. It also decides R-R communications timing, UPLINK and DOWNLINK offsets and frequencies so that the information collection process meets delay, reliability, accuracy, flexibility or other user-defined requirements. CMS can directly use or combine basically all the centralized routing ideas of the scientific literature. It can use heuristics, simulation-based algorithms as well as automatic algorithms. Its high-level processing power makes the decision-making quick and easily controllable at any time. It can also be upgraded/modified if major parameters of the network change. CMS considers topology, expected and actual number of active routers, expected and actual distribution and number active routers, expected and actual distribution and number of badges detected. A broad range of different routing-tree building methods are to be applied. Since routing decisions are centralized, testing and scaling the network protocol becomes feasible at CMS at a low-cost. This makes the further developments of application-specific centralized routing algorithms much easier. For emergency situations, special boundaries on certain parameters change routing decisions and may provide different routes than that of normal (or stationary) operations.

6. SIMULATIONS

In OPNET (*Optimized Network Engineering Tool*[2]) Modeler, each node's process model description the same transmitter and receiver „boxes" and characteristics are applied to physical layer communications. Both receiver and transmitter units implement FSK2 modulation for simulation purposes, data rate is set to 76800 bps, channel bandwidth is 500 kHz and minimum frequency is 902 MHz. At CMS, routing details have been set either manually or by the use of a simple "greedy" tree-building algorithm on the basis of First-Come-First-Serve for the routers.

6.1. Router Grid Topology Setup

The grid topology contains the CMS and 15 routers deployed in a grid fashion (Figure 8). The smallest distance between two routers as well as antenna range in this grid is 10 meters. For simulating the initialization process of routers, CMS sets up the routing tree depicted on Figure 10. Once CMS receives a units' router ID data, it immediately bounces back an authorization management packet. Upon reception of this packet, the final destination router starts its routing schedule. Absolute EPOCH START offsets are set as they are defined on Figure 7 for routers in the same positions. Note, that routers receive the relative offset to their reference neighbors. For example, R24's absolute offset to CMS's schedule is (1)* T_M and the UPLINK (R12) has the absolute offset of (2) * T_M. Calculating [(1) * T_M]- [(2) * T_M] = (-1) * T_M , the relative offset of R24 results in (-1) * T_M. UPLINK and DOWNLINK communications frequencies are assigned based on Figure 8.

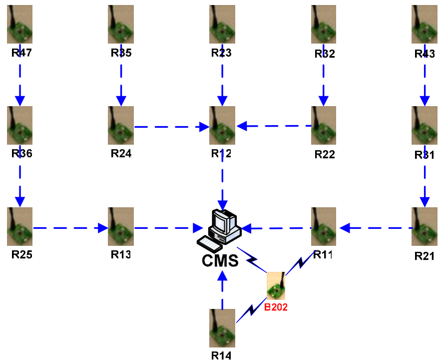

Figure 10: Routing Tree for Grid Topology

For the calculations of UPLINK and DOWNLINK communications starting times and durations of routers, a heuristic method is used. Starting from the CMS, the available DOWNLINK bandwidth is divided into portions by the number of DOWNLINK connections. After that – if it is possible – equal-length portions are assigned to each DOWNLINK router.

Later, if badge traffic level makes it necessary, linear *weight*s are used to assign larger bandwidth (time) for DOWNLINK routers having more traffic.

Epoch time is 5 seconds, (T_M, T_B, T_R) triplet is set to (0.1s, 3.6s, 1.3s). Slot time is 0.03 seconds. Therefore, each router can handle up to 120 badges locally.

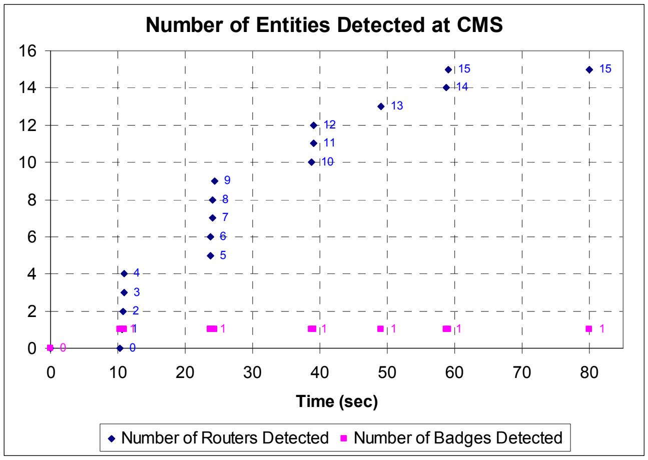

Figure 11: Number of Entities Detected at CMS

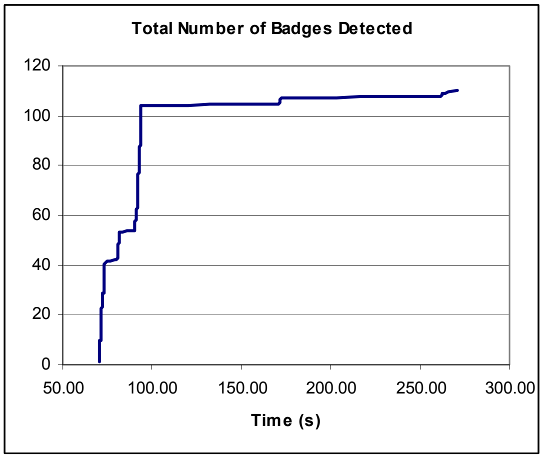

Figure 12: Cafeteria, Number of Badges Detected at R47

WILSP protocol's simulation shows that after the initialization transients, the system periodically tracks badge B_202. In this setup the protocol ensures that all routers wake up and become active in 65 seconds.

There is a significant delay between the recognition of a router unit at CMS and the start of its active routing mode. For 15 routers, the overall average delay is 5.72 seconds. Results showed that routers R21, R23 and R24 receive control information faster than other units. The reason of this latency difference is that DOWNLINK information path contains only *positive* relative EPOCH START offset values. As an example, for R21 (Figure 13), management information from CMS is received by R11 and forwarded in the following T_M interval to R21. Since R21 has a positive relative offset, it can start its schedule immediately after its R11 uplink T_M.

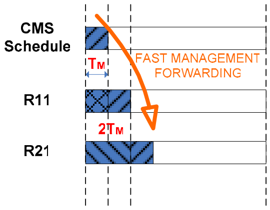

Figure 13: Fast Forwarding of Management Information

Contrarily, considering the data path to R35, R12 receives and forwards management packet but R24 - having a *negative* relative offset, it can forward it to R35 only at the start of its next time epoch. It means that R35 has to wait for at least one epoch time for its authorization and later any other management data from CMS.

In Cafeteria simulations, router topology, original scheduling and system parameters and settings do not change (see Figure 9). Around Router R47, 120 badges are deployed (ID range is between 202 and 321). Results show that in this Cafeteria scenario, R47 can detect 110 out of the total number of 120 badges. R47 starts its active routing schedule at simulation time 70.2 seconds. After a 0.1 seconds management time, it begins the collection of badge data. R47, however, has to listen to its two neighbors' management times for synchronization purposes, during their T_M. For two units, it is 2 * 0.1 seconds. Since time slot interval is set to 0.03 seconds, T_M /0.03 seconds ≈ 3.33. T_M –long listening period makes three full time slots unavailable, additionally, it prevents communications at the end of one and at the start of an another slot – a total of five time slots become unavailable. Thus two T_Ms result in 10 unavailable time slots at R47. It explains why only 110 free slots can be occupied by badges. Figure 12 shows the increase of total number of badges detected by R47. Starting from 65.2 seconds simulation time, R47 is considered to be active. The ALOHA-like protocol for badges provides fast startups at 70-80 seconds. However, some of the badges will get their schedules much later.

7. SUMMARY AND FUTURE WORK

This paper proposes the use of a novel communications scheme for application-specific wireless indoor localization systems. In such a system, wireless badges attached to people or devices send periodical RSSI bytes at several selected frequencies to wireless router units. Wireless Indoor Localization System Protocol (WILSP) introduces an FDMA/TDMA method for wireless communications. At routers, in a fixed time epoch three major phases have been distinguished. B-R communications time (T_B) is proportional to the number of badges an individual router can handle epoch-by-epoch. Time epoch offsets of different routers are to be set to the multiple values of T_M.

OPNET simulation results prove that WILSP performs well in grid-structure scenarios, and the multi-hop scheme introduced meets the specified requirements. The choice of positive relative EPOCH START offsets results in less router initialization times. Cafeteria scenario results prove that the protocol can handle situations at a high reliability even if the number of badges becomes high in the neighborhood of one or more particular router units.

Further improvements on the top of WILSP may include delta-policy, the use of temporary IDs, a multiple-zone routing scheme and time slot occupation bit-map in the management phase. Future hardware improvements offer different, better characteristics and more flexibility in terms of radio range, code space, energy dissipation and raw data rate. Controllability of radiated power of communicating entities makes the protocol more robust. At badge level, this is of high importance because by assigning the proper communications range, more energy can be conserved. Meanwhile at routers, connectivity of the wireless connections' graph can be controlled within certain limits. Integration of radiated power control features represents the next challenge in the development process of a more advanced wireless indoor localization system.

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