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Youssef Zatout, Rahim Kacimi, Jean-François Llibre, Eric Campo. Mobility-aware protocol for wireless sensor networks in health-care monitoring. Consumer Communications and Networking Conference (CCNC), 2011 IEEE, Jan 2011, Las Vegas, United States. hal-01695428

HAL Id: hal-01695428

<https://hal.science/hal-01695428>

Submitted on 29 Jan 2018

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To link to this article : DOI:10.1109/CCNC.2011.5766319
URL : <http://dx.doi.org/10.1109/CCNC.2011.5766319>

To cite this version : Zatout, Youssouf  and Kacimi, Rahim  and Llibre, Jean-François  and Campo, Eric *Mobility-aware Protocol for Wireless Sensor Networks in Health-care Monitoring*. (2011) In: Consumer Communications and Networking Conference (CCNC), 2011 IEEE, 9 January 2011 - 12 January 2011 (Las Vegas, United States).

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Mobility-aware Protocol for Wireless Sensor Networks in Health-care Monitoring

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Abstract—Health-care monitoring with Wireless Sensor Networks (WSN) has become a major interest during the last few years. The use of efficient communication protocols is crucial in minimizing transmission delay and energy consumption of sensor nodes. In a heterogeneous WSN context, we propose, efficient mobility aware mechanisms which may be implemented in large three-tier WSN. These mechanisms must be designed to be optimal. The aim of this paper addresses common sensor behavior such as data exchange meanwhile responding to the mobility issue in the fore mentioned context. The mechanisms are based on two main protocols: topology creation and data collection in intra- and inter-tiers. Our mechanisms minimize collisions and optimize the duty-cycle of each node. Furthermore, a performance evaluation study detailed by an analytical model is presented in order to validate the designed protocols.

Index Terms—Health-care monitoring, Heterogeneous WSNs, IEEE-802.15.4, Mobility, Delay, Energy-Efficiency, Performance analysis.

I. INTRODUCTION

Nowadays, the advantages provided by these smart, tiny, and distributed communicating and sensing objects allow people to interact with their smart living environment and to be surrounded by high controlled comfort and safety [1]. Actually, advances in key areas such as Wireless Sensor Networks and Body Sensor Networks (BSN) are an enabling technology for the application domain of unobtrusive medical monitoring [8]. For instance, health-care monitoring provided by wireless sensors is becoming increasingly important due to several advantages. Indeed, this application domain includes: continuous cable-free monitoring of vital health signs in intensive care units, remote monitoring of chronically ill patients, monitoring people in their everyday lives by providing early detection and intervention for various types of diseases, computer-assisted physical rehabilitation in ambulatory settings and assisted living for the elderly at home.

The objective of WSN and BSN deployment in health-care monitoring is to keep recordings of the health of elderly and patients and to survey the state of their living space. Thus, the network could be composed by heterogeneous nodes enabling transfer of different types of data including medical and environmental contents. Sensors may be embedded on the person's body and inter-connected in a BSN to control the human physiological data (e.g. temperature, ECG) or placed on the ceiling of the house to monitor the patient's environment. Furthermore, the strong advantage of this application is the

early detection of anomalies and emergencies. In order to achieve those objectives, we proposed in our last work [9] a WSN solution (Figure 1) where the sensor nodes are organized into groups in order to manage their shared tasks (medical nodes, coordinators, video nodes and sink). The solution architecture is composed of three tiers and to achieve the common goal (health-care monitoring at home), a sensor node may interact with other nodes in inter- or intra-tiers. In this work, we design the communication protocols of those interactions. The designed protocols include medium access mechanisms and data transfer to the Sink. Transmission delay and energy-efficiency represent the important performance criteria in our application. These criteria depend on many parameters such as: network size, energy dissipation by each node, data type and some impacting factors: medium access method, transfer type, mobility and scalability, etc.

Related work: Several previous work have been proposed to address solutions for mobile Ad hoc and sensor networks. In [6], a new routing approach in mobile three tiers networks has been proposed. The authors propose multi-virtual backbone (MVP) protocol that takes into account the challenges related to the coverage problem with support of the quality of service (QoS). In [3], a “Frisbee model” is designed to organize the sensors wake-up. Nodes are active only during brief periods to collect data according to the presence and mobility of the monitored target. Many propositions have been considered to assign scheduling mechanisms in cluster three-tier networks. A collision-free beacon scheduling mechanism for IEEE 802.15.4 WSN is proposed in [5]. The description of a synchronized cluster tree network is available. Two protocols are described: scheduling beacon mechanism and duty cycle management for cluster heads taking into account bandwidth resources. In [2] a three tiers hospital WSN is presented, which addresses the performances of IEEE 802.15.4a. Other approaches address the challenges related to the use of WSN for health-care monitoring using wire and wireless networks (either for assisted living or for multimedia) [9]. However few of them address the mobility issue in this context.

Motivation: transmission delay is certainly one of the most important performance criteria in health-care monitoring. However, in such specific application context and especially for its emergency feature, this delay is strongly influenced by the patient movement. Thus, when a BSN coordinator must absolutely join a video node (it operates as a router between

coordinator and sink), in a mobility case, it should use reactive and effective mechanisms in order to re-associate rapidly to another video node and remain connected to the network.

Contributions: In this paper we have proposed and compared several mechanisms for medium access for each tier of the network architecture in order to take into account the mobility issue. We have also detailed an efficient solution based on IEEE802.15.4 MAC [7] adjustment to improve network performances in terms of delay and energy efficiency.

Organization: The rest of the paper is organized as follows: Context of work and problematic are presented in Section II. In section III, we describe the protocol design overview. We provide an analysis of our protocol in section IV followed by analytical results in Section V. We conclude the paper in Section VI.

II. CONTEXT AND PROBLEM

A. Scenario

Each application scenario has its specific constraints. In our work we consider a WSN solution composed of three tiers as described in Figure 1. The main features of this network architecture are enumerated below:

- Low density of heterogeneous nodes deployed in a reduced space such as a house. In order to form a hierarchical network, all nodes are organized into groups (or tiers) to achieve the common purpose which consists in monitoring a person's health-care and its surrounding environment. Three tiers architecture provides better capacity, coverage, and reliability than single tier ad hoc networks (without infrastructure) as described in [10]. In our system the network is constituted as follow:
 - The first tier is represented by BSNs with medical nodes (MN) embedded on the person/patient body;
 - The second tier represents a network called Video network represented by Video Nodes (VN) equipped with environmental sensors and camera. The Video nodes communicate with the BSNs;
 - The third tier is represented by the set of communications between the Video nodes and the Sink (S) which collects all data.
- The Video network is stationary instead of the BSNs which move with the person.
- In this application context we distinguish between two kinds of traffic: the first one is periodical (medical nodes send regularly the patient health state, for example: shocks, temperature, Electrocardiogram (ECG), pulse, etc.) and the second one is sporadic representing alarms and anomalies sent by medical nodes and/or Video nodes when an incident is detected.

Note that in this very constrained context, the question that we ask is how to maintain connectivity while the person moves around inside the house? The transmission of data between the Coordinator and the Video node could be interrupted (BSN and VN tiers). The need of efficient and reliable mobility-aware protocol is necessary in this application context. Organizing

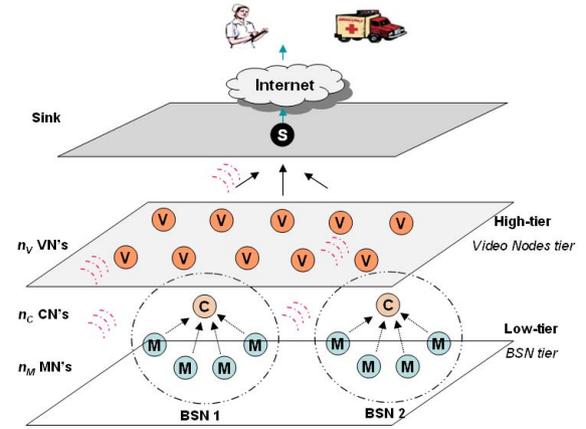


Figure 1. WSN solution for health-care monitoring.

data transmissions between nodes in intra- and inter- tiers should be adapted to each tier's requirements. Moreover, the protocol should be adapted and dimensioned to minimize delay and energy consumption. The type of data and number of nodes are important metrics which need to be taken into account in the network performances. Other application requirements are detailed in our previous work developed in [9].

B. Assumptions

The deployed network should operate under the following conditions and constraints:

- Centralized hierarchical deployment: four groups of nodes constitute the network: Medical nodes (MN), Coordinator nodes (CN), Video nodes (VN) and the Sink (S). BSN networks are formed by clusters of MN and one CN. A detailed description of each node function is described in [9];
- The resulting traffic model is "many-to-one" managed by the sink node;
- All the periodic data and alarms sent by the MN are collected by the CN then forwarded to the Sink via the VN;
- Video nodes could be a source of data and handle forwarding functions.
- Nodes operate under periodical sleep/active schedule; The scheduling depends on each tier organization.
- The typical range inside the house depends on links between inter and intra- tiers. The mobility issue of BSN depends on the range between CN and VNs.

To create this network architecture, all the medical nodes of each BSN associate to the CN forming a star, then the CN try also to associate with a VN which is within range. Finally each VN which are associated with at least one CN must be associated with the Sink. It is very important to have reliable association protocols which are reactive especially to BSN mobility. Saving energy and optimizing transfer delay could be managed in many layers. In MAC layer for instance, it can be reduced by using the adequate schedule for data transmitting hence avoiding sources of delay and energy wasting (collisions, overhearing, etc.).

The two primary contributions of our design are:

- Proposal of efficient mechanisms to organize data transmission in the three-*tiers* network.
- Making adaptation of our protocols to take into account the BSN mobility, and to be employed in large spaces in order to minimize transmission delay with respect to network lifetime.

III. PROTOCOL DESIGN OVERVIEW

A. Design framework

In the three-*tier* network, the protocol design is based on two primordial phases: topology creation (initialization) and data collection. The topology creation phase permits to synchronize all nodes in the network for mutual recognition and to organize data transmission between nodes of inter- and intra-*tiers*. The two phases are presented in Figure 2. First, the Sink node starts the initialization phase by sending a “*S_Beacon*” message to the Video Nodes (VN_i). Then, the association phase between $VN_{i \in \{1..N_v\}}$ and $CN_{i \in \{1..N_c\}}$ takes place. A VN sends a “*B_Beacon*” message to the CN node. This later sends association request message “*ASC_RQ*” to a VN which indicates the accepted association with “*ASC_ACK*”. Then VN node is associated with the Sink by sending an “*ASC_RQ*” message and receiving an “*ASC_ACK*” message. The BSN network initialization takes place with the transmission of “*C_Beacon*”, “*ASC_RQ*” and “*ASC_ACK*” messages. After that, the BSN network is built, and the data exchange phase starts. The data exchange phase permits regular scheduling of communications between tiers 1, *tier 2* and *tier 3*.

The MN node collects data, builds the first “*DATA*” message and sends it to its associated CN node which responds with an “*ACK*” message. The “*DATA*” message is then forwarded from CN to VN, and finally reaches the sink (with the exchange of “*DATA*” and “*ACK*”).

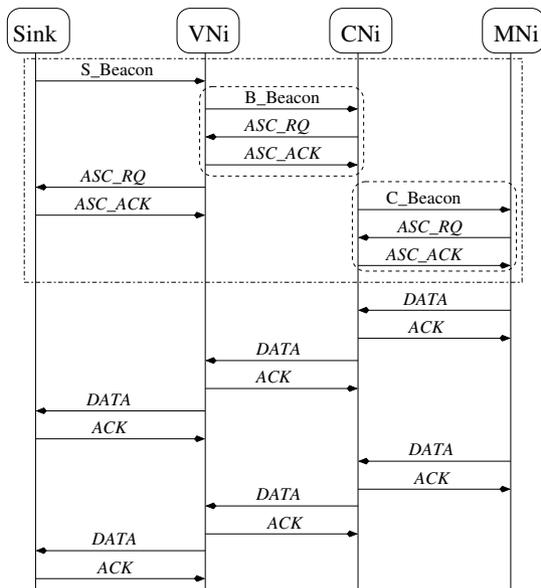


Figure 2. Association and data collection mechanisms.

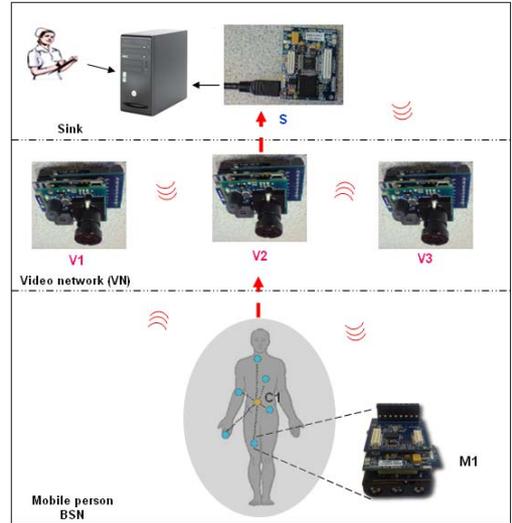


Figure 3. Design overview.

Other design framework for inter tiers exchange was developed based on specific sensor behavior [9]. In the designed framework described above, the need of a reliable medium access method is required with the objective to reduce delay and energy consumption.

B. Choice of Medium Access Method

The choice of a medium access method depends on each *tier*'s constraints (nodes number, mobility, etc.). Efficient access method permits to reduce collisions and retransmissions which result in minimizing delay and energy consumption depending on the scalability of the network. The activity periods of the nodes must be as short as possible and might be dimensioned depending on the size and the number of data transmitted. The number of retransmissions should be parametrized to avoid errors and interferences in the house. The medium access method must be organized between nodes of intra tiers then between nodes of inter tiers. For simplicity, we can adopt a case study of monitoring two persons (one Coordinator embedded on each person body) with a BSN composed of N_m medical nodes, and we defined N_v as the number of Video nodes communicating with the BSN and with one Sink.

- In the first *tier*, medical nodes are the most constrained in term of delay. The use of CSMA/CA between the concurrent M nodes (to reach CN node) results in no guaranteed access and possible collisions and retransmissions. The TDMA method is more reliable in the BSN *tier* (because of the reduced number of medical nodes).
- However, in the second *tier*, the use of TDMA between CN and VN is not more efficient than CSMA/CA (because the probability of collisions is $(\frac{1}{2})$ for each CN node). Thus, a trade-off between delay and energy consumption is necessary.
- In the other hand, in the third *tier*, the use of CSMA/CA access method between V and S node is also more

adapted than TDMA because of the important number of Video nodes (node must wait $M-1$ slots before sending).

With all these conclusions we construct a hybrid access in the three tiers architecture as follow: TDMA for (MN, CN) , CSMA/CA for (CN, VN) , and CSMA/CA for (VN, S) .

Hence, to study the performance of the hybrid access in the three tiers network, we think to map the access method to be adapted to IEEE-802.15.4 protocol. These choices require adapting the parameter setting of the “super-frame” constituting each *tier* with adapting the sleep/active schedule. In the first *tier*, the communications between C and medical nodes are organized in super-frames managed by the coordinator.

The super-frames are delimited by Beacons sent by the coordinator, within it provides information about synchronization, GTS (*Guaranteed Time Slot*) allocation, etc. The first super-frame may not contain CFP (*Contention Free Period*). In fact, there will be only CAP (*Contention Access Period*) where medical nodes compete to associate to coordinator and reserve a certain number of GTS (using “ASC_RQ” message). The other super-frames may contain only CFP period and remove the CAP. Figure 4 shows the parametrized super-frame.

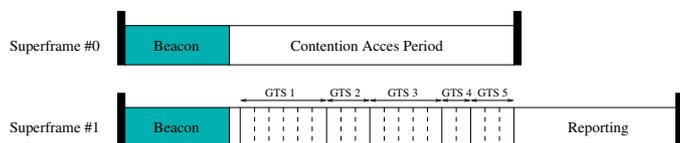


Figure 4. First *tier* super-frames.

The number of reserved GTS depends on the type and length of data. As shown in Figure 4, in the “Reporting” period, the coordinator sends the collected data to the VN to which it is associated, which will report data to the sink. During this period, medical nodes can turn off their radios (sleep mode).

C. Mobility management

In our application context, the mobility is a crucial issue. It concerns the link reliability and re-association problem of BSN *tier* with Video nodes *tier*. It includes the re-association between coordinator and Video nodes as described in Figure 5. This study permits to know whether the proposed mechanisms maintain their performances if we apply them for monitoring mobile people in large applications such as hospitals.

The re-association procedure will start in the reserved “Reporting” period of the coordinators. To adapt the protocols described above we propose reactive mechanism described below:

- 1) The mechanism is based on observing the link quality (number of retransmissions is reached with the lack of “ACK” message) to draw conclusions about starting the re-association procedure (which depends on the range constraint). If a coordinator detects that its associated

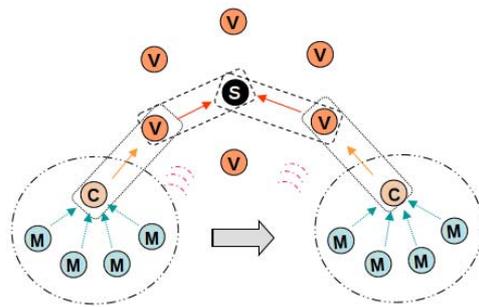


Figure 5. Coordinator mobility.

Video node does not respond; it sends a “ping” message “ASC_RQ” to reach a new Video node.

- 2) At least, one Video node listens the message of re-association “ASC_RQ” sent by the coordinator. Video nodes wait a random period before transmitting the “ASC_ACK” message.

The super-frame of the Video node should be parametrized to request GTS from the Sink in order to transmit the “ASC_RQ” message of the coordinator. The Sink will reserve GTS periods which will become effective in the next super-frame.

IV. ANALYSIS AND PROTOCOL DIMENSIONING

In this section we proceed to the performance analysis of our protocol. The performance criteria are delay and energy consumption.

Association analysis: The first association phase between all medical nodes and the coordinator is represented by the D duration:

$$D = \sum_{i=1}^{N_m} D_{ASC}(i) \quad (1)$$

Where $D_{ASC}(i)$ is the association duration of one node i and N_m the number of medical nodes. Then, let $D_{ASC}(i)$ the mean association time of node i with the CN of its BSN is:

$$D_{ASC}(i) = \delta + T_{Beacon} + T_{ASC_RQ} + T_{ASC_ACK} \quad (2)$$

δ is a random duration before each node i sends its “ASC_RQ” (to avoid collisions, each node initially sense the channel during a random duration δ uniformly distributed in the interval $[0, \Delta]$, where Δ is the maximum of the random duration [4]).

- When the other medical nodes hear the first “ASC_RQ” they must wait for a time equal to $(T_{ASC_RQ} + T_{ASC_ACK})$ before starting to draw again a random duration δ .
- The number of reserved GTS depends on the kind and the length of data.

Energy consumption: To calculate the energy consumption of the first node we can reuse the formula (2) by adding consumption corresponding to each mode (reception or transmission), then we obtain:

$$E_{ASC}(i)_{i=1} = e_{rx} \cdot (T_{Beacon} + T_{ASC_ACK}) + e_{tx} \cdot (T_{ASC_RQ} + \delta) \quad (3)$$

The amount of $(e_{rx} \cdot T_{Beacon})$ corresponds to the receiving of the coordinator Beacon (“C_Beacon”) and e_{rx} , e_{tx} are respectively the energy consumed when receiving and transmitting data. The energy consumption of the other nodes during the association phase can be written as follows :

$$E_{ASC}(i)_{i \neq 1} = e_{rx} \cdot (D_{ASC}(i-1) + T_{ASC_ACK} + T_{Beacon}) + e_{tx} \cdot (T_{ASC_RQ} + \delta) \quad (4)$$

Data collection analysis: As shown in Figure 4, in the reporting period, CN sends the collected data to the VN to which it is associated. During this period, medical nodes may turn off their radios (sleep mode) to save energy.

Energy consumed during the other super-frames: It corresponds to the data sending consumption and differs from the association consumption because this time, medical nodes don’t have to compete for the medium access, however they have to send “DATA” messages larger than “ASC_RQ”.

$$E_{DC} = e_{rx} \cdot T_{Beacon} + e_{tx} \cdot T_{DATA} + e_{rx} \cdot T_{ACK}$$

In the same way, we can evaluate the upper tiers (C,V) and (V,S). As described in section III.B our study were focused on 2 monitored persons. Indeed, we have two coordinators. The number of VN communicating with the sink is 2 at most among N_v (each CN is associated with one VN). To study the scalability parameter of N_c and N_v nodes we use simulations (not described in this work).

V. RESULTS

In this section we present numerical results of our analytical model. The parameters presented in Table I concern the real values of the Imote2 that we obtained by previous experiments in our laboratory. The Imote2 transceiver operates at ISM 2.4 GHz frequency, 17.4 mA (0 dBm) power output and allows data rates of up to 250 Kbps. The micro-controller runs at 13 – 416MHz. This device requires 3.2 – 4.5 Volts, and are powered by three 1.5V (3AAA) batteries in series.

Parameter	Value	Unit
T_{ASC_RQ}	1.31	ms
T_{ASC_ACK}	1.34	ms
T_{DATA}	1.92	ms
T_{ACK}	1.38	ms
e_{TX}	53	mA
e_{RX}	70	mA

Table I
EVALUATION PARAMETERS.

We estimated analytically the average duration of the association in the first tier (D_{ASC}) followed by the average energy

consumption of this mechanisms (E_{ASC}) and the energy consumption of data collection (E_{DC}). We considered a scenario of 12-hours application functioning with one association and one data collection per hour.

	D_{ASC} (ms)	E_{ASC} (mAh)	E_{DC} (mAh)
Medical Nodes (MN)	6.13	0.42×10^{-3}	4.2×10^{-3}
Coordinator (CN)	3.86	0.67×10^{-3}	23.9×10^{-3}

Table II
ANALYTICAL RESULTS FOR THE 1ST tier. A 12-HOURS APPLICATION FUNCTIONING WITH 1 DATA COLLECTION PER HOUR.

From the results presented in Table II, we note that association mechanism and data collection in the first tier save energy and reduce the association duration which is an advantage in mobility cases. Furthermore an experimental indoor implementation in laboratory was carried out to evaluate the performance of the three-tier system. Figure 3 shows the network elements.

VI. CONCLUSION

In this paper we presented a WSN/BSN solution for health-care monitoring at home. Our solution is based on mobility-aware and energy-efficient protocols. While the solution distinguishes between three tiers, we proposed an appropriate medium access method for each tier and we organized efficiently the communications between tiers. Subsequently, in order to manage the mobility of BSN coordinator we have proposed a mechanism based on an adjustment of IEEE802.15.4 MAC layer. A perspective of this work is to implement the protocol and make real measurements in order to improve and validate our mechanisms.

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