Personalized Building-Embedded and Wearable Monitoring Infrastructures with Mediated Data Transfer

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***Abstract*—This paper presents the design, prototype implementation and results of two cooperating infrastructures for a vital sign-based multimodal monitoring. The building-embedded and wearable systems provide complementary measurements in human and share a data transfer channel where possible. Managed by the common server, both systems are configurable in order to follow the subject's state and specific needs. Indoor and outdoor tests for various subjects shows significant savings (up to 80%) of communication costs and extention (up to 42%) of the wearable system autonomy.**

I. Introduction

HOME care systems are recently one of the most investigated area in context of improvement of live quality in ageing societies. At the same time the prolongation of professional activity is considered by regulations of many countries for both men and women. This implies the innovators to propose various mobile solutions [1], [2], however until now in prevailing number of cases they are portable, thus reduced in weight and size, but functional copies of their stationary ancestors.

Home care systems are usually developed as independent, continuously operating systems based on closed acquire-process-and-send architecture [3], [4]. The cooperative or upgradeable systems suffer from the lack of interoperability and serious security issues. Most of personalized health care monitors are designed as wearable, what requires the application of a wireless data link [5]. That provides almost unlimited patient mobility, but increases the operation costs, and imperils the system to communication errors in the unstable electromagnetic environment.

Based on various estimates, an average professionally active human spends 80% of his or here living time within buildings (45% in living premises, 35% in office). The assumed mobility, although of virtually unrestricted range, occurs in limited time, estimated for about five hours a day. Beyond this limit, health services of long-distance mobility are economically not justified and yielding several technical problems, of which a prominent example is the variability of data carrier strength.

In this paper we propose a complex system for personal health-based surveillance, partly designed as a wearable body sensor network (BSN), and partly as a home- or office-embedded infrastructure. The prototype system is designed for the monitoring of cardiovascular response to the physical load and for detection of subject's states selected as lifestyle descriptors. The scenarios of cooperation between the personal and home care monitoring systems were presented in [6], however only the joint usage of communication resources was successfully implemented and tested. This paper extends the concept of one-to-one cooperation graph to the case of multiple house-embedded infrastructures cooperating with a single wearable BSN. It also designs a perspective for a many-to-many cooperation allowing for independent, personalized monitoring of several subjects within the same room.

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II. Monitoring Infrastructure Design

The system design uses an IP-based network composed of the central server and two types of remote sensors: wearable and building-embedded. The role of the server, besides of accommodation and integration of various types of vital signs, relies on the personalization of remote sensors accordingly to the needs of particular subjects. Both types of sensors are remotely configurable: the wearable system follows the changes of the subject's state, while the embedded system adapts to the presence of particular subjects. The subject-specific requirements for monitoring are based on the subject’s state calculated by the server and disseminated to both: personal wearable sensor and stationary system, where subject's presence has been detected. Principal technical aspects of these systems are presented in following subsections.

A. Network configuration

Considering the contribution of time spent by the subject within premises, we postulate to cease the usage of long-distance wireless transmission channel (GPRS), when the subject enters into the house. Instead, the building-embedded monitoring system is prepared to share its communication resources providing the service of transmission for the external (wearable) system messages within its proper (wired) communication protocol (fig. 1). For this purpose, besides its principal monitoring function, the embedded system includes the short-range wireless communication module (WiFi) and software services for subject identification and data flow mediation. Two other scenarios of cooperation for the home care and personal monitoring systems are proposed in [6]. The details on connectivity and data transfer protocol defining the rules of communication and resource sharing are described in details in [7]. Thanks to the use of short-range free wireless transmission instead of long-range payable service, our approach saves the operation costs, and extends the battery life in the wearable system, although preserves the subject's mobility in the house.

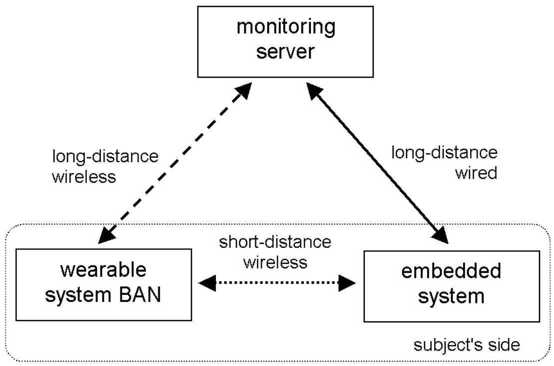

Fig. 1. Block diagram of two monitoring systems cooperation at the level of communication resources sharing.

A typical wearable monitoring system contains biological sensors, the mobile server and the transmission module integrated within a body sensor network (BSN). For the postulated functionality, two solutions are reasonable:

– conditional integration of the embedded system's wireless interface into the BSN,
– additional short-distance wireless module used within the BSN alternately to the long-distance service.

As far, as the cooperation of only two systems is considered, first option seems to be less complex and thus more appropriate. However, expecting a BSN to cooperate with multiple embedded infrastructures (home, office, vehicle, etc.) requires them all to follow a common BSN-specific settings. In case of the Bluetooth technology, widely used as a support of BSNs, a serious drawback is also the limit of active devices. Therefore, for the support of monitoring of many subjects in many premises, a BSN-independent, standardized communication module is more appropriate (fig. 2). This module is in the idle state when the subject is outdoor or within not serviced buildings. It works as a low-power receiver in order to properly detect the subject's presence within monitored buildings.

B. Data buffering

The data continuity is potentially endangered in any telemedical system and particularly in wireless applications using radio data carriers of variable throughput. Although in most regular solutions this issue is supported by TCP/IP data control mechanisms, we use additional data buffering for maintaining the continuity of diagnostic data transmission. This prevents occasional data loss due to carrier discontinuity or caused by unpredictable time and result of negotiations between data transfer services.

Three data recipients are designed for the wearable BSN-based monitoring system: the long-distance wireless link, the short distance wireless link working alternately and the circular memory buffer working continuously in parallel as data backup.

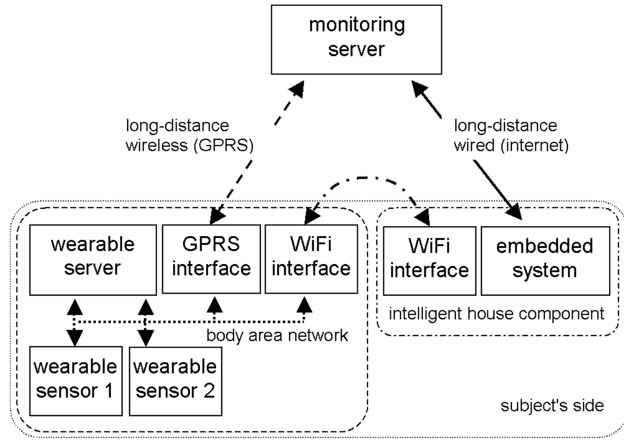

Fig. 2. Block diagram of the prototype cooperation of wearable and home care monitoring systems.

The circular buffer has large capacity (10MB) and three separate pointers for writing, reading and deleting (fig. 3):

– Write pointer is moving forward only, each time the patient data is ready for sending.
– Read pointer is advancing each time the data packet is sent to the communication module, but it may be set backward by the negative recipient confirmation.
– Delete pointer is moving forward only, each time the data reception is confirmed.

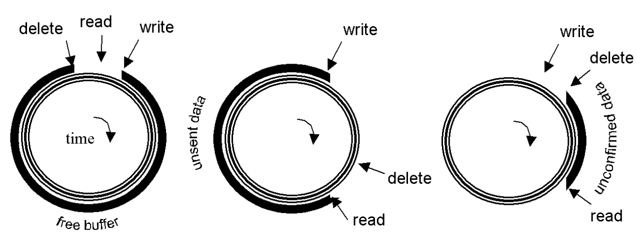

Fig. 3. Circular buffer pointers in various correlations a) connection state, b) delayed transmission state, c) low memory state.

Depending on the carrier availability, the writing, reading and deletion of data are asynchronous. The distance between the pointers defines one of the recorder states:

– connection state - the read pointer is following the write pointer at the same average speed,
– follow-up state - the read pointer advances faster than the write pointer decreasing the data delay,
– data delay state - the read pointer advances slower than the write pointer increasing the data delay,
– low memory state - the write pointer is approaching the delete pointer causing free memory alert.

From the server's viewpoint, the monitoring data may be identified as synchronous or asynchronous, depending on the delay between the data time marker and the server clock.

C. Presence detection and system personalization

The wearable monitoring system is designed as strictly personal, thus the subject's presence detection, performed by the building-embedded monitor, is equivalent to the wearable system detection. For the reason of energy saving, the wearable short-distance communication module is regularly switched on in the receiver mode, while the embedded system is continuously propagating the identification data. Once the premise-specific data are received, the wearable communication is set up for transmission sending the subject identification and the request for data transfer service (fig. 4). The purpose of presence detection is threefold:

– informs about the subject's position,
– authorizes the system wearer as a subject of building-embedded monitoring, and his BSN as a client of data transfer service provided by the embedded system,
– identifies the subject-specific monitoring setup for download to the embedded system.

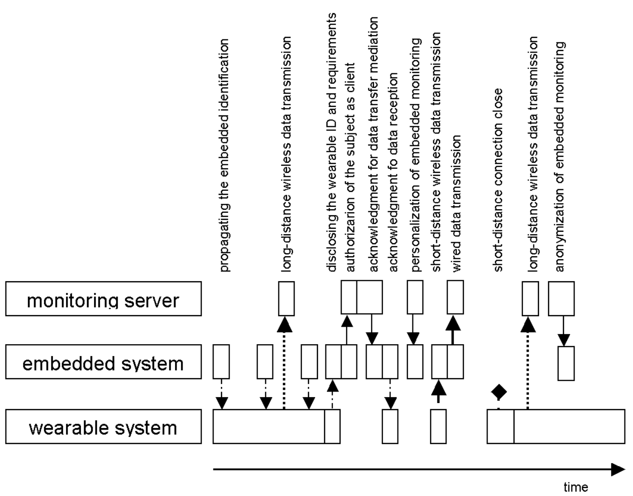

Fig. 4. Detailed time sequence of information interchange between the wearable and embedded monitoring systems and the monitoring server.

The latter purpose allows for personalization of building-embedded monitoring system. This innovation is designed to help achieving two further requisites:

– optimization of the home monitoring for a specific subject, in case of health changes occurring during his or her absence,
– adaptation of the monitoring in premises visited by subjects of different demands.

D. Prototype setup

The prototype monitoring infrastructure was designed for two subjects of different requirements and two rooms called "home" and "office". Each subject wore a body area network (BAN)-based cardiac monitor including the MW705D GPS receiver (Mainnav), the Aspekt500 12-leads ECG recorder (Aspel), the TeleMyo 2400 G2 Telemetry System (Noraxon) and the PXA-270 portable evaluation kit (Collibri) powered from the 4800 mAh 7.2V Li-Ion rechargeable battery pack [8]. The BAN used the Bluetooth technology-based communication between its components, whereas the GPRS and WiFi interfaces were used for the external long- and short-distance communication respectively (standard datastream of 18kbps). Each room was supported by a video-based presence detection and motion tracking system designed as a component of the intelligent house infrastructure. The embedded systems use the wired broadband internet connection supporting the real-time motion picture transmission (standard datastream of 1800kbps). The monitoring server was a typical PC-based workstation with static IP address.

Two volunteers simulated cardiac-endangered subjects requiring estimation of:

– body motion quantity (in subject-specific selected zones),
– the heart rate and
– amount of manual work expressed by hands acceleration

Both wearable systems were also personalized in their interpretation software layers designed for the mobile ECG analyses. As it is typical for cardiac patients monitoring, the wearable systems were expected to report:

– HRV and EDR analysis below a patient-specific heart rate (HR) and lack of motion.
– ST-T assessment above a patient-specific HR,

Additionally, the correlation between the video-based and the acceleration-based motion estimation was calculated as example of integrated parameter requiring the cooperation of building-embedded and wearable monitoring.

III. RESULTS

Two volunteers were investigated during the total of 14 days each, moving between the rooms at least 10 times daily, and performing the physical exercises or resting accordingly to a predefined schedule. For each subject, transitions between states occurred 47 (±12) times and the data carrier switching was performed 211 times. The adaptation of the wearable systems occurred respectively 8 and 10 times, and the adaptation of the embedded systems was performed 68 times (38 of which because of the subject changes)

The data carrier switching between the wireless and the wired channel was performed in 6.35 (±1.05) s, unfortunately, the restoration of long-distance wireless communication takes 17.3 (±8.10) s. For the latter operation, the success rate is also significantly lower and equals 71% (vs. 93%). This justifies our attention to the data flow control and proper buffering, however the volume used (102kB) was only 1% of the designed limit (10MB). The experiment confirmed also the expectations of considerable extension of the wearable monitor autonomy time to 23h (vs. 16.3h, i.e. by 41.1%) and economical savings on long-distance wireless communication service. In the Poland-specific billing system for telecommunication services (typical also for other European and American countries, but not e.g. Japan) long-distance wireless data transfers e.g. GPRS are paid per data packet (e.g. 100kB costs 18.48 cents), therefore reduction of the datastream may be highly beneficial to the user. The initial daily costs of 32.7 USD was reduced to 6.55 USD that is by 80%. The average correlation coefficient between the video-based and the acceleration-based motion estimation was 0.83.

The subject identification and subsequent adaptation of subject-related monitoring conditions were operating accordingly to the specification within 7.2 (±2.41) s. Simultaneous data transfer from two subjects' wearable monitors by a single embedded system was performed correctly, however the video-based motion estimation was not precisely distinguishing two separate subjects, in that case, the motion estimate has ambiguous value.

Besides the cardiac parameters (ST-T, HRV and EDR), subject data were investigated towards the identification of four basic states: working, walking, resting and sleeping. accordingly to [9].

IV. Discussion

This paper focuses on the infrastructure problems related to continuous monitoring of a subject performed partly by the building-embedded and partly by the wearable system. The cardiac-based monitoring was selected as one of the option most applicable today, supported by mature recording equipment, well accepted analysis standards and using various recording modes. Our prototype shows, that:

- both systems has partly overlapping competence areas and the calculation of parameters integrated from system-specific measurements is possible,
- both systems allow for some extent of personalization with respect to monitoring goals and subject's state,
- the systems can cooperate towards the optimization of diagnosis quality (multimodal measurement) and reduction of costs (optimal data carrier).

The proposed infrastructure guarantees quasi continuous monitoring, although the data available to the server are asynchronous in the case of connection loss. The proposed cardiology-oriented setup aims at investigating the subject in his or her everyday living conditions in order to asses the danger of the coronary disease or sleep apnea. The setup could be almost freely adapted to the subject’s needs by using of different sensors and interpretation software, within the proposed infrastructures and with the use of hereby specified system cooperation and data exchange rules.

The prototype proved wide range of adaptivity, depending on the subject-related local setup managed remotely by the server. The remote configuration of sensors and software is used for adjustment of alerting conditions and diagnosis range. The automatic recognition of the subject’s states opens the area of lifestyle control as prospective application of monitoring systems.

Although the main assumptions were verified in practical implementation and tests, two problems are worth to be considered in the future:

- extension of cooperation between the embedded and wearable monitors for cases of overlapping competences and for a joint estimation of diagnostic outcome (including a mutually dependent remote configuration)
- support of multiple subjects [10] present in the area monitored by embedded systems (including the subject recognition and individual zone processing in case of video-based system).

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