Complementary Application of House-Embedded and Wearable Infrastructures for Health Monitoring

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Abstract. **This paper focuses on the design of wearable system operation modes in context of cooperation between personal healthcare systems. The patient is currently provided with telemedical solutions for home care and seamless diagnosis based on selected vital parameters. When two or more specialized systems are applied for monitoring of the same subject, the possible interference and cooperation are in question. The cooperation between home care and wearable systems is of particular interest, because of their complementary features. Considerations of various cooperation scenarios led to the specification of three cooperation levels with regard to the required software integration. The paper presents also the design of a cooperation protocol for two prototype surveillance systems. The reported cooperation enables the use of communication resources of the stationary system as a carrier of messages from the wearable system over the wired channel.**

***Keywords*: e-health, telemedicine, services integration.**

I. INTRODUCTION

For most patients the telemedicine manifests its advantages through two kinds of everyday diagnostic instruments: home care devices, often embedded in the infrastructure of intelligent house and personal wearable devices. The first category is nowadays developed for the homes of bed-ridden patients or elderly people living on their own. Most favorite solutions use the dedicated equipment discreetly and repeatedly monitoring the disease-dependent diagnostic parameters and automatic distant interpretation of the data transmitted over a wired digital link (e.g. Internet). The second category is designed for active patients and usually is based on a body area network (BAN) communicating several physiological sensors with the wearable server providing the data interpretation and the long-distance wireless link with the medical surveillance center [1-4]. This solution is limited by the technological constraints which are not justified when the subject remains within the premises.

The question investigated throuhgout this paper concerns the possible cooperation between two health monitoring systems applied in the same subject. In aspects of diagnostic range and quality, both systems may mutually join their competences and compensate for their drawbacks yielding an optimized diagnosis for the moving patient. For people requiring the monitoring but still active professionally, the most expected usage scenario asumes that the surveillance system provides a broad-range patient diagnostics within the closed surface of his or her home but also follows his or her outdoor activities making best possible compromise between the diagnostic range and the mobility when necessary.

Most of recent solutions for home care diagnostic systems are based on the network of star-shaped topology. It is composed of the central monitoring server (also with archive and expert system services) and multiple patient-side units considered as independent clients. This assumes a direct one-to-one connection between the central and remote components without interaction between simultaneous monitoring tasks. In case of two different systems (e.g. motion tracking and cardiac) dedicated to the same patient, two independent diagnostic procedures covering a common subset of parameters (e.g. the heart rate) are running in parallel. The use of various measurement methodology and signal processing techniques implies difference in diagnostic outcomes. Rarely both such systems come from the same manufacturer and are open enough to be interchanged within a common database. In most cases, however, both systems work independently and the results coexist in the patient's health record being the possible cause of ambiguity.

In the bibliography information systems for telemedicine are usually described as closed [5-6], excluding the possible interaction with other systems or integration in the framework of a complex patient-oriented service. Therefore, the cooperation of two patient-side units requires the modification of both: their embedded software, and also the supervising nodes software. In result of the studies of possible usage scenarios [7], considering the expenses necessary for the adaptation of the existing monitoring systems software, we postulated to distinguish three cooperation levels:

– sharing of the communication resources,
– overlapping measurement and interpretation

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competences,
- collaboration in estimation of diagnostic outcome.

This paper is focused on the details of prototype cooperation following the first level scenario.

II. SYSTEM COOPERATION SCHEMES

This section provides a more detailed description of the proposed scenarios of systems cooperation.

A. Joint usage of the communication resources

Accordingly to different intended usage, each considered realization of monitoring system usually has a specific communication interface:

- Wearable systems commonly use wireless interfaces, allowing for a virtually unlimited operation range at the cost of high energy required for the long-distance transmission (GPRS, satellite, etc.),
- Home care systems use wired, relatively cheap wideband connections, however this limits their operation range to the in-house patients.

There is no economical reason for continuing the usage of separate transmission channels, when two or more different systems operate in the same area (e.g. a wearable system is used in house). *Sharing the communication resources* provides the service of transmission of the external (wearable) system messages within the (wired) communication protocol (fig. 1).

Although the service looks simple, it's design requires the consideration of:

- selection criteria for the optimal transmission channel,
- rules and constraints of automatic initiation and termination of the mediation service,
- definition of the external message embedding (at the source) and dispatching (at the recipient).

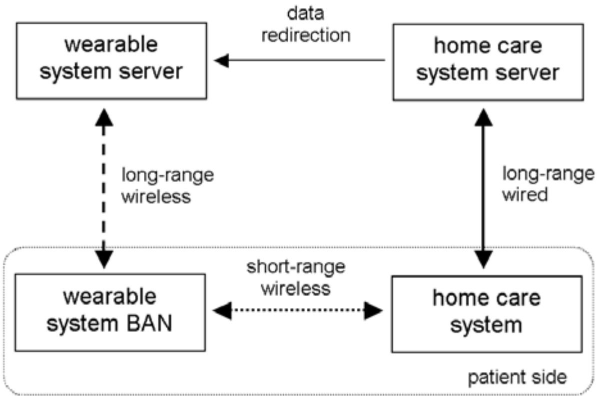

Fig.1 Block diagram of two monitoring systems cooperation in the scenario of joint usage of the long-distance wired communication channel.

Besides the software adaptation mentioned above, the cooperation of two systems requires the hardware data interfaces to comply with a common standard. Since the subject's mobility is desired also in house, the only reasonable solution is adding a wireless low-range digital interface to the home care system. Bluetooth, ZigBee and WiFi were the considered platforms.

B. Overlapping measurement and interpretation competences

The competition-like cooperation scenario is applicable for systems of partly *overlapping competences* lists (e.g. calculation of the heart rate in both motion tracking and cardiac monitoring systems). A kind of rivalry between the concurrent systems results from differences of measurement of the physiological phenomena - based on different methods or calculations of the diagnostic parameters - based on different algorithms. Provided there exists an independent validation of the diagnostic outcome quality, this rivalry is an opportunity for the optimization of system outcome (fig. 2).

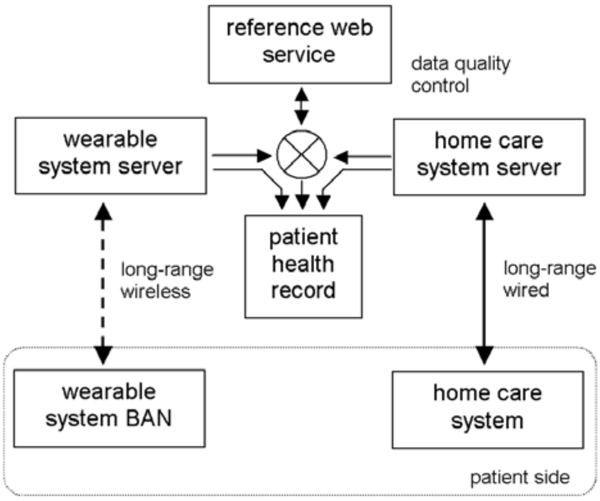

Fig.2 Block diagram of two monitoring systems cooperation when measurement and interpretation competences are partly overlapping.

This process favorites the result of best quality to override the others, when multiple values are available as results from different monitoring systems. The following requires to specified aiming at the optimization of patient's diagnostic description:

- optimization criteria based on a disease-dependent validation of diagnostic results quality, or an arbitrary selection of results priority,
- rules of data interchange between the systems on the level of patient-side devices.

For *overlapping competences* of currently applied monitoring systems working with a common database (e.g. patient health record), the arbitrary selection of best result is the only practical method. For only a few most used parameters the international regulations require independent quality tests with use of reference data sets and the manufacturers rarely specify the results in user-accessible documents. The optimization of multiple-systems monitoring quality needs conditional accuracy lists for each diagnostic parameter for the automatic selection of best result. Better option is the external reference algorithm (e.g. a web service [8]) occasionally called for providing the close-to-true diagnostic results that are used as a background for the selection between output values of concurrent patient systems.

C. Collaboration in estimation of diagnostic outcome

The *collaboration* of monitoring systems *in the estimation of diagnostic outcome* assumes the contribution from a wide range of diagnostic parameters issued by all concurrently working monitoring systems. The improvement of diagnostic quality is based on the extension of the basis of considered physiological facts. The main system has to optionally support the external parameters and its design has to consider a mechanism for active prompt for the data from the cooperating systems when necessary (fig. 3).

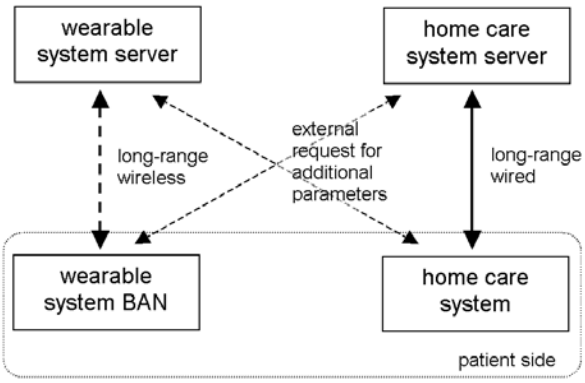

Fig.3 Block diagram of two monitoring systems collaboration in estimation of diagnostic outcome.

Although a manufacturer-independent application of such collaboration in real monitoring systems seems to be particularly difficult, this mode of cooperation mimics a grid measurement approach to the optimal diagnostic result and offers the unprecedented flexibility. This approach requires the implementation of:

- medical rules specifying the parameters accuracy as dependent on the applied measurement methods and the expected data reliability improvement when considering the outcomes of several method,
- technical specification of search and query for the additional parameters from external monitoring systems with the authentication and quality estimation procedures.

The efforts for such implementation needs a standard data requesting protocol to be implemented by various manufacturers in the supervising servers and the authorization for data requesting allowing the patient-side devices to provide the measurement results to the external centers.

III. PROTOTYPE COOPERATION OF MONITORING SYSTEMS

A. System description

The prototype cooperation was designed, established and tested between two laboratory systems for seamless monitoring of mobile patient:

1. The wearable, body area network (BAN)-based cardiac monitor including the MW705D GPS receiver (Mainnav), the Aspekt500 12-leads ECG recorder (Aspel) and the PXA-270 portable evaluation kit (Collibri) powered from the 4800 mAh 7.2V Li-Ion rechargeable battery pack [9-10],
2. The home care video-based presence detection and motion tracking system designed as a component of the intelligent house infrastructure.

The purpose of the system is multimodal tracking of subject's physical activity and detection of potentially dangerous events (e.g. motionless with high heart rate).

For the remote-to-server communication the wearable system uses the packet radio (GPRS) wireless connection payable per data volume (standard datastream of 18 kbps). The home care system uses the wired broadband internet connection supporting the real-time motion picture transmission (standard datastream of 1800 kbps). Since the GPRS connection does not provide the bandwidth required for the video transmission, the *sharing of the communication resources* was implemented in the asymmetrical way. The prototype cooperation consists of the following modifications of the standard communication protocols in considered systems:

- The wearable monitoring system may be switched for using the alternative (wired) communication channel when the patient is in house,
- The home care system may accept the external (non-video) data, embed it into the packets, separate it at the recipient and redirect to the cardiac system server.

The home care system was additionally equipped with the Bluetooth class II digital interface of the range of 10m, being the input for the external (cardiac) data. The home care system is conditionally included as a node of the body area network of the wearable system, which may use it as a long-range communication server instead of the GPRS interface (fig. 4).

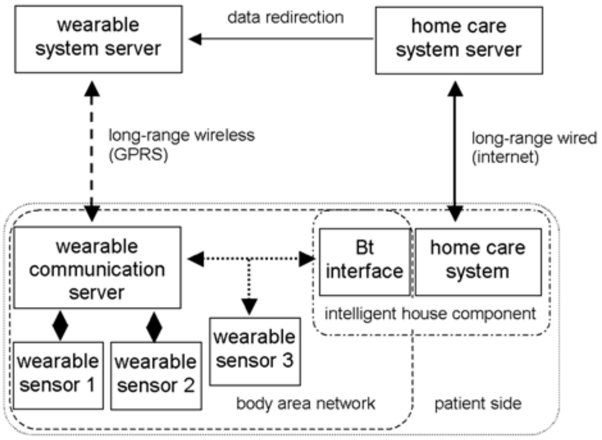

Fig. 4 Block diagram of the prototype cooperation of wearable and home care monitoring systems.

B. *Definitions of cooperation rules*

The cooperation between two systems is initiated and terminated automatically depending on the measured conditions and accordingly to the specified rules. The conditions set has to be complete, i.e. to cover all possible situations and the rules have to cover all possible behavior of both systems. Even for this relatively simple prototype consisting of two cooperating systems and two patient states (in- and out house), we have to consider:

– the detection of patient status by the presence on the video system,
– the detection of patient status by the quality of the Bluetooth communication between systems,
– the authentication and authorization for the external data support,
– the detection of quality of the GPRS connection,
– the quality of GPS positioning (usually affected in house).

Cooperation rules for sharing of the communication resources between two systems are displayed in table 1.

TABLE 1: PROTOTYPE COOPERATION RULES FOR SHARING OF THE COMMUNICATION RESOURCES BETWEEN THE WEARABLE AND HOME CARE SYSTEMS.

rules	*conditions*	*actions*
1. patient identified as "in house"	1. Patient is present on video system, 2. Bluetooth link established successfully, 3. Successful authentication and authorization for external data support by home care system.	1. Switch off the GPS module and set the data flag to not present, 2. Use the alternative long-range communication server, 3. Switch off the GPRS interface.
2. patient identified as "out house"	1. Bluetooth link weak or broken, 2. Patient is not present on video system.	1. Terminate the mediated communication session and mark the last data sent, 2. Try to establish GPRS link, buffer the data until successful, 3. Switch on the GPRS interface.

The presentation of the applied cooperation rules does not include the server software modification, in this prototype we assume that both servers unconditionally allow for sharing of the communication resources and the redirection of the cardiac data by the server of video surveillance system is defined.

C. *Data continuity service*

The data continuity is potentially endangered in any telemedical system and particularly in wireless applications using data carriers of variable throughput. This area is sufficiently supported from TCP/IP data control mechanisms in most regular solutions. The carrier switching, however, implies an additional challenge for maintaining the continuity of diagnostic data transmission. The negotiations' time and result are unpredictable and additional buffering service was designed to prevent occasional data lost.

The data continuity service is based on a circular buffer of large capacity (10MB) and three separate pointers for writing, reading and deleting (fig. 5).

– write pointer (unidirectional) is moving each time the patient data is ready for sending
– read pointer (bidirectional) 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 (unidirectional) is advancing each time the data reception is confirmed.

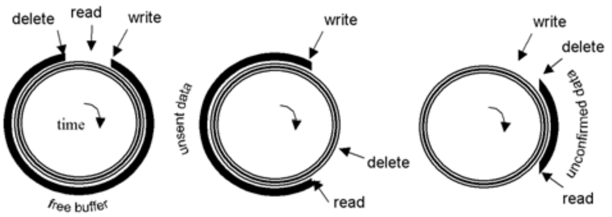

Figure 5. Circular buffer pointers in various correlations a) connection state, b) delayed transmission state, c) low memory state.

Distance between the pointers was used to define the recorder state:

– connection state - the read pointer is following the write pointer at the same average speed in steps corresponding to the size of data packets,
– follow-up state - the read pointer is catching up with the write pointer, the data transmission is faster than the data collection,
– delayed transmission (recording) state - the read pointer advances slower than the write pointer e.g. due to the limited or broken transmission,
– low memory state - the write pointer is approaching to the delete pointer indicating a given amount of remaining free memory.

Data packets contain the time marker, therefore when collected by the recipient may be identified as:

– synchronized - when the delay between time marker and local clock is within a predefined margin (usually 5s),
– desynchronized - otherwise.

In case of data reception in the correct order, the server issued the positive recipient confirmation. This message contains packet ID and grants the advancement of delete pointer in the remote circular buffer and data deletion for the recycling of memory. In case of missing data or when the data delay exceeds a given time (ca. 30 min) the server issues the negative recipient confirmation. This message also contains packet ID and returns the read pointer to the specified location of the circular buffer.

Thanks to a large size of the buffer, the designed service helps to maintain the data continuity even if no carrier is available for 60 minutes. This solution selects an optimal operation of the patient's unit upon the environmental conditions and closes the gap between recording and reporting wearable diagnostic devices.

D. *Negotiation for data embedding*

In this extended prototype a full negotiation protocol is implemented in order to simulate the temporary suspension of resource sharing, the non-availability of the final data recipient and the break of transmission in the alternative channel.

The remote device is seeking for the alternative transmission channel once the short-distance connection is broken and the device falls in delayed transmission (recording) state. After completing a TCP-based connection via wireless channel, the device first enters in the follow-up state to resynchronize delayed data. Depending on the link quality, once the data are synchronized, the recorder works in connection or delayed transmission state. In the latter case, when the delay cumulates, the recorder may enter in low memory state.

When the subject is leaving the house, the short-range communication module (being part of the body area network) remains active and seeks for the possibility of restoring the connection. In case of video-based presence detector used in our prototype, this activity may be modulated by the subject presence. The negotiation procedure is initiated by house-embedded system immediately after the detection of wearable components. It is performed in three steps:

- verification of the wearable system identifier and checking for acknowledgment from the wired network management server, preparation of data separation routine,
- routing and verification of operation of the server being final recipient of data from the wearable system-based diagnostic service,
- verification of short-distance wireless link quality and the transmission bandwidth granted by the house-embedded system.

It is noteworthy, that the bandwidth necessary for the connection state of the wearable system is a rough estimate of the minimum throughput of the data mediation service. The bandwidth used in the follow-up state may be significantly higher for short periods of time.

IV. PROTOTYPE TESTS AND RESULTS

The tests of prototype cooperation between the wearable and home care systems were focused on two aspects:

- The technical correctness of data carrier switching between the default (wireless) and the alternative (wired) channel, with particular attention to the data buffering in the wearable system,
- The savings on the payment for the telecommunication service provider and the usage of the wearable system battery determining its autonomic operation time.

The results of carrier switching delay are displayed in table 2.

TABLE 2: DELAY TIME BETWEEN THE PACKETS USING THE STANDARD AND ALTERNATIVE DATA CARRIERS.

switching direction	*success rate [%]*	*average delay time [s]*	*standard deviation delay time [s]*
wireless to wired	93	6.35	1.05
wired to wireless	71	17.3	8.10

Despite the simplified cooperation mode, the success rate representing the percentage of successful switching between the carriers is far from 100%. The most common reasons for inefficient switching were the errors in conditions detection and the average quality of both (GPRS and Bluetooth) wireless digital links.

The results of the economical aspects tests are displayed in table 3.

V. DISCUSSSION

The implementation of a prototype cooperation between the wearable and home care systems revealed several practical conclusions (for the communication mode ratio of 80% of in house time as the most probable scenario):

- Significant (76PLN daily or 80%) cost economy due to the suspending of the GPRS connection when unnecessary (see tab. 3),
- Moderate (41.1%) energy economy due to the use of the short-range wireless connection within the BAN (Bluetooth) instead of the long-range connection based on the GPRS.

From the technical point of view, the most important result is a relatively long response time (6.35 or 17.3 seconds, see tab. 2) resulted from the fact that the wearable system has to buffer the messages until it has the reception of every data packet confirmed by the server.

This paper focuses on the design of wearable system operation modes in context of available connections between the components of body area network. The system behavior was designed for any connectivity condition, even if data transmission is broken for a long period of time. Data continuity was granted thanks to the use of large circular buffer, temporarily turning the telemedical monitor into an independent recorder in dependence on the link quality. The resulting system has three data recipients:

- wired, house-embedded telecommunication infrastructure, minimizing the operation costs, available when the subject is in house, but not limiting his or her mobility within the premises,
- wireless, transmission service, allowing for maximum mobility of the subject with wearable

TABLE 3: ECONOMICAL BENEFITS OF CONDITIONAL USE OF THE STANDARD AND ALTERNATIVE DATA CARRIERS.

communication mode ratio	*autonomy time [hours]*	*autonomy time gain [%]*	*communication payment [PLN]*	*communication payment savings [%]*
in house 100% of time	24.7	51,5	0	100
in house 80% of time	23	41.1	19	80
in house 60% of time	21.3	30,7	38	60
in house 40% of time	19.6	20.2	57	40
out house 100% of time (no cooperation)	16.3	0	95	0

monitor at the price of increased operation costs and viable connection quality,

- local storage, assuring for data continuity when no direct transmission is available or during the switching of data carriers.

The project, although based on the lowest of the proposed cooperation levels, revealed several problems the open systems designers should solve.

Overlapping competences requires the use of open systems and standardized processing lists, the competences reliability may also be assessed for each particular case, as it is done within the continuous quality control,

Collaboration in estimation of diagnostic outcome needs even more open systems including the rules of use of the external diagnostic data and the rules of querying for such information. It rises many questions concerning mutual reliability, time synchronization and mutual authentication.

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