Management of Non-uniform Data Transfer in Cardiac Monitoring Systems with Adaptive Interpretation

P Augustyniak

AGH University of Science and Technology, Krakow, Poland

Abstract

Our research concerns the problem of data queuing in telemedical non-uniformly reporting surveillance systems, recently introduced to cardiology. Automatic scheduling of reports was achieved with taking into consideration of two auxiliary data attributes in the information structure: the validity period and the priority, set individually for each ECG diagnostic measurement. The patient-side recorder-interpreter works in one of two reporting modes: in the delayed mode the transmission is deferred until packets are filled with valid data, while in the immediate mode diagnostic packets are transmitted as promptly as implied by sampling requirements.

In the delayed reporting mode, the packet size lasts for 6 minutes of recording, while the wireless transfer session is completed within 10 seconds, allowing for reduction of 94% of required power. In the immediate reporting mode, the packet is collected within 4.63 seconds, which is still acceptable as real time monitoring.

1. Introduction

Adaptive processing of the ECG signal has been recently introduced as an efficient telemedical method for improve the personalized diagnostics and the usage of limited resources in a wearable recorder [1-2]. Unfortunately, due to the adaptation of diagnostic parameters calculation, this promising technique implies non-uniform reporting, which is not usual in the clinical practice and not covered by current data transmission standards. Interpolation of the data in the recorder, although technically possible, is not interesting for the reasons of additional calculations and increasing of the report volume.

This paper presents the patient-side service for non-uniform report management. Our service is designed to meet a compromise between providing maximum flexibility in report content and frequency, and short delay required for real time monitoring. Therefore the service offers two reporting modes: delayed and immediate and uses up to 256 data structures custom-defined for each session. Switching between the reporting modes is made automatically depending on the patient's status and data carrier availability.

The prototype is designed for cardiology-based surveillance of patients in motion and uses a star-shaped topology managed by the central server over the bi-directional digital data link [3-6]. The interpretation process is shared between the remote recorder and the corresponding thread running on the central server. The interpretation of the recorded ECG signal and the adaptivity of diagnostic report content are subjects of multicriterial optimization performed by the server [7]. The adaptation of the remote interpretation process is performed in real time with the use of diagnostically-oriented libraries of subroutines. Selected functions are uploaded from the repository managed by the supervising central server [8-9] and dynamically linked with the software running in the patient's recorder. The adaptation, however performed automatically, is occasionally, in critical cases, supervised by a human expert.

2. Report management mechanisms

2.1. Adaptation of the report content

In order to take all advantages of adaptive diagnostic system, the reporting format was designed to provide as much flexibility as possible. We implemented three-layer data format consisting of three components:

- header describing the recorder's status, packet synchronization data and packets' content,
- data description fields with pointers to data,
- data containers.

The header is mandatory since it identifies the recorder and its status in a static structure of 18 bytes [10]. The header contains also the session identifier, sequential packet number and the value of time interval to the subsequent report. These data helps the correct report queuing and automatic validation of data continuity and integrity. The third section of the header defines first data field type and contains the pointer to the first byte of its structure. First such field is mandatory even if the report contains only the recorder's information, but in the header of a regular diagnostic report definitions of data fields accompanied by respective pointers are repeated as many times as necessary. This header structure allows for individual setup of any diagnostic report as a combination of predefined data structures. The description of data organization preceding the actual report contents is justified by the use of different data meanings (including raw signals, meta data, diagnostic parameters) and forms (simple variables, vectors, matrices and structures).

Each data type specification is followed in the data description layer (the second), by one or more data allocation triplet: index, length and pointer to the report data serialized in the data layer (the third). Several records following a common data type definition are integrated to a vector with use of index in data description layer.

The unique content of the data layer are medical data serialized in the same order as defined. In case where the recorder's status is the unique report content, the end-of-file mark is written here. Minimum length of the diagnostic report is 20 bytes, however in the delayed reporting mode several records are buffered to reach a minimum length of 256 bytes. The maximum length of the record depends only on the transmitted data volume, but due to the limitation from the TCP/IP specification [11-12] reports are split if exceed 1500 bytes.

2.2. Nested data structures

Data organization in the diagnostic report is a part of the adaptation process of patient's recorder software. Up to 256 different data structures may be defined for remote reporting individually for each monitoring session. Data structure definitions are distributed by the monitoring server at the beginning of the session and referenced to in the reports by a single-byte (char type) identifier. Moreover, the definitions of complex structures may embed the simpler, previously defined types or isolated data fields (fig.1). Nesting the frequently used simple data structures within the complex, but rarely used structures provides a support for individual reporting intervals for particular components of the report.

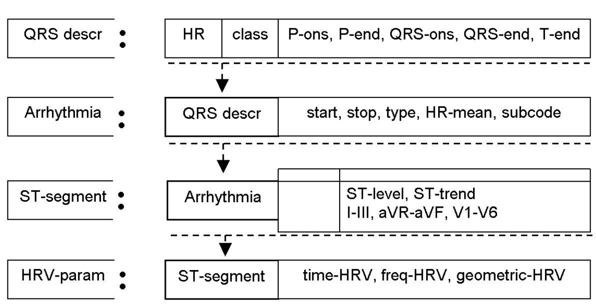

Fig. 1. Design of sample information structures for the adaptive reporting in the prototype of seamless cardiac supervising system.

The ECG record interpretation and the set of resulting parameters integrated in the report are determined by the patient's status. Each diagnostic parameter is attributed with the priority and the validity time, implying the minimum update rate required to maintain the continuity of each time series. Independent reporting of each diagnostic parameter, although optimally reduces the medical data stream, significantly raises the contribution of the TCP/IP overhead. Therefore report components of similar validity time are aggregated into a common structure updated accordingly to the requirements of the most varying parameter, causing a slight oversampling of the others.

During the session, adaptation of the ECG interpretation software changes the presence and priority of report components. In that case the report reservation procedure fits the diagnostic parameters into the information structures available for the session:

– Diagnostic parameters of similar update interval are integrated together and represented by the structure best reflecting its content.
– Reporting interval for data structures is individually defined as corresponding to the shorter validity time.

The proposed data aggregation and scheduling rule guarantees the reporting continuity for each parameter and maintains lowest possible global data volume.

2.3. Immediate reporting

The report is delivered to the air immediately when all constituent diagnostic parameters are calculated. This mode is designed for best data continuity and minimum delay of the diagnostic patient's representation available at the server. It is used for monitoring of high-risk patients, for synchronization of the patient-doctor interaction or for the immediate assessment of adaptation of the recorder's interpretation software.

Unfortunately, similarly to the centralized interpretation model, this mode requires a continuous operation of the radio transmission module what rises the monitoring costs and limits the recorder autonomy time. Moreover, the reporting is immediate as long as the wireless data carrier is available. To maintain the monitoring continuity, the immediate reporting may be programmed as automatically switched to the delayed reporting mode in absence of wireless data carrier.

2.4. Delayed reporting

The report is delivered to the air once the collected diagnostic data volume fills the entire packet or a given time limit is reached. Delayed reporting gathers the data accordingly to the required update rate, but allows for collecting the consecutive low volume reports in a single packet. The delay in information delivery saves the protocol control data volume and the transmission energy, and was designed for the routine monitoring of stable subjects.

Due to data buffering, the transmission module may be temporarily switched to the low-power state in order to extend the recorder's autonomy time. The diagnostic patient's representation received by the server is continuous, however due to the delay, the last available data may not be recent. The delayed reporting doesn't require the continuous availability of wireless data carrier.

The delayed reporting may be programmed as automatically switched to the immediate reporting mode in presence of wireless data carrier in case of:

– Occurrence of pathological events in the ECG,
– Activation of the patient's button,

Moreover, adaptation of the remote recorder interpreting software, requires the immediate reporting for correctly validate the ECG interpretation quality.

2.5. Content and frequency management

The report reservation procedure queuing the diagnostic data in adaptive reports is implemented in the remote recorder. It analyses the combination, the priority and the validity intervals of diagnostic parameters once the adaptation of the interpretation software is completed. Most appropriate nested data structures and their repetition intervals are determined as components of the report sequence. The sequence starts with the most complex structure (fig. 2, point t_0) and the subsequent simpler structures with their intervals are scheduled with regard to the update rate required by included parameters. In case when several structures are applicable for a given parameters' combination, the structure of minimum size is selected. When the use of the structure composed of all considered parameters is necessary again (point t_1), the queuing procedure assumes the report sequence is completed. It is used for the reporting until the next adaptation of the recorder's interpretive software.

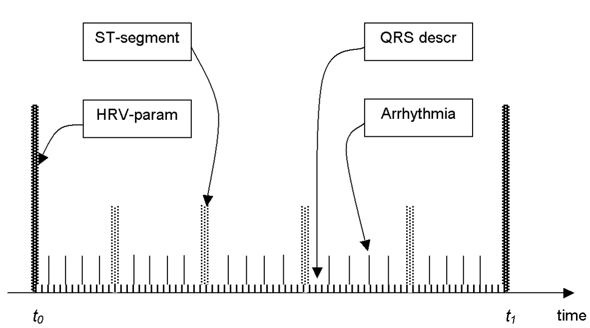

Fig. 2. Sample sequence of medical data structures used for reporting of the heart rate, arrhythmia events and level of ST section.

3. Prototype and experiment setup

In the prototype implementation, the delayed reporting mode buffers the subsequent diagnostic reports up to the size of 32kB or up to the delay of 360s. If one of these limits is reached, the transmission module is activated and the packet containing several consecutive diagnostic reports is sent. In a stable subject there is no reason for transmission of raw ECG signal. Since filling the volume of 32kB requires diagnostic parameters from 580s (9 min 40 seconds) of recording, the data buffering first achieves the interval limit of 360s (6 minutes), and the report, despite its size of only 20kB, is delivered to the air.

Prior to being coded in the target operating system [13], the prototype data queuing procedure was implemented in Matlab. This implementation was aimed at testing the automatic building of report sequences for various combination of diagnostic parameters and their update intervals.

4. Results

Main results presented in table 1. show the data volume only for the reports composed of few basic diagnostic parameters and their most probable update intervals. These results differ accordingly to the patient status, since various pathologies require specific diagnostic data set and assume individual variability of these data implying variations of update intervals.

Table 1. Comparison of the data stream volume for constant reporting rate and adaptive reporting with data queuing method proposed in this paper (12-lead ECG)

component	volume [b]	interval [s]	data stream [bps] theoretical	adaptive rate	constant rate
heart rate	1	0.3	55,2	65,67	181,5
morphology	1	0.3			
wave borders	14	0.3			
arrhythmia events	5	3			
ST-segment elevation	24	30			
HRV parameters	10	360			

In the delayed reporting mode the wireless communication module is operating every 360s for ca. 4 to 10 seconds depending on the speed of data transfer (16 to 40kbps). The average energy in delayed reporting is reduced below 3mA (i.e. to 6% of the original value). In the immediate reporting mode, the minimum packet size of 256 bytes is collected within 4,63 seconds, which is slightly longer than the delay in the interpretation process (typically 2s), but still acceptable as real time monitoring.

5. Discussion

An effective solution was proposed for management of non-uniform data transfer in cardiac monitoring systems with adaptive interpretation. For each adaptively selected combination of diagnostic parameters requiring individual specification of time-varying update rate, the automatic procedure schedules the minimum size data structure sequence which preserves the continuity of reported data.

Regular ECG reporting implies a significant oversampling of certain parameters, and consequently - the waste of energy and telecommunication resources (tab. 1). Sending each data independently, results in appending a considerable volume of TCP/IP control information due to high fragmentation of diagnostic reports.

The intelligent data queuing requires the use of various custom-designed and nested data structures as well as individual management of packet delivery. Building the compound information structures of diagnostic data requiring similar update interval seems to be the most reasonable solution. It helps to maintain minimum data volume thanks to the use of larger data blocks and consequently lower contribution from the control information.

Acknowledgements

The scientific work supported by Polish State Committee of Scientific Research in the years 2009-2011 under the grant no N518 426736 (18.18.120.875).

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Address for correspondence.

Piotr Augustyniak
AGH University of Science and Technology, 30, Mickiewicz Ave. 30-059 Krakow, Poland
august@agh.edu.pl.