Discrete Nonlinear Control of the Diagnostic Quality in Distributed Telemedical Systems

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Abstract This paper addresses principles of discrete nonlinear control performed towards the diagnostic quality-based interpretive software optimization for cardiology-based monitoring system. Thanks to the pervasive access to wireless digital communication, distributed biosignal interpretation networks may not only optimally solve difficult medical cases, but also adapt the data acquisition, interpretation and transmission to the variable patient's status and availability of technical resources. The adaptation is based on the innovative use of results from the automatic ECG analysis to the seamless remote modification of the interpreting software. This paper focuses on the static properties and control accuracy and dynamic properties of the ECG processing optimization. It provides also details on the automatic scoring of the performance of ECG interpretation procedures. Testing of the prototype, despite its limited scale, yields significant quantitative benefits and improvement of diagnostic quality.

1 Introduction

The easy-to-use technical surrounding of a human, created mainly with the software, is in todays information society an often-referenced quality-of-life estimator. A prominent example is the remote surveillance and heart diagnostic, benefiting from wearable computers and wireless digital communication [9], [10]. Besides cardiovascular off-hospital patients [5], [7], [8], this technique concerns also seamless monitoring of vital signs from sportsmen, elderly people living on their own or members of military or civil services exposed to danger. Wearable recorders do not limit the everyday subject activity while the embedded intelligence simulates well the continuous assistance of medical experts.

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Our approach postulates that the interpretation process is performed as a network-distributed computing task. Particular subtasks of the interpretation process are flexibly shared between the remote recorder and the central server and automatically controlled via bi-directional digital wireless transmission channel. The adaptivity of data interpretation and transmission is based on the quality of diagnostic parameters, continuously estimated in context of the patient's status by a procedure mimicking the human performance. The adaptation is modulated by several technical constraints.

An interesting issue is the discrete and non-uniform nature of the adaptation. In regular control systems, the control signal is linearly proportional to the error value accordingly to the feedback transmittance. In discrete systems, this proportion is modulated by discrete steps, usually having the uniform size. In the proposed system, the available procedures are attributed by their inherent performance and requirements factors and a linear response to the diagnostic error cannot be expected.

The remote adaptation of selected procedures for automatic interpretation of electrocardiogram has been recently proposed [2], [4] as a remedy for the unnecessary remote computing and data transmission. Besides the significant reduction of the datastream, the advantage of the method is a patient-oriented optimization of the processing, opening fields for improvement of diagnosis quality and patient's comfort. The economical aspect of the software flexibility-based approach also cannot be neglected, since the patient's units may be mass-produced as general-purpose biosignal recorders and their desired functionality may be remotely programmed upon request.

The non-uniform adaptation of the software is the main topic considered in this paper. Chapter 2 presents theoretical principles of the non-uniform control, chapter 3 reveals implementation details and chapter 4 includes test results and discussion.

2 Principles of non-uniform control

The remote adaptation of automatic ECG interpretation is driven by two sources:

- changes of the patient's status (objective - by diagnostic parameters values or subjective - by the event button), where existing interpretation setup is no longer optimal,
- changes of the environment including alteration of diagnostic goals, recording conditions or data transmission quality.

As in a regular control system, the processing error is compared to a reference which is a procedure running on the server and re-interpreting a selected ECG strip on a virtually unlimited platform. The value of difference in diagnostic parameters values plays the role of error signal and triggers actions towards alteration of the remote processing statements or code. The results of that action in the form of updated diagnostic parameters values are next evaluated with respect to two aspects:

- is the direction of changes appropriate to approach the reference values?

- is the amount of changes sufficient to meet diagnostic quality criteria?

The iterative and error-based nature of this adaptation justifies the control theory approach developed in following subsections.

2.1 Components of the control loopback

The idea of on-the-run software adaptation comes from the availability of different-grade procedures designed for the same computational purpose, but with different prerequisites for the resources requirements and result quality. Standardized data gateways enable the commutation between procedures while the interpretation is running, aiming at optimization of the remote interpretation process. Each subroutine is described by attributes of quality, resources requirements and external dependency, specifying its relations with other components in the signal interpretation tree. The optimization loopback is composed of three elements (see fig. 1):

- error verification procedure, issuing the error vector of values proportional to divergence between actual and expected remote system output,
- adaptation management procedure, selecting in the repository the most appropriate executable code, corresponding to control signal,
- software transport and relinking mechanism, being the analogy of summation node.

Unlike in regular control systems, the control signal has a form of selectable software code characterized by inherent features not possible to be precisely defined. In the domains of particular features, the values corresponding to subsequent procedures are thus discrete and non-uniform, moreover, no intermediate values can be achieved.

The verification is performed occasionally in predefined time intervals, or is asynchronously triggered as a result of data consistency check or by external (e.g. patient-activated) events. It begins with sending a short strip (8s) of raw electrocardiogram from the recorder's buffer along with the results of remote interpretation. This signal is next re-interpreted by the server and the values received from the remote recorder are individually compared to this reference. Based on the guidelines for required calculation accuracy [11] are specific values of tolerance thresholds *RAT* (see tab. 1) applied to the individual evaluation of measurement parameters differences (1).

$$\Delta v_i = \frac{v_i^{meas} - v_i^{ref}}{v_i^{ref}} \tag{1}$$

Excessive dissimilarity values trigger the decision on the automatic modification of the remote recorder interpretation software. Besides the diagnostic parameter-specific measure, we use also a global estimate of diagnostic quality. It is issued automatically by the server and used to assess the efficiency of the remote ECG interpretation. The disease-dependent global dissimilarity measure *DSm* (2) uses

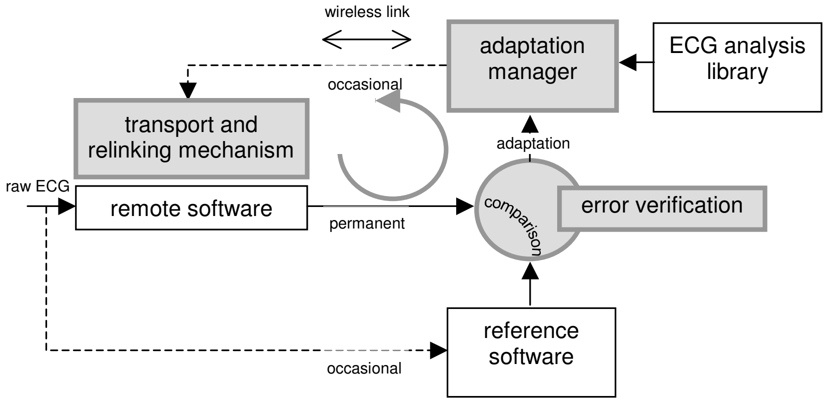

Fig. 1 Block diagram of the ECG processing optimization loopback

differences Δv_i between respective values of measurement parameters i weighted by corresponding relevance value w_i derived from the pursuit of knowledge expressed involuntarily by the human expert during the ECG interpretation [3].

$$DSm = \sum_{i=1}^{I} \Delta v_i \cdot w_i \quad where \sum_{i=1}^{I} w_i = 1 \tag{2}$$

Table 1 Expert-derived individual thresholds of measurements and diagnostic result tolerance

parameters group	procedure example	relative accuracy threshold RAT [%]
1	heart rate	2
2	wave limits detection	5
3	morphology classification	10
4	QRS electrical axis reconstruction	20

2.2 Static properties and control accuracy

Besides technical constraints (e.g. limitation of available memory) limiting the procedures availability in specific conditions, the selection of the most appropriate replacement procedure is based on the values Δv_i of error vector and subroutine description. For each procedure, the requirements of resources, restricting the range of procedure replacements, are derived from the code analysis. This method, however, is not applicable to the evaluation of algorithm quality, nor to the prediction of expected interpretation improvement. We used the expert system to estimate the performance improvement based on analysis of the usage history and past quality scores. Each procedure i is attributed by quality indicators AA_i and RA_i unified within the interpretation-oriented library, being a background of replacement decisions and improvement expectations. As the indicators are in fact experimental values, its non-uniform nature is intrinsic.

At a given time point the description of the commutable procedures may be considered as constant. For a given diagnostic parameter i (i.e. the one which value is found most outstanding from the reference), the *adaptation manager* expert system uses the corresponding series of $AA_i(c_m)$ where c_m is the identifier of m^{-th} $m \in M_i$ commutable procedure for the parameter i, as stepwise (i.e. discrete, with irregular steps) forecast of the absolute accuracy, determining the selection of replacing code. From the viewpoint of a particular diagnostic parameter, the commutable procedures are thus temporarily ordered by their quality expressed by the $AA_i(c_m)$ value. The *adaptation manager* uses this hierarchy to propose the software upgrade or downgrade, when necessary.

In case of sudden changes of the patient status or recording conditions, selection of the next better or next worse replacement procedure may not be optimal and result in an iterative, time consuming approach. This impacts the system response time for the possibly life-threaten events and requires longer storage of buffered raw ECG signal, particularly when data link quality is weak. Therefore in cases where diagnostic error suddenly exceeds the tolerance threshold, the radical change of interpreting software is alleged and the *adaptation manager* expert system uses the relative quality descriptors RA_i. For each diagnostic parameter i they are stored in a triangular matrix $RA_i(c_1, c_2)$ which facilitates the selection of a procedure better (or worse) than the current by an extent closest to the given factor.

The management of the commutable procedures aims at limiting the unsuccessful software replacement, however it should be considered that:

- the procedures hierarchy is history-dependent,
- the quality estimators are historical values with limited predictive value.

Therefore, the only reliable method for evaluation of the software optimization lies in repeated interpretation and validation of results quality. Asymptotic accuracy is the absolute value of diagnostic error st the time point when the transient-evoked software adaptation is completed. Assuming no other transient is present in the subsequent input signal, the asymptotic accuracy AAc for each parameter i is expressed as (3):

$$AAc_i = \lim_{t \to \infty} \left| v_i^{meas}(t) - v_i^{ref} \right| \tag{3}$$

where $v_i^{meas}(t)$ is the subsequent measurement outcome and v_i^{ref} is the server-calculated reference value. Although the definition of the AAc is linear, it is valid also in the particular case of discrete non-uniform adaptation and with constraints on the number of modification attempts applied in our system. Taking the analogy from the theory of control, the software adaptation plays the role of a feedback correcting the diagnoses made automatically. If the software modification decisions are correct, the outcome altered by the interpreting software modification approaches to the true value, the modification request signal is removed in consequence of decreasing error and the system is stable. Incorrect decisions lead to the growth of diagnostic outcome error and imply even stronger request for modification. The outcome value may stabilize on an incorrect value or swing the measurement range in response to subsequent modification attempts. In such case the system is unstable and the diagnostic outcome does not converge to the true value.

2.3 Automatic scoring of the procedure performance

Without loosing the generality, we assume here that each interpretation procedure yields a unique main outcome, the accuracy of which determines the procedure performance. Although it is not always true in real applications, procedures can be decomposed to comply with this assumption. The quality indicators for procedures are continuously updated each time the procedure outcome is evaluated. Two scenarios yield new quality values:

- absolute accuracy AA_i calculated when regular re-interpretation is made in predefined time intervals, as averaged absolute difference between the remotely-calculated result and the server-issued reference (4); this value is used to determine whether the usage of the particular procedure as replacement is sufficient to yield a result fitting within the tolerance margins for a particular parameter,

  $$AA_i = \frac{1}{N_i} \sum_{n=1}^{N_i} |\Delta v_{n,i}| \tag{4}$$

  where N is the length of the usage history set individually for each parameter i,
- relative accuracy $RA_i(c)$ calculated when the procedure replacement has been decided as ratio of desired improvement between the previously used and newly applied executable code (5); this value is calculated with respect to all commutable procedures C_i and used as an estimator of expected improvement and limits the number of necessary try-and-evaluate iterations.

  $$\forall c_m \in \{c_1 \cdots c_M\}\ RA_i(c, c_m) = \frac{1}{N_i} \sum_{n=1}^{N_i} \left| \frac{\Delta v_{n,i}^{c}}{\Delta v_{n,i}^{c_m}} \right| \tag{5}$$

  where c_m is the identifier of commutable procedure $m \in M_i$ and c is the identifier of procedure currently concerned as replacement

The list of procedure attributes (see fig. 2) contains few static values (e.g. *processing* $PR_{i,c}$ and *memory requirements* $MR_{i,c}$) filled in at the moment of code analysis and experimental quality indicators AA_i and RA_i varying with the time in context of patient needs. It is noteworthy here, that the notions of ”better” or ”worse” procedure became patient-relative and the processing adaptation in particular case is performed with regard to the patient’s history.

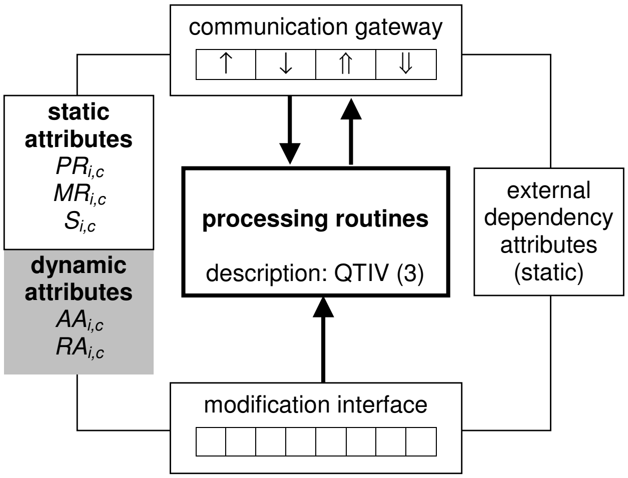

Fig. 2 Attributes of the commutable procedures

2.4 Dynamic properties of the ECG processing optimization

In an early version of the prototype, due to the limitation of program memory write cycles, all libraries were permanently implemented in the recorder's ROM. The working version of the interpretation software was adaptively build up with use of the flags system selecting libraries to be linked. Different approach was selected in the last prototype with unlimited program memory write cycles. The agile software of the remote recorder consists of 9 facultative interpretive components. For each of them the working code can be selected by the management expert system from specialized library containing 2 to 5 mutually commutable subroutines precompiled for the remote platform. Selected procedures are downloaded from the server each time before linking. Although the adaptation using software upgrade needs considerable more time, the range of alternative procedures is not limited at the recorder's manufacturing stage. The volume of largest single procedure is 17kB, and the download time is 3,4s assuming the use of full bandwidth of the GPRS downlink (40 kbps). Memory requirements specified for each procedure in tab. 2 includes maximum declared memory amount for local variables and are significantly larger than the volume of executable code. The volume of the 8s signal strip is considerable (48kB), resulting in the upload time of 24s (GPRS uplink bandwidth 16 kbps). As a compromise between the control response time and additional occupation of the wireless channel, the redundant re-interpretation interval is set to four minutes (average data stream of 1kbps). The particular signal strip is sent once for the control or adaptation purpose, while alternative procedures may be replaced several times approaching the reference results in the remote recorder. For practical reasons, how-

Table 2 Inventory of interpreting procedures with respective CPU/memory requirements [%]/[kB]

procedure name	version number				
	1	2	3	4	5
heartbeat detector	7/25	8/32	10/38	15/42	16/48
heartbeat classifier	15/18	17/26	20/35		
wave delimitation procedure	35/22	65/26			
ST-segment assessment	10/10	12/17	13/25		
arrhythmia detector	5/7	8/10	13/12	19/15	
heart rate variability analyzer	30/25	51/38	68/44		
electrical axes calculator	7/8	27/21			
rhythm identification procedure	5/12	6/18	8/26		
QT-segment assessment	13/20	17/31	33/35		

ever, the count of replacement iterations was limited to four per a single adaptation attempt.

This approach results in presence of an additional time factor delaying the adaptation of the remote software and justifying additional studies of dynamic behavior of the control loopback. The adaptation time depends on the size of the replacing executable code and can be roughly estimated from the indicator of link quality. Adaptation delay is defined by (6) as the time period from the transient occurrence t_0 to the moment t_D when the diagnostic outcome altered by the interpreting software modification starts falling into a given tolerance margin ε around its final value.

$$D = t_D - t_0 : \forall t > t_D \; v(t) \in (v(\infty) - \varepsilon, v(\infty) + \varepsilon) \tag{6}$$

The device status message describing basic technical conditions of the remote recorder, independently or within the diagnostic report, provides the estimate of wireless link quality. Together with the static procedure attribute *code size* $S_{i,c}$, this value is used to calculate the expected adaptation delay caused by the procedure code transmission. The delay exceeding a given threshold (e.g. in bad transmission conditions) inhibits the upgrade of interpreting software. In relation to the length of remote recorder raw signal buffer (64 s), this threshold is given to 30 s.

3 Experiments and results

3.1 Prototype details

The prototype remote recorder was based on a development kit of the PXA-270 CPU [12] running GNU/Linux operating system with the Aspect-500 (Aspel) ECG acquisition module (8 channels, 12 bits, 500 sps) and bi-directional GPRS connection [14]. The prototype server was based on a PC with Linux OS and the 100Mbps static IP Internet connection. The largest partition of the remote system memory

(512kB) is allocated for the raw ECG circular buffer of the capacity of 64 s. The second largest memory block is allocated for the variables and the executable code of the interpretive software. The prototype software provided options for selective disabling the adaptation.

3.2 Experimental setup

In all the experiments we used 2751 artificially combined signals originating from 58 records of Common Standards for quantitative Electrocardiography (CSE) Multilead Database [13]. Cardiologists annotated the CSE records since the database does not directly disclose the pathology information. In each test signal the appearance of a single pathology was simulated by the concatenation of a record annotated as normal followed by a pathology-specific record. The count of samples was adjusted accordingly to the precedent RR interval in the vicinity of the border point. Also the baseline level of the subsequent record was corrected for each lead independently. Such test records simulate the abrupt cardiac changes and facilitate the technical analysis of the adaptive system behavior. A multi-channel arbitrary generator reproduced the analog signals of the total duration of 1-1.5 hour. Reference values of wave borders for the assessment of interpretation in the distributed system were calculated as the mean of CSE results.

3.3 Static accuracy of the processing optimization

The test procedure was focused on the following aspects:

- Efficiency of the iterative software adaptation expressed by the required number of iterations,
- Convergence of the remotely computed diagnostic parameters to the server-computed reference values.

In case the remote software is modified in result of the data inconsistency, the iterative interpretation of the buffered ECG is repeated up to four times, until the values of the remotely calculated diagnostic results are out of the tolerance margins (see tab. 1). Main results of the test are presented in tab. 3. In the medical aspect, the correctness of the single attempt of software optimization was measured by the percentage of cases (tab. 4) for which in result of the software adaptation new diagnostic parameters approach to the reference values and reduce the *DSm* value (see 2). The calculation of *DSm* uses the relevance of diagnostic data and thus favorites certain procedures over others.

The medical correctness of software replacement decisions summarized in the last row of table 4 is the quality estimator of the software management expert sys-

Table 3 Results of remote diagnostic results convergence test after the consecutive steps of interpretation software modification

software modification steps	converging [%]	non-converging [%]
first	63.1	36.9
second	74.5	25.5
third	79.1	20.9
fourth	80.7	19.3

Table 4 Medical correctness of software adaptation

optimization type	diagnosis improvement	diagnosis degradation
software upgrade	643 (99,4%)	4 (0,6%)
software replacement	97 (80,2%)	24 (19,8%)

tem. For over 80% of cases, the software replacement improved the diagnostic result.

3.4 *Dynamic properties and temporal convergence*

The delay of messages varied from 1.3s (abnormal finding message of high priority) to 6s (regular report). The diagnostic data quality and the transmission delay were measured with respect to the procedures recommended by IEC [11]. Estimation of the longest adaptation delay was performed with use of the real wireless GPRS connection (tab. 5).

Table 5 Delay to the remote recorder adaptation

optimization type	longest delay [s]	average delay [s]	standard deviation
coefficients update (CU)	17.1	4.3	1.3
software upgrade (SU)	6.0	4.4	1.5
software replacement (SR)	5.9	4.5	1.5
server-side allotment (ST)	2.4	0.8	0.3

4 Discussion

Discrete nonlinear control of the diagnostic quality in distributed telemedical system was designed, prototyped and tested. The quality control is based on the diseasespecific hierarchy of diagnostic parameters and on the hierarchy of commutable diagnostic procedures. Two principal quantitative benefits measured in the system are: reduction of digital communication costs (by 5.6 times on average) and extended autonomy time (by 65% on average), both being a result of avoiding the unnecessary computation and data transmission.

Test results show a considerable improvement on the diagnosis quality against the rigid software, however further analysis of outliers is required. The adaptive processing and transmission combine the advantages of two solutions being in use today (e.g. [1]):

- Load of the transmission channel is nearly as low as when the remote interpretation was used,
- Interpretation reliability is almost as high as in the centralized interpretation architectures with an occasional assistance from human expert.

Further considerable impact to the diagnostics quality comes from the use of content-dependent data format.

Future investigations are necessary for the compatibility of the interpretive software designed for different platforms (i.e. remote recorder and central server). Designing both variants based on identical rules affects the optimization of the server interpretation thread. Consequently, the processing chain of the server thread tends to mimic the design of its remote counterpart, losing the potential benefits of efficient hardware platform.

The selection of the replacing code is based on the value of parameter-specific error Δv_i and on the reported resources availability. If the replacing procedure sufficiently ameliorates the diagnostic result, further adaptation is not performed even if the availability of resources reported after the replacement allows for a higher-grade procedure.

Technical constraints are main source of inaccuracy of the ECG interpretation made by the software of wearable remote recorder. Such limitations are not present in a server-side application using virtually unlimited resources. Therefore the diagnostic result occasionally issued by the server is accurate enough to play the role of the reference in the assessment of remote interpretation quality (see 3). The resulting similarity-based estimate of recorder-side interpretation quality is issued automatically by the server and used to adapt the remote ECG interpretation. Nevertheless, other limitations of the automatic interpretation are intrinsic for an algorithmic approach, therefore the surveillance from a human expert is indispensable for the system reliability. The role of the expert is twofold: interpreting medically difficult cases and correcting the automatic adjustment of remote interpretation software.

The system behavior in presence of outliers and the raw signal noise needs more testing in clinical conditions (in parallel to currently approved systems). The influences of the noise and propagated processing errors on the subsequent interpretation stages highly depend on the quality of interpretive procedures. Another limitation influencing the experimental results comes from relying on manufacturer-specific software resources (from Aspel S.A.), and more sophisticated software collection will improve the noise immunity of the system.

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References

1. Atoui H., Telisson D., Fayn J., Rubel P., (2008), Ambient Intelligence and Pervasive Architecture Designed within the EPI-MEDICS Personal ECG Monitor, International Journal of Healthcare Information Systems and Informatics, Volume 3, Issue 4,
2. Augustyniak P., (2005), Content-Adaptive Signal and Data in Pervasive Cardiac Monitoring, Computers in Cardiology, vol. 32, pp. 825-828,
3. Augustyniak P., (2008), Exploring the knowledge of human expert beyond his willing expression, [in:] Pietka E., Kawa J. (eds.), Information technologies in biomedicine, Springer-Verlag, Advances in Soft Computing vol. 47, pp. 314,
4. Augustyniak P., (2009), Strategies of Software Adaptation in Home Care Systems, [in:] M. Kurzynski and M. Wozniak (Eds.), Computer Recognition Systems 3, pp. 393-400, Springer,
5. Bousseljot R. , et al., (2003), Telemetric ECG Diagnosis Follow-Up, Computers in Cardiology, vol. 30, pp. 121-124,
6. Chen X., Ho C.T., Lim E.T., Kyaw T.Z., (2007), Cellular Phone Based Online ECG Processing for Ambulatory and Continuous Detection, Computers in Cardiology, vol. 34, pp.653-656,
7. Chiarugi F., et al., (2003), Continuous ECG Monitoring in the Management of Pre-Hospital Health Emergencies, Computers in Cardiology, vol. 30, pp. 205-208,
8. Fayn J., et al., (2003), Towards New Integrated Information and Communication Infrastructures in E-Health. Examples from Cardiology, Computers in Cardiology, vol. 30, pp. 113-116,
9. R. Gonzlez R., Jimnez D., Vargas O., (2005), WalkECG: A Mobile Cardiac Care Device, Computers in Cardiology, vol. 32, pp. 371-374,
10. Gouaux F. et. al., (2002), Ambient Intelligence and Pervasive Systems for the Monitoring of Citizens at Cardiac Risk: New Solutions from the EPI-MEDICS Project, Computers in Cardiology, vol. 29, pp. 289-292,
11. IEC 60601-2-51, (2003), Medical electrical equipment: Particular requirements for the safety, including essential performance, of ambulatory electrocardiographic systems, First edition 2003-02, International Electrotechnical Commission, Geneva,
12. www.toradex.com (visited on March, 31, 2008)
13. Willems JL., (1990), Common Standards for Quantitative Electrocardiography 10-th CSE Progress Report, Leuven: ACCO publ.,
14. Ziecik P., (2008), Mobile Development Platform for Wide Area ECG Monitoring System, Proc. of Biosignal2008 Conference, paper 72,