# Towards the Development of Next-Generation Remote Healthcare System: Some Practical Considerations

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***Abstract*—In this paper first we present an overview of the state-of-the-art remote patient monitoring systems in the backdrop of real clinical needs. The paper establishes a clear guideline in terms of clinical expectations from such a system from the viewpoint of practicing clinicians. It provides in-depth analysis of the shortcomings of the existing architectures and paves a way towards developing a practical "patient-centric" architecture that could be useful in the day-to-day clinical practice for providing "continuum of care". Subsequently, the restrictions imposed by the resource constrained nature of such a system on development of appropriate hardware for supporting information processing on the data acquired by body-worn sensors are analyzed.**

***Index Terms*—Remote monitoring, Healthcare, Low-Energy Systems**

## I. Introduction

Ageing population and continuous prevalence of chronic diseases have put the current healthcare systems worldwide under serious strain in terms of quality of care delivery and its associated cost. As an example, most EU member states spend around 30 - 40% of the total health expenditure on elderly population and long-term care [1]. It is predicted that the healthcare cost will increase from a worldwide average of 9% of GDP in 2005 to 11% by 2015 [1], and therefore leading to a formidable socio-economic challenge. The only way to avoid this critical situation is to implement radical changes in the current healthcare systems starting from diagnosis to the level of care delivery in a resource-optimal way. Disease management and prediction of an impending episode at an early level are viewed as the key factors which may help in drastically reducing the cost of care delivery, enhancing quality of care/life and significantly reducing mortality and hospitalizations. Successful implementation of such a system depends on continuous acquisition, analysis and information fusion of heterogeneous vital sign data and interpreting the results in a "context-aware" way under the backdrop of practical clinical knowledge. Importantly, from the clinical perspective, due to varying case scenarios and for cutting the cost of hospital in-patient stay period, the system needs to support patient monitoring in nomadic settings.

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Advances in Information and Communication Technology (ICT), especially in the fields of miniaturised sensors development, low-power VLSI technology enabling performing complex signal processing tasks within small silicon area at the expense of little power; and wireless communication/sensor network technology, integrated together in a proper collaborative way, may create the very backbone of such a remote healthcare system which enables delivering high-quality resource-optimal care "anytime anywhere". Such a system is deemed to transform the traditional "reactive" healthcare system to a "proactive" system that may enable preemptive intervention leading to significant cost and mortality reduction.

In this paper, after reviewing the basic philosophy of the remote healthcare system currently deployed in practice, a clinician's perspective of an "effective" remote monitoring system is presented in Section II. High-level architectural alternatives for such effective system and the associated technological challenges for each of them are discussed in Section III. An architecture introducing on-body information analysis and how it may overcome the technological barriers for implementation of an effective remote monitoring system is discussed in Section IV. Conclusions are drawn in Section V.

## II. Philosophy of Remote Monitoring: A Clinician's Perspective

Typical modalities for remote monitoring currently deployed in practice include telephone-based symptom monitoring, automated monitoring of signs and symptoms and automated physiologic monitoring [2] as shown in Fig.1. In all the three modalities the nurses play central role in assessing the patient's conditions leading to home visits or involvement of consultants as appropriate. While the first modality is widely used in practice, the last two are deployed only in some narrow fields - like Implantable Cardioverter Defibrillator (ICD) and stroke patients - although several commercial companies have developed home monitoring systems based on the latter two methodologies, for assisting the clinical needs (for example see [3]). From our working experience in the field of ICD, although such a system is helpful, it does not always satisfy the exact clinical needs and also involve costly human intervention. As the nurse plays the central role in all the modalities, case load/nurse is increasing significantly with the prevalence of long-term conditions which may lead to an unsustainable system in future. Moreover, the benefit of such remote monitoring system in terms of cost and mortality reduction is still debatable.


Fig. 1. Traditional Remote Monitoring Modalities

The key missing element of the currently developed remote monitoring systems is the ability to predict an impending episode even before the symptoms are fully manifested. Such ability in principle not only will reduce the cost factors associated with hospitalization and management but also will significantly reduce mortality and disability conditions resulting from the disease by employing preemptive therapy. This needs integration of heterogeneous vital sign data and patient's input into a robust and expert risk predictor model that personalizes its analysis according to the specific case/patient and assesses the temporal evolution of the clinical status of the patient in an autonomous way modulated by practical clinical knowledge. The process for such integration and assessment of temporal evolution of the disease state needs to run continuously on a patient identified at-risk irrespective of the patient's physical location. In case the outcome falls within a predefined disease state, the system should be able to automatically direct the patient towards appropriate management strategy and otherwise notify the appropriate clinical personnel in an automated way.

Advances in miniaturized sensor technology are instrumental under such scenario. However the constraints are twofold. Firstly, the sensors need to be pervasive in nature so that they do not interfere with the day-to-day activities of the patients and from our practical experience, the patients do not accept more than three patches on their body. Although it is essential to track as many vital signs as possible (for some diseases this is clearly defined), the latter requirement asks for integrating multiple sensors within a patch without destroying its pervasive nature. Secondly, once the data is captured, relevant clinical features need to be extracted and a disease state classifier that utilizes a personalized patient model in the backdrop of practical clinical understanding has to be invoked to track the prognosis of the disease in a context-aware way.

## III. High-Level System Architecture and Technological Constraints

To satisfy clinical expectations described in the previous section, two fundamental criteria need to be considered for development of such a system. Firstly, integration of heterogeneous sensors with associated electronics within at the most three patches and secondly, continuous measurement and analysis of data. A high-level system diagram that may satisfy these needs is shown in Fig.2. Simplistically, it consists of three parts: a mobile system consisting of multiple parameter measurement sensors, a back-office service platform and an external platform for long term data storage and statistical analysis. It is imperative that physically the sensors need to be body-worn and non-invasive in nature, equipped with pre-processing circuitry (like ADC, filters and microcontroller) capable of communicating wirelessly with the back-office service platform. To date, several sensors have been developed for satisfying these needs capable of forming a body-area network. However, the major technological challenge is to integrate several sensors with heterogeneous specifications within one patch. Because of the body-worn nature, the sensors are battery powered. Therefore it is important to design the circuitry in such a way that each of the sensor nodes consume very low energy so that they can sustain long-term operation in continuous way. Depending on the specific clinical need, the duty cycle, data encoding strategy and data transmission rate of different sensors vary wildly resulting in significant variability of the associated processing circuitry. Owing to the low energy requirement, a design space exploration needs to be done for finding out the commonality in specifications so that the resulting hardware can be implemented in an energy optimal way. This is a huge challenge that needs rigorous addressing.

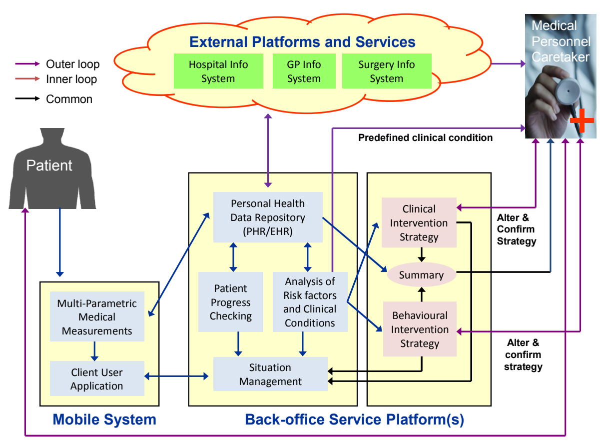


Fig. 2. High-Level System Architecture

The back-office service platform is responsible for clinical feature extraction and analysis of the data by invoking computationally intensive signal processing and classification techniques. Owing to this computationally intensive nature under energy requirement constraints, the best solution is to run it on a remote server, presumably located at the clinical settings. This necessitates continuous transmission of data from the sensors to the server using wireless protocols to take care of the nomadic environment. This can be achieved in two ways: the sensor node communicating to the remote server directly using GSM/WiFi protocol or sensor nodes communicating with the patient's mobile device as a gateway for accessing the remote server. In this case, the sensor nodes first communicate with the mobile device using Bluetooth or Zigbee network and the mobile device uses GSM/WiFi to access the remote server. Considering a smartphone or a tablet PC as the patient's mobile device, the obvious choice is Bluetooth since these devices do not support Zigbee yet.

The fundamental problem with continuous data transmission scenario using either of the two methods described above is the energy requirement. Typical Bluetooth v2 transceivers consume approximately 40 mA to 55 mA during transmission with typical operating voltage in the range of 3 - 3.6 V. However, the Bluetooth module can be operated exploiting its sniff mode where the module can consume as low as 3 mA [4]. On the other hand, typical battery capacities based on various chemical technologies are within the range of 80 mAh - 3700 mAh. Considering an example of continuous ECG data transmission sampled at 1 KHz, 16-bit quantization, 470 ms sniff interval (used by AliveTec Inc.), on-current of 50 mA in active mode and 2.5 mA in sniff mode, following the analysis presented in [5] the typical battery life-time under continuous data transmission scenario is shown in Table I. The results show that the fundamental notion of continuous data transmission cannot be supported for long time. It is to be noted that the batteries with an appropriate size for on-body platforms typically can produce 1200 mAh, which leaves us with only 24 hr. monitoring. Another point to consider here is that the results shown in Table 1 only consider purely transmission energy and do not include the energy involved in preprocessing data at the sensor node which include A/D conversion, quantization, filtering and the operation of the microcontroller. Including energy expenditure of those components it can be firmly deduced that in reality continuous transmission cannot be supported for more than 8 - 12 hrs. One way is to use batteries with higher energy capacity. However, as the energy capacity increases the batteries become bulky and therefore are not suitable for on-body applications. The energy capacity of the medical community favored latest prismatic zinc-air battery is 1800 mAh operating at 1.4 V[6]. Therefore for accommodating the operating voltage demand of a Bluetooth radio about three of such batteries need to be connected together which once again will not be suitable due to the total volume. One important point to be noted here is that there is a possibility for operating the sensors and their associated electronics at much lower operating voltage than that required for the Bluetooth radio. This results in using multiple power supply based system design which may not be an appropriate solution for such a resource constrained environment. On the other hand, if the entire sensor node is operated with the supply voltage dictated by the Bluetooth then the energy dissipation of the associated electronics will become more significant as power dissipation is quadratically proportional to the supply voltage and therefore will have a negative impact on the continuous operational life-time.

| Battery Capacity | Lifetime Cont. Transmission | Lifetime Sniff Subrating |
|---|---|---|
| 250mAh | 5h | 52h |
| 800mAh | 16h | 167h |
| 1200mAh | 24h | 250h |
| 1800mAh (AA only) | 36h | 375h |
| 3000mAh (AA only) | 50h | 626h |

TABLE I
APPROXIMATE LIFETIME FOR VARIOUS BATTERY CAPACITIES

The situation is not much different if dedicated GSM radio is used as it exhibit high energy/bit transmission and low bandwidth. Again referring to the results in [5], the approximate power consumption for a data production rate of 1 KHz is 128.6 mW yielding 50 hr lifetime for 1800 mAh Li-ion battery under 3.6 V (once again the processing power is not included here).

Energy harvesting has received significant attention now-a-days for powering on-body sensors from body movements. Typically human body can generate 0.5 W/Kg in various parts [7]. This can be coupled with vibrational energy harvesting. However, typically on-body energy harvesters are expected to produce few mW aperiodically [8] and therefore are far away from satisfying the energy demand of the system under consideration. Apart from the energy issue, one important criteria of the remote monitoring system is that no data loss is allowed owing to the sensitive nature of clinical data. Once again considering Bluetooth as the main means of communication, the overall energy dissipation strongly depends on the packet format the system utilizes as it has an impact on the bandwidth. An optimization for energy dissipation using standard duty-cycling may lead to significant delays and packet loss which is very much undesirable for the target system.

Considering problems described above, it is suffice to say that continuous data transmission based remote monitoring system development with the current state-of-the-art technological components is extremely challenging to achieve at present mainly due to the energy constraint unless significant innovations are made.

## IV. ON-BODY INFORMATION PROCESSING: AN ALTERNATIVE ARCHITECTURE

The fundamental requirement of an effective remote patient monitoring system is the ability to analyze the evolving clinical status of the patient under monitoring in a continuous way so that any impending episode can be estimated beforehand. Continuous data transmission is required for enabling the remote server for running the analysis invoking complex signal processing and classification algorithms. While satisfying this basic need, the problem of energy requirement for continuous transmission may be reduced considerably by using an alternative architecture where sensors are not only used for mere data capturing but also are used for distributed on-body information processing. The basic philosophy of this approach is shown in Fig. 3. In this scheme, each of the sensors is integrated with an ASIC chip dedicated for on-board signal denoising, artefact separation and feature extraction. Since each of the vital sign parameters has its own well documented characteristics and clinically relevant features, it is possible to tailor the signal processing and feature extraction algorithms in a more effective and energy optimal way. Only the extracted features (which in principle can be coded by a few bits since in essence they can be represented by a numerical value) from different sensor nodes are transmitted to an on-body classifier implemented in hardware (with a memory module) following clinically defined rules. At the same time the raw data could be stored in memory on-board the sensors. The final results from the classifier (again a numerical value that can be coded using a few bits) can be transmitted to the remote server using standard communication protocol on a periodic basis. However, if the classifier concludes the possibility of an impending episode (by comparing the result with a pre-defined threshold stored in its memory that is set using practical clinical understanding), an alarm flag is generated which is immediately transmitted to the responsible clinicians mobile device. The clinician, in such a case may interrogate individual sensors for raw data and results of its statistical analyzes which are stored within the sensor memory. Adopting this approach results in significant reduction of energy requirement for continuous data transmission encountered in the conventional architectures since only few data are transmitted to the remote server on periodic basis under normal scenario whereas keeping flexibility for transmitting raw data only on demand. This architecture is currently in use in ARTEMIS Joint Undertaking funded project CHIRON [9] that is intended for developing a remote patient monitoring system that may enable to provide "continuum of care".

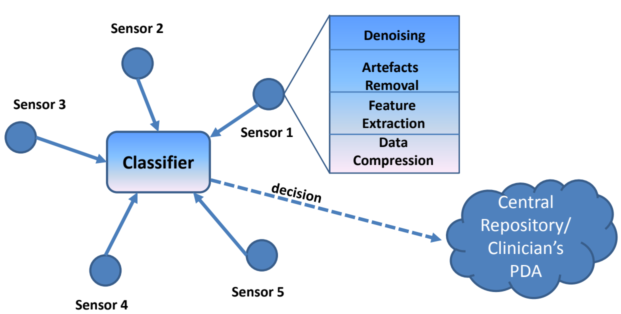


Fig. 3. On-Sensor Processing Architecture

It may be argued that in this case the energy requirement for the overall system is simply shifted from continuous transmission to the on-body computational infrastructure that needs to invoke complex signal processing tasks. It is to be noted that here it is possible to tailor the information processing part according to the "actual requirement" and therefore the information processing hardware can be designed in optimal way. As an example, let's consider a typical scenario of using one skin temperature sensor, an activity monitoring sensor and a wearable ECG system. It is evident that most computationally intensive processing has to be dedicated for ECG feature extraction and this in true sense is continuous processing of high volume data. As part of CHIRON project, our team has developed a complete ECG feature extraction algorithm (clinically validated) and the associated hardware. When implemented in 120 nm technology node the dynamic power consumed by the hardware dedicated for this purpose is only 600 nW which corresponds to approximately 550 nA current. These figures show the effectiveness of this methodology.

However, it is to be noted that the information processing algorithms typically used in clinical settings running on server may not be appropriate for attending low energy in this methodology. It is imperative that novel and appropriate signal processing algorithms need to be developed depending on the actual application scenario in a case-by-case basis.

## V. Conclusions

This article is mainly aimed at pointing towards the possibility of realization of an effective remote monitoring system using the state-of-the-art technology. The practical considerations for developing such system are often undermined. Therefore here we describe the actually needed functionality of such a system from clinicians' perspective and where exactly traditionally proposed systems fail to satisfy this need. It is imperative that energy requirement is the biggest constraint for implementing such system and therefore novel techniques starting from the level of sensor development, information processing, VLSI design up to communication technology need to be developed and should be applied in a cooperative way for its successful development.

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