Editorial: Special Issue on Mobile and Wireless Technologies for Healthcare Delivery

I. Introduction

HEALTHCARE challenges, including rising healthcare costs, aging populations, and emerging disease threats rank among the most serious concerns in the world. Recent global focus on healthcare issues has stimulated research and development of innovative technologies that may address the unsustainability of current healthcare provision models. Several healthcare organizations are seeking new techniques to deliver quality healthcare in a timely, cost effective and efficient manner.

Rapid advances in wireless communications [1], mobile computing [2], and sensing technologies [3], [4] are opening new opportunities in healthcare [5]. The aim is to optimally utilize the capabilities of diverse wireless technologies and effectively manage the complexity of wireless and mobile networks for healthcare applications, toward advancing prevention, medical diagnosis, treatment, and patient care [6]. Current and emerging developments in wireless communications integrated with advances in pervasive and wearable technologies have the potential to transform healthcare delivery by substantially improving healthcare processes while providing a unified communication framework for staff members. With an increasing deployment of mobile and wireless networks, the role of wireless infrastructure in healthcare applications is expected to become significantly more prominent in the years to come.

II. Significance of the Area

Exploitation of Information and Communications Technologies (ICT) can assist in a fundamental redesign of the healthcare processes based on the use and integration of communication technologies at all levels. Recent advances in ICT enable cost effective and efficient healthcare delivery in home, hospital, assisted living, and nursing home settings to promote disease management and wellness [7], [8]. Disease management programs aim to support patient-specific care plans and the provider-patient relationship via evidence-based guidelines, while focusing on prevention of deteriorations and/or complications. Aiming at citizen empowerment, the paradigm of disease management can be extended to wellness management, where the focus is on disease prevention, maintenance, and improvement of the health status of any individual.

Citizen-centered applications enable a partnership among practitioners, patients, and their families (when appropriate) to ensure that procedures and decisions respect patients' needs and preferences. Such applications bridge clinical and nonclinical sectors and include both individual and population health-oriented tools [9]. They encompass different communication channels such as web-based systems, portable monitoring tools, and mobile devices. Some examples include remote diagnosis, patient and elderly monitoring, computer assisted rehabilitation and therapy, control of vital parameters of people suffering from chronic diseases such as asthma, diabetes, epilepsy, Parkinson's disease and heart attacks, sensing of individual's health-related activities and vital signals, and smart management of medical records with the help of on/in body biosensors, radio frequency medical devices and intrabody communication systems [10]–[12].

Healthcare ICT are expected to empower patients/citizens and support a transition from a role in which the citizen is the passive recipient of care services to an active role in which the citizen is informed, has choices, and is involved in the decision-making process. These modern healthcare systems set some additional critical requirements and challenges compared to traditional wireless networks. Key factors to support the transition to a citizen-centered healthcare model include: timely access to diagnostic information in many acute care settings, energy-efficient biosensor design, and stringent standards for electromagnetic interference characteristics of wireless devices, biocompatibility and "chronic implantability," system integration, sensor miniaturization, patient safety, and emergency detection and response [11].

III. Overview of the Special Issue

The target of this Special Issue on *Mobile and Wireless Technologies for Healthcare Delivery* is to address innovative research activities, which reveal the rapidly changing face and context of patient monitoring and healthcare delivery services facilitated by wireless communications and sensing technologies. This special issue presents current and emerging trends; highlights challenges related to design, evaluation, and usability; and identifies open issues and steps needed for future advances.

A total of 160 manuscripts were submitted in response to our call for papers. All submitted papers went through a peer-review procedure, and 25 papers are selected for inclusion in the Special Issue following peer review. Ten of these papers address issues related to the design, operation and performance of portable, wearable and implantable medical devices, nine papers deal with the development of novel algorithms and protocols for medical data processing and transmission, three papers explore medical device coexistence and networking issues, and three papers investigate power and/or data transmission and modeling for wireless healthcare systems. The collection of papers in this issue nicely covers a broad range of applications related to mobile voice monitoring, remote monitoring

Digital Object Identifier 10.1109/TBME.2012.2212775

of drug-related hearing changes, minimally-invasive diagnosis by means of wireless intraocular microrobot, respiration measurement and respiratory disease monitoring, detection and synchronization of walking and breathing conditions, mobile gait measurement and analysis, gastroesophageal reflux disease (GERD) monitoring, capsule endoscopy, monitoring and recognition of human physical activity, accidental fall detection, wireless neural recording, monitoring and detection of simple motor seizures, long-term monitoring of hypertension patients, and wireless electrocardiogram (ECG). Manuscripts appearing in this issue also address important challenges in areas like intrabody communication (IBC), implantable antennas, interference in battery-powered physiological monitoring devices, virtual group formation among devices on patients, nurses and doctors, and real-time clinical video transmission over wireless networks.

The first ten papers present the design, operation, and performance of wireless medical devices, which can be carried, worn on or implanted into the human body for diagnosis and therapy.

Improvement in diagnosis and treatment of many common voice disorders requires quantification and tracking of the daily status of vocal hyperfunction. Mehta *et al.* report on the development of a novel clinical device for mobile voice monitoring, which acquires data from an accelerometer sensor placed on the neck skin above the collarbone. Using a smartphone as the data-acquisition platform, the prototype device provides a user friendly interface for voice monitoring, daily sensor calibration, and periodic alert capabilities. Reported pilot data demonstrate the potential of the device to yield standard measures of fundamental frequency and sound pressure level.

Cancer treatment often requires patients to be exposed to drugs that can damage hearing. Jacobs *et al.* describe the design of the O to ID, a device which includes a portable audiometer with high frequency test functionality, and is capable of reliably detecting a person's drug-related hearing changes relative to a baseline period using an automated test. The system includes a wireless cellular modem providing notification to a remote healthcare professional in the event of a significant change in hearing. Evaluation results indicate that the OtoID can be used to effectively monitor hearing changes remotely, ultimately enabling early detection of ototoxicity, and potentially avoiding hearing loss.

Ergeneman *et al.* present a luminescence oxygen sensor integrated with a wireless intraocular microrobot for minimally invasive diagnosis, which can be accurately controlled by applying magnetic fields. The sensor works based on quenching of luminescence in the presence of oxygen, and a custom device is designed and built to use this sensor for intraocular measurements with the microrobot. An alternative sensor design with improved performance is also demonstrated by using poly(styrene-co-maleic anhydride) (PS-MA) and PtOEP nanospheres.

Zhu *et al.* propose a Bluetooth portable monitoring system for respiratory diseases using microsensors which measure the user's respiratory airflow, blood oxygen saturation, and body posture. The system can serve as a sleep recorder and/or a spirometer, while a mobile phone or a PC enable telemedicine capabilities. Feasibility and effectiveness of the proposed system are experimentally evaluated for monitoring and diagnosing obstructive sleep apnea, chronic obstructive pulmonary disease and asthma.

Li *et al.* present a dc-coupled continuous-wave radar sensor as a noncontact and noninvasive approach to respiration measurement for motion-adaptive cancer radiotherapy. Using a dc coupled adaptive tuning architecture, the radar sensor can precisely measure movement with stationary moment, while always working with the maximum dynamic range. Experiments carried out to evaluate the accuracy of respiration measurement with the proposed radar sensor indicate feasibility of respiration measurement while the radiation beam is on, and the sub-mm accuracy of measurement.

Bamberg *et al.*[1] describe the design and fabrication of a wearable, and wireless insole-based gait analysis device which uses low-cost force sensitive resistors. Subject-specific linear regression models are used to determine ground reaction forces plus moments corresponding to ankle dorsiflexion/plantarflexion, knee flexion/extension, and knee abduction/adduction. Comparisons with data collected from a clinical motion analysis laboratory demonstrate that the insole results for ground reaction force and ankle moment are highly correlated (all >0.95), while the two knee moments are less strongly correlated (generally >0.80).

Breathwalk is the science of combining specific patterns of footsteps synchronized with the breathing. Hung *et al.*[1] propose a system which detects user's walking and breathing conditions and provides appropriate multimedia guidance on the smartphone to enhance the user's awareness of walking and breathing behaviors. A walking-aware system is developed and evaluated. Experimental results show that the system could effectively assist beginners in slowing down the walking speed and decreasing incorrect footsteps, and that the visual-auditory mechanism is the preferred multimedia assisted mechanism while walking.

Munties *et al.* present a novel fully implantable wireless sensor system intended for long-term monitoring of hypertension patients, designed for implantation into the femoral artery with CT-angiography. It consists of a pressure sensor and a telemetric unit, which is wirelessly connected to an extracorporeal readout station for energy supply and data recording. The system measures intraarterial pressure at a sampling rate of 30 Hz and an accuracy of ± 1.0 mmHg over a range of 30–300 mmHg, while consuming up to 300 μW of power. Reported results are in good agreement with reference sensor systems.

Cao *et al.* prototype a device for GERD monitoring, consisting of an implantable, batteryless and wireless transponder with integrated impedance and pH sensors, and a wearable, external reader. *In vitro* experiments are conducted in a mannequin model, while live pigs under anesthesia are used as animal models. Results show that in short reflux cases, the proposed sensors can respond immediately to the stimulated reflux episodes, and detect each episode of either acid or nonacid nature.

Kiourti *et al.* address the design and testing of implantable antennas for medical telemetry. A model of a novel miniature antenna is proposed and an iterative design-and-testing method-

[1] To be published in the December 2012 issue.

ology is suggested. Validation is performed within a specific prototype fabrication/testing approach for miniature antennas. The study provides valuable insight into the design of implantable antennas, assessing the significance of fabrication-specific details in numerical simulations and uncertainties in experimental testing for miniature structures.

The next nine papers deal with the development and evaluation of novel algorithms and protocols for medical data processing and transmission.

In wireless ECG transmission, data latency is significant when battery power level and transmission distance are not maintained. Pandya *et al.* introduce a novel algorithm, identified as peak rejection adaptive sampling modified moving average (PRASMMA) algorithm, to overcome the joint effect of these issues on wireless ECG transmission and other measurement noises. The algorithm removes errors in the bit pattern of the received data, implements a modified moving average and sets its filtering parameters according to different sampling rates selected for signal acquisition. The performance of the PRASMMA algorithm is compared with the moving average and S-Golay algorithms, showing that the PRASMMA algorithm can significantly improve ECG reconstruction.

In order to achieve an optimal effect in endurance training, heart rates should reach sufficiently high values to trigger the aerobic metabolism, while avoiding very high values that can bring about significant risks of myocardial infarction. Cea *et al.* define and evaluate a functional model for an ambient intelligence system that monitors, evaluates, and trains aerobic endurance, based on an Android System and the GOW Running smart shirt. Measurement results confirm validity of the model. A high hit rate was observed between training sessions of the users and the objective training functions defined in the training programs.

Mariani *et al.* present a new method to estimate clearance using a foot-worn and wireless inertial sensor system, relying on the computation of foot orientation and trajectory, combined with the temporal detection of toe-off and heel-strike events. Based on a kinematic model that automatically calculates sensor position relative to the foot, heel, and toe, trajectories are estimated. 2-D and 3-D models are presented and validated against an optical motion capture system. Results indicate accuracy $\pm$ precision of 4.1 ± 2.3 cm for maximal heel clearance, and 1.3 ± 0.9 cm for minimal toe clearance compared to the reference.

Xu *et al.* present a compressed sensing-based approach to recognize human activity and sensor location in a single framework. In this way, the sensor deployment is much easier and not necessarily constrained in the prefix position. A pilot study is carried out to validate the effectiveness of this approach, for the task of recognizing 14 human activities and 7 on body locations. On average, the proposed approach achieves an 88.27% classification accuracy (the mean of precision and recall).

Naranjo *et al.* present the design and implementation of a wearable and unobstructive intelligent accelerometer sensor for monitoring physical activities. Activity monitoring is performed in a holistic manner in the same device through different approaches: 1) a classification of the level of activity that allows to establish patterns of behavior, 2) a daily activity living classifier that is able to distinguish activities, and 3) an estimation of metabolic expenditure independently of the activity performed and the anthropometric characteristics of the user.

One serious issue related to falling among the elderly living at home or in a residential care facility is the "long lie" scenario, which involves being unable to get up from the floor after a fall for 60 min or more. Ariani *et al.* use a path-finding algorithm to simulate the movement of one or more persons through the residential area, in an attempt to investigate the potential effectiveness of using wireless ambient sensors to track the movement of multiple persons and to unobtrusively detect falls when they occur. A fall algorithm, based on a heuristic decision tree classifier model, is tested under 15 scenarios, and its sensitivity, specificity, and accuracy are found to be 100.00%, 77.14% , and 89.33%, respectively.

Rodriguez–Villegas *et al.* present and experimentally evaluate a novel method to identify and remove systematic interference in battery-powered physiological monitoring devices. The proposed method exhibits low computational complexity in order to allow for low cost, real-time implementations on low-power platforms, either in the system front or back end. Guidelines on how to choose some of the operating conditions of the transceiver in order to minimize the effect of interference by applying the proposed method are also provided.

Dalton *et al.* discuss the development of a remote monitoring system to monitor and detect simple motor seizures. Using accelerometer-based kinematic sensors, data are gathered from subjects undergoing medication titration, and a template matching algorithm is developed to distinguish seizure events from iADLs. The algorithm is further ported onto a commercially available internet tablet using Mercury platform. From a data set of 21 seizures the sensitivity and specificity of the proposed algorithm are found to be 0.91 and 0.84, respectively.

Cavero *et al.* present a methodology to transmit clinical video over wireless networks in real time, proposing a 3-D set partitioning in hierarchical trees (SPIHT) compression prior to transmission. A video-specific clinical evaluation is initially made, and a reliable application protocol is developed using hybrid forward error correction (FEC) techniques. Assessment of the 2-D mode of an echocardiogram shows that the proposed protocol achieves guaranteed clinical quality for bit error rates higher than with the other protocols, being for a mobile speed of 60 km/h up to 3.3 times higher for high-speed uplink packet access (HSUPA) and 10 times for WiMAX.

The next three papers address issues related to the integration, coexistence, and networking of multiple medical devices.

LaSorte *et al.* recommend a practice for assessing the coexistence of a wireless medical device in a nonline-of-sight environment utilizing 802.15.4 in a practical, versatile, and reproducible test setup. Extensive surveys are also provided related to other coexistence studies concerning 802.15.4 and 802.11, as well as reports on the authors' coexistence testing inside and outside an anechoic chamber. Results are compared against a nonline-of-sight test setup. Findings relative to cochannel and adjacent channel interference are consistent with results reported in the literature.

Gao *et al.* design a wearable multisensor integrated system for real time measurement of the energy expenditure and breathing volume of human subjects under free-living conditions. To address challenges posed by the limited battery life and data synchronization requirement among multiple sensors in the system, the ZigBee communication platform is explored for energy-efficient design. Experiments show that the design enables continuous operation of the wearable system for up to 68 h, and is able to correctly recognize the activity intensity level 86% of the time.

Ivanov *et al.* propose and numerically evaluate an architecture that allows virtual groups to be formed between devices on patients, nurses and doctors in order to enable remote analysis of WBAN data. Group formation and modification is performed with respect to patients' conditions and medical personnel's requirements, which could be easily adjusted through high-level policies. A new metric called quality of health monitoring is also proposed, which allows medical personnel to provide feedback on quality of WBAN data received. The WBAN data gathered is transmitted to the virtual group members through an underlying environmental sensor network.

The final three papers investigate issues related to power/data transmission and modeling for wireless healthcare systems.

Sun *et al.* present a two-hop wireless power transfer system for a motion-free capsule endoscopy inspection. First, power is transferred from a floor to a power relay in the patient's jacket via strong coupling. Next, power is delivered from the power relay to the capsule via loose coupling. A switch-mode rectifier (rectifying efficiency of 93.6%) and a power combination circuit (enhances combining efficiency by 18%) are developed. The proposed system is able to transfer an average power of 24 mW and a peak power of 90 mW from the floor to a 13 mm $\times$ 27 mm capsule over a distance of one meter with a maximum dc-to-dc power transfer efficiency of 3.04%.

Rush *et al.* develop a transcutaneous two-way communication and power system for wireless neural recording. Wireless powering and forward data transmission at 1.25 Mb/s is achieved using an FSK modulated Class E converter. The reverse telemetry carrier frequency is generated using an Integer-N PLL providing the necessary wide-band data link to support simultaneous reverse telemetry from multiple implanted devices on separate channels. Each channel is designed to support reverse telemetry with a data rate in excess of 3 Mb/s.

Modeling of IBC entails the understanding of the interaction between electromagnetic fields and living tissues. Callejon *et al.* propose a simple model based on a distributed-parameter structure with the flexibility to adapt to both galvanic and capacitive coupling. Experimental results for both coupling methods are acquired by means of two harmonized measurement setups, and model simulations are compared with the experimental data. Finally, based on the model and the experimental results, some practical rules are provided to optimally tackle IBC design.

IV. Future Trends

This Special Issue presents breakthrough research in wireless and mobile technologies with high impact on biomedical applications and healthcare, and illustrates the multidisciplinary nature of this important and emerging domain. Contributions represent some of the system development, evaluative, and technical issues related to citizen-centered applications. Initial clinical investigations show promise and indicate that ICT have a great potential to improve human health [9]. However, several open issues and technical challenges are identified as key factors for revitalizing healthcare delivery and assisting the shift towards preventive, personalized, and citizen-centered care. These include the following.

1) *Novel ICT solutions*. New technologies and advances in ICT will enable support of patients as active consumers in a healthcare delivery system that is evolving from an institution-centric to a citizen-centric model. New ICT tools can enhance and supplement communication between healthcare professionals and citizens/patients. A universal interface for monitoring the functioning of the human body is also required, i.e., an interface that would bring together the data gathered such as vital signs, medical conditions, and physiological responses to medications [5]. The expansion of the tools for wirelessly monitoring and diagnosing diseases, ability to remotely manage drugs and medical devices, as well as scientific evidence of the effectiveness of citizen-centered applications are required to further the field.
2) *Novel sensors and actuators*. New-generation sensors and actuators that are self-calibrating, less obtrusive, energy efficient, with onboard processing, plug-and-play capabilities into Body Area Networks and ability to link into smart systems (which learn and respond) and adjustable therapies are required. Biocompatibility and "chronic implantability" issues should be addressed [13]. Importance should also be given to develop highly pervasive and non-invasive sensors for large scale screening purposes and early detection in home settings, as well as novel actuators for improved closed-loop solutions, including feedback to the user/medical staff.
3) *Data processing and interpretation*. As more and more data is gathered, due to increased sensing capability, data processing and interpretation become more crucial in order to be useful for the patient and the clinician [9]. Expert systems and intelligent, self-adaptive, disease specific and predictive algorithms based on combination of data acquired from different sensor types have to be developed, capable of turning acquired data and information into knowledge to support medical decision making and action.
4) *Data security and privacy*. Data security needs to be integrated into the solutions, private records associated with patients' health conditions, personal history and medical treatments must be protected from disclosure to any unauthorized individuals [3], [9].
5) *Interoperability standards*. Further research on the citizen-provider relationship is critical to determine the impacts, benefits and limitations of potential solutions and to overcome a number of hindrances and restrictions, including the lack of standards to combine incompatible information

systems for healthcare delivery in hospitals and residential settings [3].

Further research is needed, including rigorous, large scale, longitudinal experimental studies, and economic evaluations, while emphasizing on usability, user acceptance, standardization, and interoperability toward ubiquitous and pervasive healthcare delivery services. Focus should be spotted on the design of more inclusive and user friendly interfaces and interaction channels that address the needs of healthcare providers and institutions to shift toward citizen-centered applications, while bearing in mind that the main aspect that will drive the adoption of these integrated wireless systems will be their cost-effectiveness [5], [9].

Acknowledgment

The Editors would like to thank all of the contributors for their submissions and the reviewers for their indepth and constructive comments. They would also like to gratefully acknowledge the enthusiastic support and valuable guidance provided throughout the whole process by Dr. A. Dhawan, Senior Editor-In-Charge for Letters and Special Issues, and Dr. B. Wheeler, Editor-in-Chief, IEEE TBME.

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