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Mobile Health (mHealth) Biomedical Imaging Paradigm

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Abstract— **Technology assisted methods for medical diagnosis and biomedical health monitoring are rapidly shifting from classical invasive methods to handheld-based non-invasive approaches. Biomedical imagining is one of the most prominent practices of non-invasive mechanisms in medical applications. This paper considers the medical imaging schemes for Mobile Health (mHealth) applications and studies the feasibility of future mobile systems for accommodating image informatics capabilities**.

I. INTRODUCTION

Imaging technologies have been used for medical purposes for a number of years, dating back to 1895 when Wilhelm Roentgen discovered X-ray and Marie Curie established nuclear medicine in 1898 with the discovery of two radioactive elements (radium and polonium) [1]. In applications involving X-ray, the patient is subjected to the radiation, which is generated by the radiation tube, penetrating the skin and soft tissues. The presence of bones and harder tissues create penetrative patterns, which are collected by X-radiation sensitive film located at the other side of the patient (inward radiation direction). On the other hand, in nuclear medicine, the patient, tissues who is undergoing nuclear medicine procedure, receives an oral or injection dosage of radiation drug. While the traces of radioactive medications pass through the body (e.g., arteries, soft, and hard tissues), a radioactive sensitive sensor can pick up a penetration map of the body (signature), which may show blockages in the tissues and arteries and other internal organs (outward radiation direction).

The organization of this paper is as follows: Section II introduces Mobile Health (mHealth). Section III summarizes a number of relevant medical image technologies. Section IV covers the feasibility study, including requirements from system and communication perspectives, followed by Section V, including mHealth medical imaging future directions. The section related to references concludes this paper.

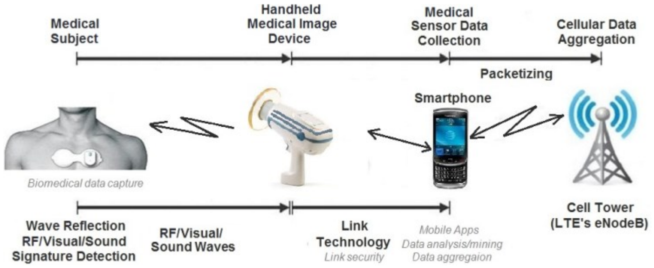

Figure 1. Mobile-Health (mHealth) Medical Imaging Framework

II. INTRODUCTION TO MOBILE HEALTH (MHEALTH)

Recent advances in smartphone technology have made medical provisioning through mobile systems a reality. Figure 1 (adapted from [2, 3]) shows the mHealth medical imaging framework, where the Handheld Medical Image Device (HMID) transmits/receives radiations to and from the medical subject (e.g., patient's body), then communicates the gathered information with the smartphone (data collector). The technologies involved in each of the segments will be discussed in more details the current and following sections.

A. *Handheld Medical Image Devices (HMIDs)*

In most cases, HMIDs are used as a transmitter of the Radio Frequency (RF) electromagnetic or ultrasonic (sound) waves onto the medical subject (patient's body). In some cases, the HMIDs may act as a wave receptor, such as in nuclear medicine, visual, and temperature-based applications.

The HMID should typically be connected to the smartphone via a link technology, which is discussed in the current section. A number of relevant applications will also be discussed in Section III.

B. *Medical Subjects*

In medical imaging, the patient is subjected to the transmission or reception of radiation to or from the HMID. There are two main application scenarios, in the first the radiation is reflected back to the HMID and in the second class of applications, the radiation passes through the body tissues; therefore an auxiliary patch of sensor may be required to collect the signatures. The sensor patch is connected by HMID or smartphone via a link technology.

C. *Link Technologies*

Link technologies are short-path communication protocols often used to connect RF transmitters within 0.1 to 100 meters from one another wirelessly [4]. Figure 1 shows the communication path for a typical mHealth imaging system, where the HMID communicates with the smartphone via a link technology and if a sensor system is used at the medical subject, it may also communicate with the HMID or the smartphone via a link technology as well.

There are a number of various protocols used for link technologies, either based on open standards or proprietary protocols. Open standard protocols are often preferred for obvious reasons (e.g., supports offered for interoperability, scalability, and security). The most prominent open standard link technologies are based on IEEE 802.15 family suits, including; IEEE 802.15.1, 802.15.4, and 802.15.6 [4]:

C.1 IEEE 802.15.1

This task group specifies Physical and MAC (Medium Access Control) layer details for Bluetooth (versions: 1.x, 2.x, 3.0, and 4.0). Bluetooth v4.0 is also known as Bluetooth

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Low Energy (BTL). BTL is based on a very low-power synchronous mechanism with a 50m (max) wireless range (10m optimal range) and an application data rates of less than 200 kbps. The number wireless nodes (sensors) a smartphone (master device) can handle is theoretically unbounded [4].

C.2 IEEE 802.15.4

This task group specifies Low Rate Wireless Personal Area Network (LR-WPAN) suitable for personal health applications. A well-known member of this group is ZigBee, which is a low-cost, low-power, mesh-based standard that comes in two flavors; ZigBee and ZigBee Pro. ZigBee's application data rate is maxed at 250 kbps, with a wireless range of 10 to 75 meters. For ZigBee Pro, the wireless range may go up to 1500 meters. Both flavors of ZigBee utilize very low-power mechanisms. A third flavor of ZigBee (ZigBee 2.0) is also known as ZigBee Smart Energy, which is currently under development [4].

C.3 IEEE 802.15.6

The objectives of this task group, which is also known as the Wireless Body Area Network (WBAN), are set to create a link technology optimized for low power wireless wearable devices, used for implanted or worn on the human body. The initiatives under this task group are still being developed [4].

C. Smartphone Platforms

Current smartphones are equipped with powerful operating systems (OS) that facilitate both the capabilities built onto the devices, as well as the communication protocols between the smartphones and the outside world (e.g., sensors, cellular towers). The capability of an OS is an important feature for the imaging context. The following OS systems are currently used in nowadays smartphones [5]:

Android – A Linux-based OS developed by Open Handset Alliance and led by Google since 2007. Android applications are expected to reach 1 million by mid-2013.

iPhone OS (iOS) – A Unix-based OS developed by Apple in 2007, which is also used on iPad, and Apple TV. The number of iOS applications is also expected to pass the 1 million mark in 2013.

Symbian – This OS is a joint-venture between Nokia, NTT DoCoMo (Japanese mobile operator), Sony Ericsson, and Symbian Ltd. Symbian was originally based on EPOC, developed by Psion in late 80's.

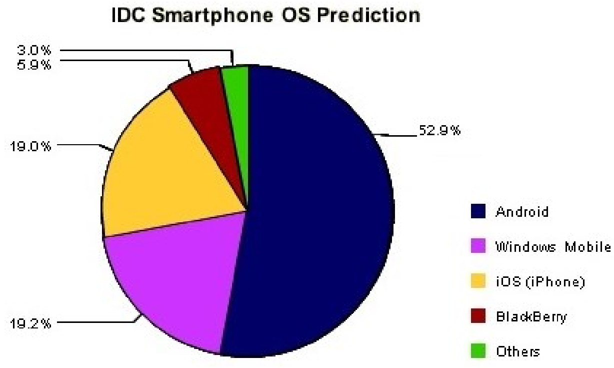

Figure 2. IDC Smartphone OS usage Prediction (adapted from [6])

Windows Mobile – Launched in second half of 2010 by Microsoft. On February 11, 2011, Microsoft officially initiated a partnership with Nokia to create their first joint smartphone; Nokia Lumia using Windows Mobile OS.

BlackBerry OS - Released by BlackBerry Corporation in 2002. This OS features BlackBerry Enterprise Server (BES), with capabilities of synchronizing with Microsoft Exchange, Lotus Domino, and Novell GroupWise. The current OS (BlackBerry 10) is based on QNX software system, a Unix-like real-time OS, compatible with Android applications.

Others – Other current, less utilized, smartphone OSs are: *MeeGo and Mer project (Linux), Bada OS (Samsung), WebOS (Palm), and Windows CE (Pocket PC).*

Palm, BlackBerry, and Windows CE/Pocket PC are thought to be the early smartphone OS systems. Figure 2 shows the International Data Corporation (IDC)'s prediction for the year of 2016 in terms of worldwide smartphone OS usage, which indicates Android's continuum domination [6].

C. Cellular Technologies

Cellular technologies are used to cover the interaction between the smartphone and the cell-tower. The Third Generation Partnership Project (3GPP) standards define the cellular technologies, including [7]: Evolved Enhanced Data Rates for GSM (EEDGE), High Speed Packet Access (HSPA), Long Term Evolution (LTE), and LTE-Advanced (LTE-A). Different technologies limit the systems based on the delay-budget, data-rate, bandwidth, and other factors.

III. BIOMEDICAL IMAGING TECHNOLOGIES

In this section a number medical imaging technologies are considered, which are defined by the types of physical properties between the HMIDs and the medical subjects and the medical conditions they target.

A. Physical Properties in Medical Imaging

There are a number physical properties used in medical imaging, such as:

Electromagnetic Radiations (EMRs) – EMR covers a number of subcategories, including: X-ray, Magnetic Resonance Imaging (MRI), Nuclear Medicine (NM), and visible light. Based on the energy level of the radiations, there are two categories of EMRs; ionizing and non-ionizing. Ionizing radiations carry sufficient levels of energy to alter the structure of the atoms by liberating electronics, such as in X-ray. Non-ionizing radiations do not cause such a structural change, thus safer to use. Figure 3 shows the frequency spectrum of EMR imaging technologies, including millimeter Wave (mmW) and microwave (MW).

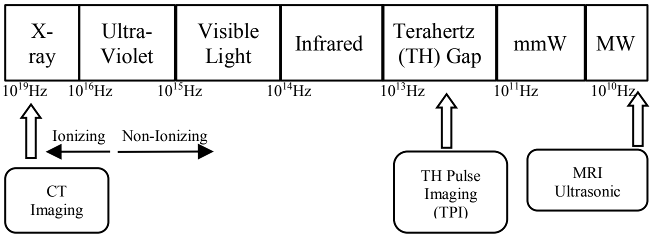

Figure 3. Frequency Spectrum of EMR Imaging Technologies (adapted from [8])

A.1 Magnetic Resonance Imaging (MRI)

MRI is based on the Nuclear Magnetic Resonance (NMR) property to map the nuclei image of atoms inside the body. MRI scanners are used to align atoms nuclei magnetization, resulting in the creation of 2D and 3D images with high resolutions. MRI has been used extensively for medical purposes and is well documented in the literature [8-10].

A.2 X-Ray

X-ray is a member of ionizing electromagnetic radiation image technologies and has a wavelength between 10^{-11} and 10^{-8} meters, which corresponds to frequency range of 3×10^{16} to 3×10^{19} Hz [10, 11]. X-ray is widely used for general radiology as it penetrates through thick tissues with limited absorption, however due to its ionizing properties, excessive usage may cause tissue damage, thus has to be limited.

A.3 Nuclear Medicine (NM)

Nuclear medicine was introduced earlier in this paper. There are a number diagnostic techniques associated with this, including [8, 12, 13]: two dimensional scintigraphy using internal radio nuclides and three dimensional based on Single Photon Emission Computed Tomography (SPECT).

A.4 Visible Light

There is no mystery in using the visible light in the medical diagnoses, including the medical diagnoses and treatments given by the doctors based on face-to-face examinations, remote patient examinations using web camera, and other visual-based diagnosis and treatments. Other methods using visible light include: Structured Light Plethysmography (SLP), which captures the image of the patient, tracks and measures the movement in the image and produces real-time and accurate data on respiration changes [14]. Pulse oximeter in another light-based application that is used to calculate the amount of oxygen in the person's blood.

A.5 Terahertz and Millimeter-Wave Technologies

According to Figure 3, the frequency spectrum from 10^{10} Hz to 10^{13} Hz is related to the terahertz and millimeter-wave technologies. The systems using these technologies are based on the transmission of terahertz and mm-Wave radiations and analyzing the signatures (changes in the reflections) [15].

A.6 Ultrasonic Medical Diagnosis (UMD)

UMD is used to locate and size tumors and other medical conditions under the skin (skin-depth analysis) [16]. This is done by transmitting high frequency sound signals and analyzing the reflected sound waves.

B. X-Ray-based Medical Imaging Technologies

Other X-ray-based medical imaging technologies including:

B.1 Computed Axial Tomography (CAT or CT Scan)

CT Scan is a computerized (digital) version of the X-ray technology, which uses digital geometry processing algorithms to generate 3-D images of the inside of human body using large series of 2-D X-ray images, which are taken around a single rotation axis [10, 11].

B.2 Digital Subtraction Angiography (DSA)

DSA is based on fluoroscopy, which uses X-rays for obtaining real-time motion images of the patient's internal organs. DSA is used to visualize blood vessels in a dense soft tissue or bony areas of the patient's body. [17].

B.3 Computed Digital Radiography (CDR)

CDR is very similar to the conventional radiography except that it uses a Digital Imaging Plate (DIP) instead of a film or other types of imaging plates (normally made from photostimulable phosphor) [18].

B.4 Digital Mammography (DM)

DM uses computer-based digital receptors instead of X-ray films to exam breast tissue for signs of breast cancer [19].

IV. FEASIBILITY STUDY

The current smartphone platforms are based on strong hardware capabilities offering far more than simple telephone usages and basic internet connectivity.

In this section a brief comparison is given based on the current top-of-the-line smartphone systems (as of April 2013), such as: iPhone 5, Samsung Galaxy S4, HTC One X+, Nokia Lumina 920, and BlackBerry Z10. Table 1 summarize the technical details of the mentioned smartphones

According to Figure 1, the mHealth imaging system is comprised of a smartphone, a HMID, and the optional medical subject sensors. The smartphone is only responsible for controlling the HMID and managing the information and not the generation of the radiated waves. Still there are a number of limitations and challenges in handheld imaging systems, which are discussed in this section.

A. Smartphone Limitations

The current nowadays smartphones come with the following capabilities:

TABLE I. COMPARISONS CHART BETWEEN VARIOUS HIGH-END SMARTPHONES (ADAPTED FROM [20, 21,22])

	iPhone 5	**Samsung S4 I9505**	**HTC One X+**	**Nokia 920**	**BlackBerry Z10**
Operating System	iOS 6	Android 4.4 Jelly Bean	Android 4.1	Windows Phone 8	Blackberry 10 QNX
Screen Size	4', 640x1136 326 ppi	5', 1080x1980 441 ppi	4.7', 720x1280 312 ppi	4.5', 768x1280 332 ppi	4.2', 768x1280 356 ppi
CPU	DC A6 1.3 GHz	QC Krait 300 QCM 1.9 GHz	QC CT-A9 1.7 GHz	DC QCM Krait 1.5GHz	QC Snapdragon DC S4 1.5 GHz
GPU	PowerVR SGX543MP3	QCM Adreno 320	Nvidia GeForce ULP 520 MHz	QCM Adreno 225	QCM Adreno 225
RAM	1GB	2GB	1GB	1GB	2GB
Memory	16/32/64 GB	16/32/64 GB	64 GB	32GB	16GB
MicroSD	No	Yes (64 GB)	No	No	32GB
SIM	Nano-SIM	Micro-SIM	Micro-SIM	Micro-SIM	Micro-SIM
Data Protocol	LTE, DC-HSPA	LTE/HSPA+	LTE/HSPA+	LTE/HSPA	2FD/HSPA/LTE
Max Data Rate	100 Mbps	100 Mbps	100 Mbps	100 Mbps	100 Mbps
Rear Camera	8MP, 1080p	13MP, 1080p	8MP, 1080p	8.7 MP, 1080p	8MP, 1080p
Bluetooth	4.0+A2DP	4.0+A2DP	4.0+A2DP	3.1+A2DP	4.0+A2DP
Wi-Fi	802.11 a/b/g/n	802.11 abgn/ac	802.11 a/b/g/n	802.11 a/b/g/n	802.11 a/b/g/n
GPS	A-GPS	A-GPS	A-GPS	A-GPS	A-GPS
NFC	No	Yes	Yes	Yes	Yes
Sensors	AL, AM, CP, GC,	AL, AM, CP, GC, BM, PM	AL, AM, CP, GC, PM	AL, AM, CP, GC, PM	AL, AM, MM, GC, PM
Battery	1440 mAh	2600 mAh	2100 mAh	2000 mAh	1800 mAh
Price	$650-$850	$750-$1000	$550-$600	$450-$650	$50-$700

DC: Dual Core
AL: Ambient Light Sensor
MM: Magnetometer
CP: Compass
BM: Barometer
A2DP: Advanced Audio Distribution Profile
QC: Quad Core
AM: Accelerometer
GC: Gyroscope
NK: Not Known
QCM: Qualcomm
CT: Cortex ARM Processor
PPI: Pixels Per Inch
CPU: Central Processing Unit
GPU: Graphics Processing Unit
NFC: Near Field Communication
A-GPS: Assisted GPS
PM: Proximity

TABLE II. COMPARISONS OF DIGITAL MEDICAL IMAGE (DMI) RESULOTIONS (ADAPTED FROM [23])

DMI Technology	Typical Resolution (resolution, bits/pixel)	Typical File Size (MB)
Nuclear Medicine (NM)	128 p X 128 p, 12 bpp	2
Terahertz Signature (TS)	256 p X 256 p, 8 bpp	6
MRI	256 p X 256 p, 12 bpp	8
DSA	512 p X 512 p, 8 bpp	7
CAT Scan	512 p X 512 p, 12 bpp	12
Ultrasonic Imaging (UI)	512 p X 512 p, 24 bpp	20
CDR	2048 p X 2048 p, 12 bpp	16
Digitized X-Ray	2048 p X 2048 p, 12 bpp	16
DM	3000 p X 4000 p, 16 bpp	160

Processing Power – According to Table I, Samsung S4 has one of the fastest CPU (Qualcomm Snapdragon 600 ARM) in the current smartphone market, which runs at 1.9 GHz and is capable of running 3.3 Dhrystone MIPS (Million Instructions Per Second, in the Dhrystone benchmarking scale) per MHz core, which is 6,270 MIPS per core [23]. This CPU processing power is more than sufficient to carry one high resolution, high definition imaging procedure at a time.

Digital Medical Images (DMI) – The specifications of DMIs vary between applications and technologies used in medical imaging. Nuclear medicine is counted as one of the least computationally intensive medical image technologies. A typical nuclear medicine image requires 128 pixels by 128 pixels by 12 bits (per pixel) [24]. One of the most computationally intensive medical image technologies is the digital mammography (DM) in which a typical image requires 3000 pixels by 4000 pixels with 16 bits resolution (per pixel) [20]. Table II shows a comparison of a number of medical imaging technologies and the typical required pixel/bit resolutions.

Communication Data Rate – Data rate depends on the application and is limited by three sources, the transmitter, receiver, and the communication protocol transmitting the data bits. Based on the literature [25-27], medical imaging data rates vary from 1 Mbps (e.g., transferring NM images) to 80 Mbps (transferring DM images), depending on the resolution and quality. Between the transmitter (i.e., HMID) and the receiver (i.e., smartphone) the link technology is the most probably bottle neck. The highest data rate that Bluetooth (Bluetooth v3.0 + HS) could offer is 24 Mbps [4], therefore the smartphone medical imaging paradigm can accommodate relatively high resolution/definition imaging technology with the current capabilities. For better resolution and quality, other communication protocols, such as low-power Wi-Fi (e.g., IEEE 802.11n) may be required.

On Device Memory (RAM) – The current RAM capacities of the current smartphone systems (Table 1) offer up to 2 GB of RAM, which may not be sufficient, in particularly for Mobile Cloud applications (where the imaging information bits are sent to the cloud using online resources) [28]. According to Table II a typical digital mammography file can be as high as 160 MB. Therefore higher RAM capacities are required for the future smartphone-based imaging systems.

Quality of Service (QoS) – In a local sense, QoS depends on the delay, offered bandwidth, and processing power of the link between HMID and the smartphone (including the capacity of the link technology). However in a global (end-to-end) sense, particularly in the mobile cloud paradigm, this becomes much more complex, which includes all the nodes, hops, and processing units all the way from the source to the destination. Local QoS requirements from the current smartphone imaging point of view is believed to be supported for relatively high quality imaging applications (up to 24 Mbps), however the global QoS requirements are out of the scope of this paper.

Security – Security requirements also follow the same patterns as for QoS. In a local sense, the link from the HMID to the smartphone needs to be secured. The current security strengths offered by Bluetooth [4] provide sufficient security power (based on Suite-B coverage [4]). However in the global sense, security of the mobile cloud needs to be analyzed, which is also out of the scope of this paper.

Other limitations of the whole smartphone imaging technology paradigm are summarized as follow.

B. *Size and Dimensions*

The actual size and dimensions of real-life medical image systems (e.g., MRI and CT Scan) are normally very huge (room size). This is due to the fact that high power radiation systems are deployed coupled with high precision radiation trajectory and effective shielding. These capabilities are currently not available for handheld imaging systems due to the limitations in size and dimensions.

C. *Operational Power*

Due to the limitations in size and weight, low-power radiation systems are required, which limit the operational deployment of handheld imaging systems. Therefore low-noise, low-power amplification is required with extensive signal processing techniques to compensate for the power limitations.

D. *Operational Safety*

Again due to the limitations in size, operational safety may become a challenge. There may not be enough shielding in place and additional exposure to radiation may limit the deployment of handheld imaging systems.

V. MHEALTH BIOMEDICAL IMAGING FUTURE DIRECTIONS

The current trends in smartphone platform show steady advances in both the hardware as well as the software portfolios. By referring to Table I, the top-of-the-line smartphone systems use advanced dual-core and quad-core CP) systems (e.g., ARM processors) with advanced GPU chips. The current CPU/GPU systems are capable enough to run concurrent and real-time signal processing algorithms for high quality imaging applications (up to 6,270 MIPS per core for 1.9 GHz clock speed). The main limitations are due to the on-device memory (RAM), which may limit mobile cloud interactions, link technology data rate limitations, and physical limitations (e.g., size, dimensions, operational power, and safety), which may initially hinder the development of handheld imaging.

Here are a few areas of improvement for the field of handheld imaging.

A. *Increasing On-Device Memory*

In a global sense (e.g., mobile cloud interactions), on-device RAM should be increased initially to at least 64 GB to satisfy cloud-based transmission imaging requirements.

B. *Deployment of Next Generation Link Technologies*

For high quality/resolution imaging, high capacity data rates are required for the link technology. The highest data rate the current Bluetooth protocol could provide is 24 Mbps (for Bluetooth v3.0 + HS), which may not be sufficient for some imaging technologies. A new family of link technologies is required to accommodate higher data rates up to 100 Mbps.

C. *Mobile Cloud Security and QoS Requirements*

In a global sense, the transmission of biomedical images may require additional security and QoS requirements, including end-to-end QoS/security schemes. Though crucial, this is out of the scope of this paper.

D. *Advances in Signal Processing*

Due to the limitations in size and weight, low-power and low-noise radiation systems are required, coupled with advanced signal processing. This is to compensate for inaccuracy of handling the device and application by hand.

E. *Reduction in Size*

Next generation MRI/X-ray/CT scan systems will enjoy smaller core systems thanks to the advances in developing magnetic and radiation sensors.

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