Chapter 1

Introduction

This chapter gives an overview of how affordable and easy to use technologies can impact the livelihood and wellbeing of communities belonging to resource limited settings. Due to the vast availability of smartphone around the globe, its usability as a possible solution for many point of care (POC) and other environmental monitoring applications have been demonstrated. In addition, this chapter also describes the remaining challenges and limitations of the demonstrated smartphone integrated technologies and finding answers for the same. The chapter ends with the research motivation, scope of the thesis and the thesis contribution.

1.1 Need of low cost and field portable instruments with reference to resource limited regions

Proper assessment of chemical, physical, and biological parameters which directly affect the human health is essential for livelihood and wellbeing of any community. In our day to day life, contamination in agricultural items and water are becoming a significant threat to health. Most significantly, consumption of contaminated water and poor sanitation becomes the primary cause of global health burden in many low and middle-income countries [1]. Monitoring of water resources or water used in households is a critical issue to be addressed in this 21^{st} century. Water with microbial contamination is one of the major causes of 1.3 million deaths due to diarrhea every year, still diarrhea is largely preventable by evaluating the potential risk factors [2]. Along with the microbial contamination, prolonged exposure to chemically contaminated water can also pose serious health hazards. Hazardous metal ions can enter into water resources from natural and anthropogenic sources; many of them are toxic at elevated concentrations as well as in trace levels. The world has witnessed the devastating Arsenic poisoning in Bangladesh; 35 to 77 million Bangladeshi people have been unknowingly exposed to arsenic contaminated drinking water resources [3].

In general, monitoring of water quality is carried out in a government approved centralized laboratory facility with the conventional laboratory procedures and benchtop measuring instruments. Water samples from a small number of predefined locations are brought to the central monitoring facility for analysis; however, if the laboratory is located far away from the location where water samples were collected then these methods become expensive and time-consuming. Along with these logistic problems, there are many other technical issues due to which conventional water quality monitoring in centralized laboratory facility fails. Many analytical procedures used in a standard laboratory for water and waste water analysis require sophisticated instruments such as spectrophotometers, chromatographs, ion-selective electrodes, and turbidimeter etc. Also, it requires specialized human resources having necessary knowledge and skills to operate these facilities. Although, simple and easy to use paper strip based test kits are available in the market but due to its limited accuracy, qualitative measurement and production of toxic gases such as arsine gas (which is more toxic than arsenic solution itself) in arsenic assay are few of the problems for which the application of such methods are limited in many applications [4]. Moreover, this technique depends on human perception to color which may vary from person to person.

For many underdeveloped or developing countries where the health burden due to contaminated water is becoming vulnerable, it is not possible to set-up laboratory facilities having the required sophistication due to many financial and political issues. Insufficient laboratory facility for testing groundwater before installation of millions of tube wells to provide drinking water to common citizens is considered as one of the significant reason of mass arsenic poisoning in Bangladesh [5]. Again, the size, cost, weight, and requirement of external power sources limits the uses of these analytical tools in resource poor settings. Due to many geographical constraints, poor connectivity and lack of governmental authorization still there are many rural and remote regions in India where no water quality monitoring programme has been initiated. To initiate any removal programme it is important to know the various physiochemical parameters that cause the contamination. Early detection and removal of water contaminates can save millions of life from being suffered from vulnerable water related diseases. The centralized water quality monitoring laboratory plays the key role in these issues related to water; however, there is an immense need of low cost water quality monitoring facilities worldwide, which are affordable and accessible by people with any economic background. It should be robust and field portable so that in-field sensing can be possible in rural and remote regions. It should have proper communication facility so that real time data sharing can be possible to the central water quality monitoring facilities of governmental and non-governmental organizations to initiate effective removal programme on time. With all these technical and logistic capabilities, the monitoring facilities should also be designed and developed with a user oriented approach so that any individual having almost no scientific expertise can easily operate it. This will also promote the decentralized monitoring of water resources which is one of the utmost need for remote and resource poor regions in our country.

Most of the laboratory grade instruments used for chemical, biological, and environmental analysis are based on standard optical principles such as absorption and scattering of light signal from the sample solution. Many research groups across the world have been continuously working on development of low cost and field deployable version of the same using low cost technological solution and the usability of such tools has been extensively demonstrated in monitoring of both physical and chemical parameters [6-9]. While, the reported tools are are robust, miniaturized and cost-effective as compared to its benchtop counterparts; they also need external computational facility for data processing and analysis which increases the overall cost in consideration to resource poor region. Also, the demonstrated devices lack communication facility which is necessary for many in-field sensing applications such as healthcare and water quality monitoring where real time data sharing is a must. The affordable technological solutions are the unmet need of low income, remote, and rural regions where the indigenous people or community can have access to such technologies and able to safeguard the livelihood and wellness of the community. The technological solutions should be easily adopted and operated by the indigenous stakeholders of these particular regions. The literacy rate in such regions are significantly low and there is almost no scientific interventions. Therefore due to this issue the demonstrated solutions may not able to find its applicability in such regions.

1.2 Realization of smartphone as sensing platform

Since the demonstration of first functional mobile phone in 1973 by Martin Cooper from Motorola [10], with rapid improvement in mobile phone technology, access to mobile phone is now become inevitable to our everyday lives. According to International Telecommunication Union (ITU), it is estimated that there are more than 7 billion mobile phone subscriptions around the globe and among them more than 4 billion have been connected with mobile broadband facility till 2017 [11]. The data shown in figure 1.1 signifies that the annual growth in mobile-broadband subscription in the least developed countries (LDCs) during 2012-2017 is outpacing the developing and developed countries. It signifies that irrespective of any

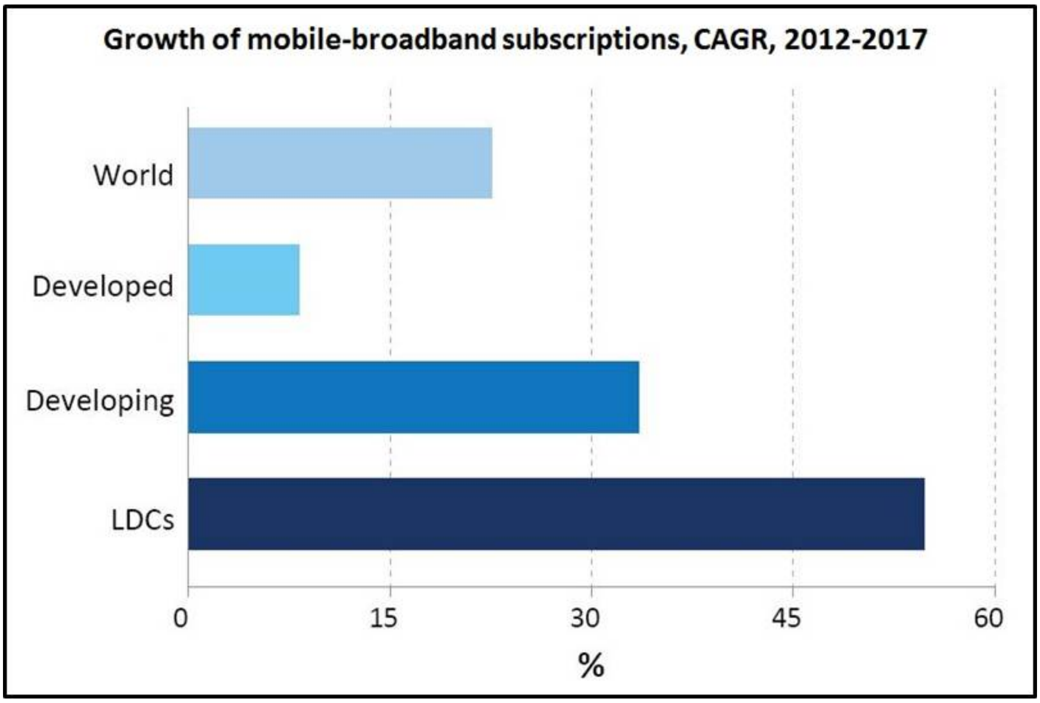

Figure 1.1: Estimated compound annual growth rate in mobile-broadband subscription globally. (Source: ICT fact and figure 2017 by ITU).

economic means, mobile phone is the most accessible consumer electronic device than any other electronic gadget globally. The penetration of mobile phones to such extent is possible due to its affordability and user oriented design approach.

Due to wide span of network and affordability, the mobile phones have great potential to connect people which are isolated from the mainstream of development due to many political and socio-economic issues. The penetration of mobile phones in developing as well as underdeveloped countries is now promoting many developmental initiatives of many governmental or non-governmental organizations [12].

Earlier mobile phones were primarily developed for voice communication and messaging applications. The rapid advancement in the embedded technology, miniaturized electronics and fast computation ability accelerate the evolution of mobile phone technology which eventually converge it into the modern day smartphone. It is estimated that there are 2.3 billion smartphone users across the globe till 2017 [13]. The modern smartphone is not only a better communication device,but also acts like a pocket computer with the improved hardware and software integration. The enormous processing power, storage capacity, and increasing battery life allows the integration of different consumer oriented sensors such as CMOS camera, LED flashlight, proximity and ambient light sensor, accelerometer, GPS, wi-fi, graphical user interface (GPU), and many other communication sensors in a modern smartphone. Along with these sensors integration, user oriented software or smartphone apps can be developed with open source software such as Android studio and MIT app inventor. The sensing data from the in-built sensors can also be extracted through developing applications with necessary algorithms using different scientific approach. In a nutshell, we can term the modern smartphone as a portable personal computer (PC) which facilitate rapid development of different scientific tools where researchers around the globe are continuously working on converting science and technology from traditional to the need based community tool due to its vast availability in almost everywhere without any economic barrier.

The CMOS camera of the smartphone can be used as a portable photodiode array detector in the visible wavelength domain. Since, LED flashlight used in the smartphone is a super bright LED with its emission wavelength ranging from 350 nm to 700 nm, therefore, it can be used as a light source in many sensing application. The USB of the phone can be used both as host and peripheral devices, therefore, triggering electronic signal or accusation of the same is possible with proper signal processing algorithms. Also, through the USB-OTG protocol, the battery of the phone can be used as a power source. Moreover, using the in-built communication facilities such as GPS, 3G-4G technologies the acquired data can be shared anywhere in the world. Since, major share of smartphones operating systems are either android or iOS, therefore, the smartphone can be used as a programmable device with the development of need based software or smart apps. Due to the availability of smartphone as a standalone platform in terms of inbuilt source, detector and the computational platform, it has been continuously exploited to develop autonomous mobile sensing devices which finds its applicability for different environmental and biochemical sensing applications [14-16].

1.3 Review of literature

Almost all the modern smartphones are embedded with digital compact camera which includes a high megapixel count CMOS image sensor. Moreover, the inclusion of high-end CPU, rapid image processing can be possible within the smartphone which leads to the development of smartphone based platforms for colorimetric, spectroscopic, and microscopic imaging applications [17]. The usability of the embedded ambient light sensor (ALS) has been demonstrated as an optical detector and its applicability has been demonstrated in many biosensing applications [18]. The USB and bluetooth module of the phone have been used to demonstrated many electrochemical sensors in different applications such as amperometric, potentiometric, and impedimetric applications [19]. Due to the inclusion of near filed communication (NFC) module in modern smartphones, its applicability has been demonstrated in many biochemical sensing applications [20]. The following sections provide a detail overview of the different sensing platforms that has been developed based on in-built smartphone sensors. The applicability of the smartphone can be catagorised mainly in the following domains:

1.3.1 Smartphone camera based optical sensing platforms

The number of pixels in the camera of the smaprtphone has been doubled almost every year with better sensitivity and frame rates with reduced pixel size[21].

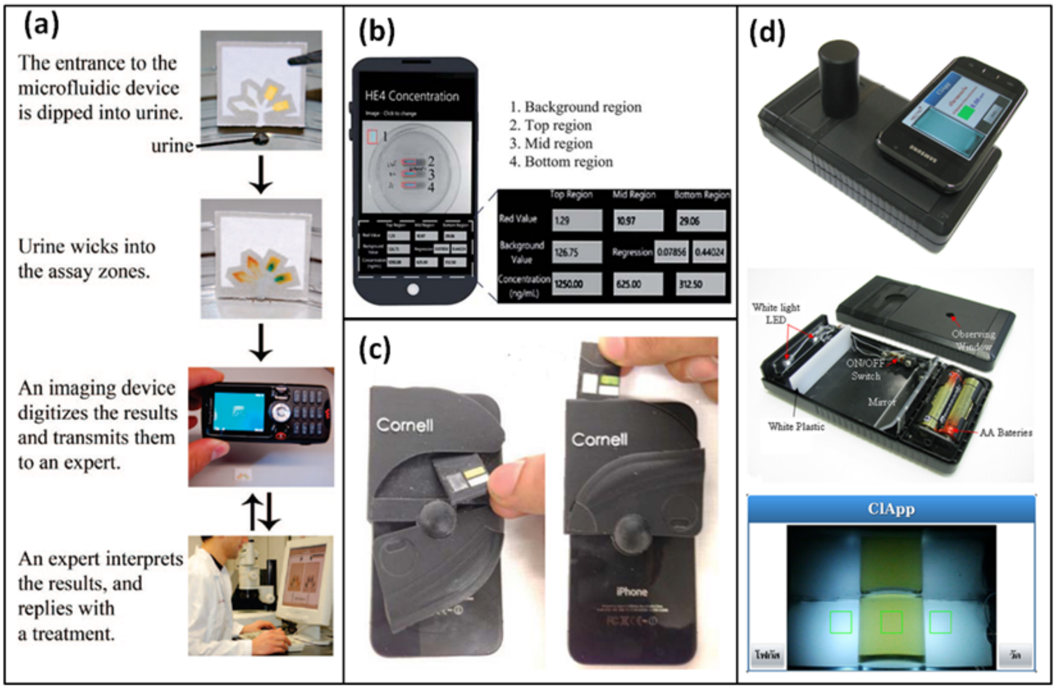

Figure 1.2: Smartphone based colorimetric detection methods; (a) working procedure of the feature phone camera based colorimetric sensor, reproduced from [23] with permission from American Chemical Society, (b) first demonstration of smartphone based standalone colorimetric platform for detection of cancer biomarker in urine, reproduced from [24] with permission from Royal Society of Chemistry, (c) demonstration of smartphone based colorimetric platform with 3D printed attachment, reproduced from [26] with permission from Royal Society of Chemistry, and (d) reference based colorimetric platform, reproduced from [28] with permission from Elsevier.

The smartphone camera is primarily developed for consumer applications, therefore, its response is limited to only visible region with the inclusion of an infrared (IR) cut-off filter. Digital colored images are generated in a smartphone by the use of Bayer color filter array(CFA) present in each pixel of the CMOS sensor [22]. Due to its ability of onboard image processing, smartphones become ideal for many colorimetric based sensing applications. The first application of in-built camera module in colorimetric application has been demonstrated by Martinez et. al where the camera of a feature phone was used to extract the color information from a microfluidic paper based device for detection of different bioanalytes [23]. Since, the feature phones at that time did not have any on-board image processing capability, therefore, the captured images were sent to a central processing unit through the communication network and after analyzing remotely, the results were sent back to the phone. With the advancement of smartphone technology, many research groups later demonstrated both colorimetric detection as well as on-board data processing within the smartphone itself with the inclusion of sophisticated smartphone applications [24,25]. Though, colorimetric methods can easily be integrated with a smartphone using the in-built camera and custom developed image processing applications, but the ambient illumination can significantly affect the measurement process or the results may vary with effective environmental surroundings. To reduce the effect of external noises, many research groups have demonstrated the use of 3D printed attachments to isolate the sample from ambient illumination and control lighting has been used to illuminate the sample while capturing the image [26,27]. Along with these mechanical attachments the use of reference has been demonstrated to reduce the background illumination errors in colorimetric sensing [28,29]. Figure 1.2 shows the development of difference smartphone colorimetric techniques used for different sensing applications. The usability of the colorimetric platforms have been extensively demonstrated for many point of care and biochemical sensing applications such as the testing of albumin in urine [30], quantification proteins and enzymes [31], and detection of cholesterol level [32] etc. Moreover, many novel application of smartphone based colorimetric sensing has been demonstrated in environmental monitoring applications such as determination of fluoride [33], chlorine [34], and mercury [35] level concentration in water.

Again, the smartphone camera has been demonstrated for development of spectroscopic based sensing applications. Though smartphone based colorimetric sensors have found its applications in many diverge areas from POC to environmental applications but it has many drawbacks in terms sensitivity and resolution. Due to the presence of Bayer CFA in the phone camera, the spectral resolution in colorimetry is limited to only three specific wavelengths or color namely red, green, and blue. With the advancement in smartphone technology, the size of the pixels in the embedded camera has reduced to on average 1.12 μm which enables the smartphone to distinguish different wavelengths by spatially separating them in different pixel positions in the CMOS sensor by using external dispersive elements

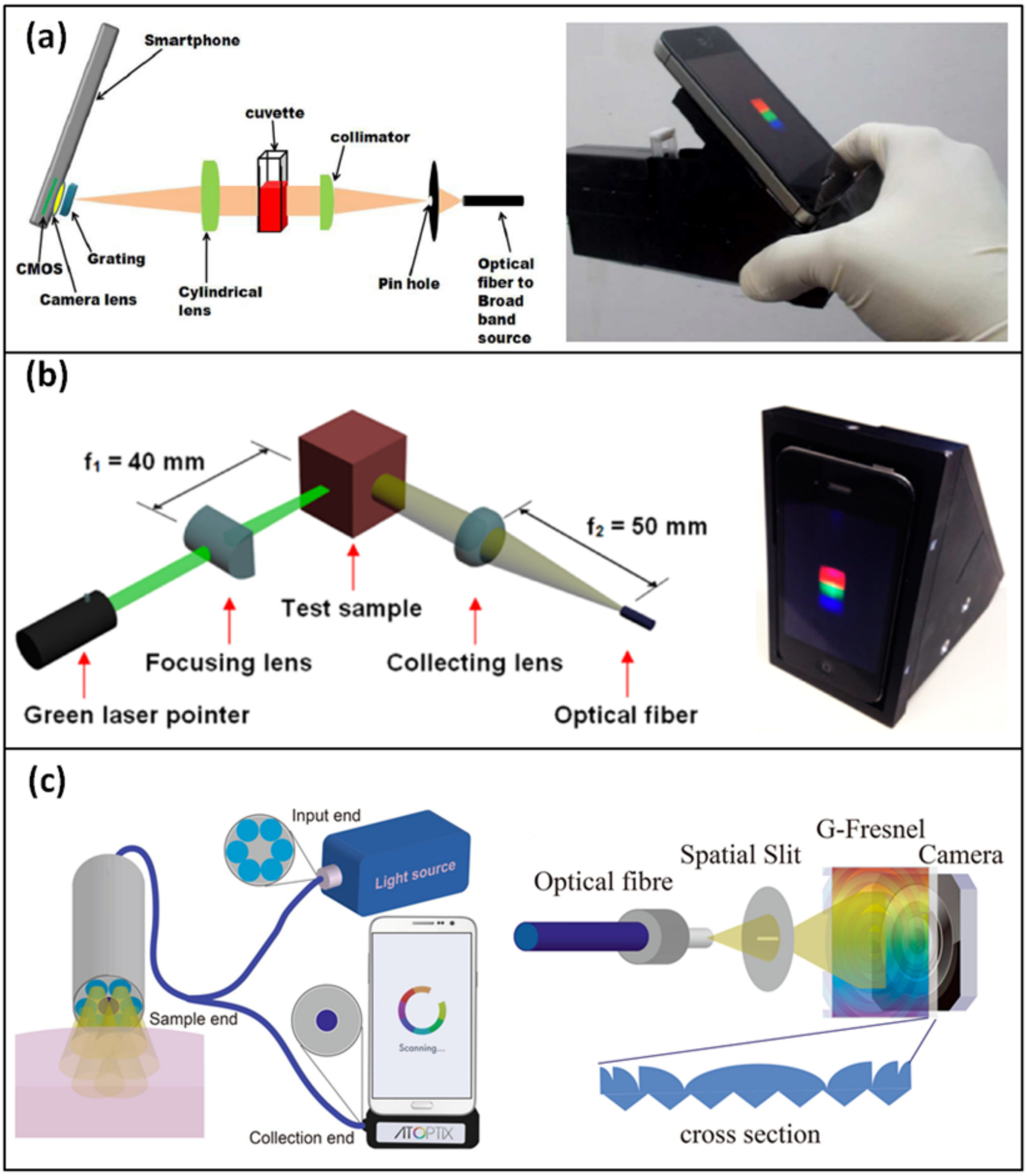

Figure 1.3: The development of smartphone based spectroscopic methods; (a) working procedure of an absorption based smartphone spectrometer, reproduced from [36] with permission from Royal Society of Chemistry, (b) demonstration of smartphone based fluorescent spectrometer, reproduced from [37] with permission from American Chemical Society and (c) demonstration of smartphone based reflectance spectroscopy, reproduced from [38] with permission from Royal Society of Chemistry.

such as grating or prism. This allows the development of different modalities of spectroscopic sensing applications such as absorption, fluorescence, and reflectance spectroscopy [36-38]. Figure 1.3 shows different spectroscopic schemes incorporated with the smartphone. In general, light from a broadband source is allowed to interact with the sample and the transmitted, scattered or reflected light is dispersed with the help of dispersing elements. The dispersed light spectrum then enters the camera aperture and captured by the phone camera. The captured spectrum is then converted to corresponding wavelength versus intensity curve within a smartphone application through rigorous wavelength conversion algorithms. Hossain et al. have demonstrated combined dual wavelength smartphone based spectrometer where both absorption and fluorescent spectroscopy based investigation can be performed with a spectral resolution of 0.42 nm/pixel [39]. The smartphone spectroscopy was confined only to visible spectral regime, for the first time Wilkes et al. have demonstrated the functionality of smartphone based spectrometer in ultraviolet spectral region with a resolution of 1 nm [40]. With the capability of smartphone in spectroscopic applications many research groups have demonstrated the applicability in different optical sensing applications such as surface plasmon resonance (SPR) and localized surface plasmon resonance (LSPR) sensing applications. Gallegos et al. have demonstrated the smartphone based photonic crystal integrated label free biodetection platform where peak resonant wavelength condition shifts due to the attachment of biomolecule which can be detected by the smartphone camera [41]. Using optical fiber as SPR sensing probe and flash light of the smartphone as a light source, Liu et al. have demonstrated low cost SPR based smartphone biosensing platform [42]. Similarly, the usability of smartphone based spectroscopic platforms have been demonstrated in many different application areas such as education [43], biosensing [44], and environmental monitoring [45].

Along with colorimetric and spectroscopic applications, one of the prominent use of smartphone camera is its microscopic imaging applications. Microscopy is an important tool for early detection and diagnosis of many significant diseases such as malaria. Therefore, efforts have been made by many research groups to develop smartphone based imaging system using different optical techniques such as integrating traditional optical components or advanced digital holographic image processing and there usability has been demonstrated for various global healthcare applications [46-49]. Different optical techniques have been used to covert the smartphone into a laboratory grade microscope. Using a single 1 mm ball lens, Smith et al. have demonstrated cellphone based microscope for educational applications [50]. Using

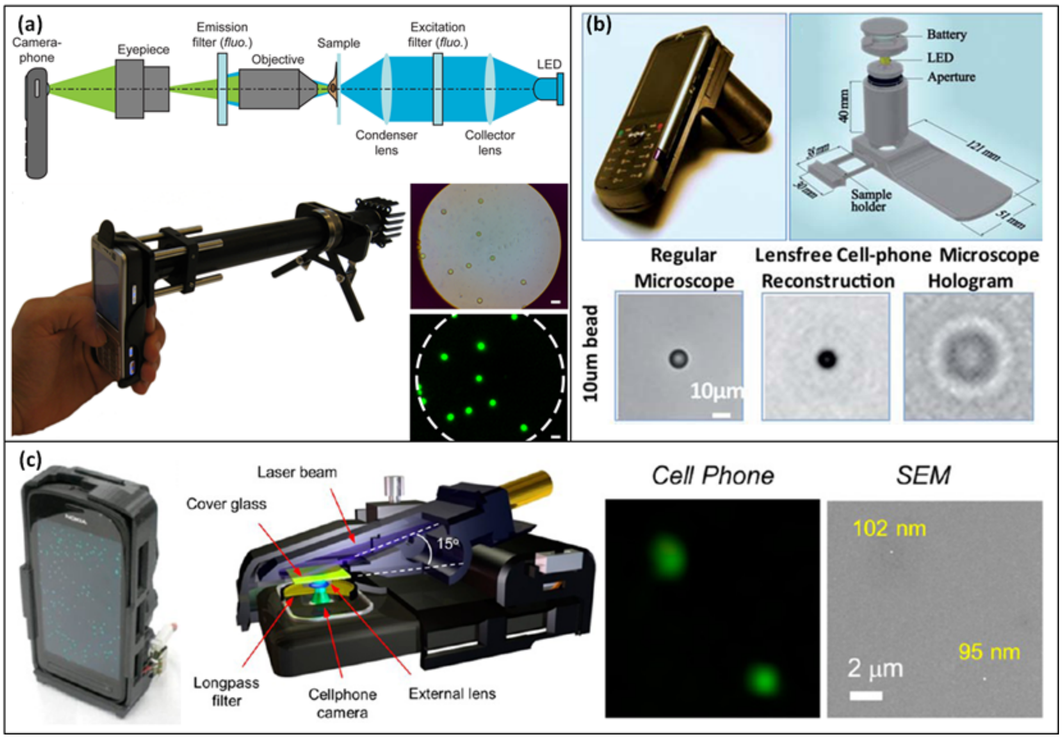

Figure 1.4: The development of smartphone based microscopic imaging platforms; (a) demonstration of mobile microscopy platform by associating traditional optical component, reproduced from [46] with permission from Public Library of Science, (b) cellphone based lensfree microscopy platform, reproduced from [47] with permission from Royal Society of Chemistry, and (c) demonstration of smartphone based fluorescent microscopy, reproduced from [56] with permission from American Chemical Society.

simple lens and LED configuration Zhu et al. have demonstrated the usability of smartphone as a cost effective imaging tool for rapid blood analysis [51]. D'Ambrosio et al. have demonstrated the first video microscopy platform in a smartphone and its usability has been demonstrated for detection and quantification of blood-borne filarial parasites [52]. Along with the conventional optical microscope, many research groups have demonstrated the smartphone based fluorescence microscopes or imaging platforms to enhance the sensitivity and specificity [53-55]. Wei et al. have demonstrated smartphone based fluorescent imaging platform to image individual fluorescent nanoparticles having diameter approximately 100 nm [56]. In the digital holographic imaging scheme, smartphone based imaging can be possible without any external lens configuration. In this scheme, the shadow of the sample is allowed to fall on the bare CMOS chip of the smartphone camera and using rigorous image processing algorithms, the image can be reconstructed from the digital hologram created on the sensor. Lee et al. have demonstrated smartphone based lensless microscope utilizing ambient illuminance as light source [57]. Similarly, Roy et al. have demonstrated lensfree shadow imaging technique in a smartphone platform for counting blood cells [58]. Figure 1.4 shows the examples of different microscopic imaging schemes demonstrated utilizing camera and on-board image processing capability of the smartphone.

1.3.2 Smartphone ALS based optical sensing platforms

Almost all modern smartphones are embedded with the ALS chip which is used to optimize the battery power consumption by controlling brightness of the display panel automatically through sensing the ambient illumination. The photodiode used in the ALS chip is a silicon (Si) photodiode having spectral responsivity ranging from 350 nm to 1000 nm. The light intensity data recieved by the ALS can be converted to the lux units by using a custome designed smartphone application. The ALS of the smartphone has a dynamic range 0 Lux to 20000 Lux with resolution of 0.01 Lux [59-60]. Since, the light intensity can be directly measured with the ALS without any further processing, the ALS sensor finds its applicability in many sensitive optical sensing applications where measurement of light intensity variation is a critical need. Park et al. have demonstrated the usability of smartphone ALS in developing immunosensing platform for detection of osteoarthritis [61]. In the work, they have used the white LED flash of the smartphone as a light source to illuminate the sample and the corresponding transmittance has been measured in the ALS using a readily available Lux meter application. The final determination of the analyte concentration was carried out in an external computer. The same research group have demonstrated similar ALS based optical sensing system for biosensing applications using ambient light such as sunlight as light source [62]. Fu et al. have demonstrated a plasmonic nanosensor readout device using the smartphone ALS to measure transmittance [63]. In this case, they have used an external LED as a light source which was powered by a 3 V button cell battery and the transmitted light through the nanosubstrate

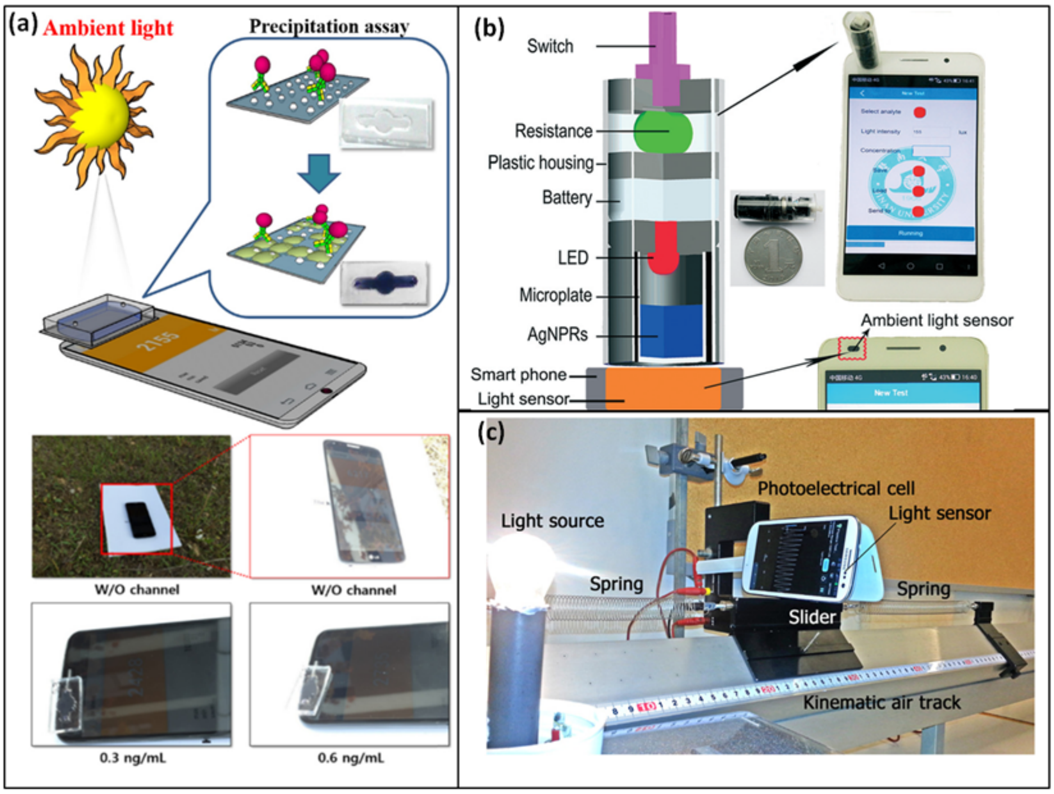

Figure 1.5: The development of smartphone ALS based sensing platforms; (a) working of a smartphone ALS based biosensor where ambient light is used as a light source [62] with permission from Elsevier, (b) demonstration of smartphone ALS based plasmonic nanosensor readout device, reproduced from [63] with permission from Royal Society of Chemistry and (c) demonstration of smartphone ALS as a platform for educational experiments, reproduced from [65] with permission from Institute of Physics.

was then detected by the ALS. The same device has been used to demonstrate a smartphone based microplate reader which can find its usability for different point of care diagnosis applications [64]. The ALS has also been used to demonstrate many physics laboratory experiments for educational purposes such as oscillation studies [65], measurement of spring constant [66], and for demonstration of the famous Beer- Lambert law [67]. Figure 1.5 shows the examples of different sensing as well as educational kits developed using ALS of the smartphone.

1.3.3 Smartphone NFC based sensing platform

Near Field Communication (NFC) is a set of communication protocol which is used to provide short range wireless connectivity between two NFC enabled electronic devices [68]. It is a specialized subset of radio-frequency identification (RFID)

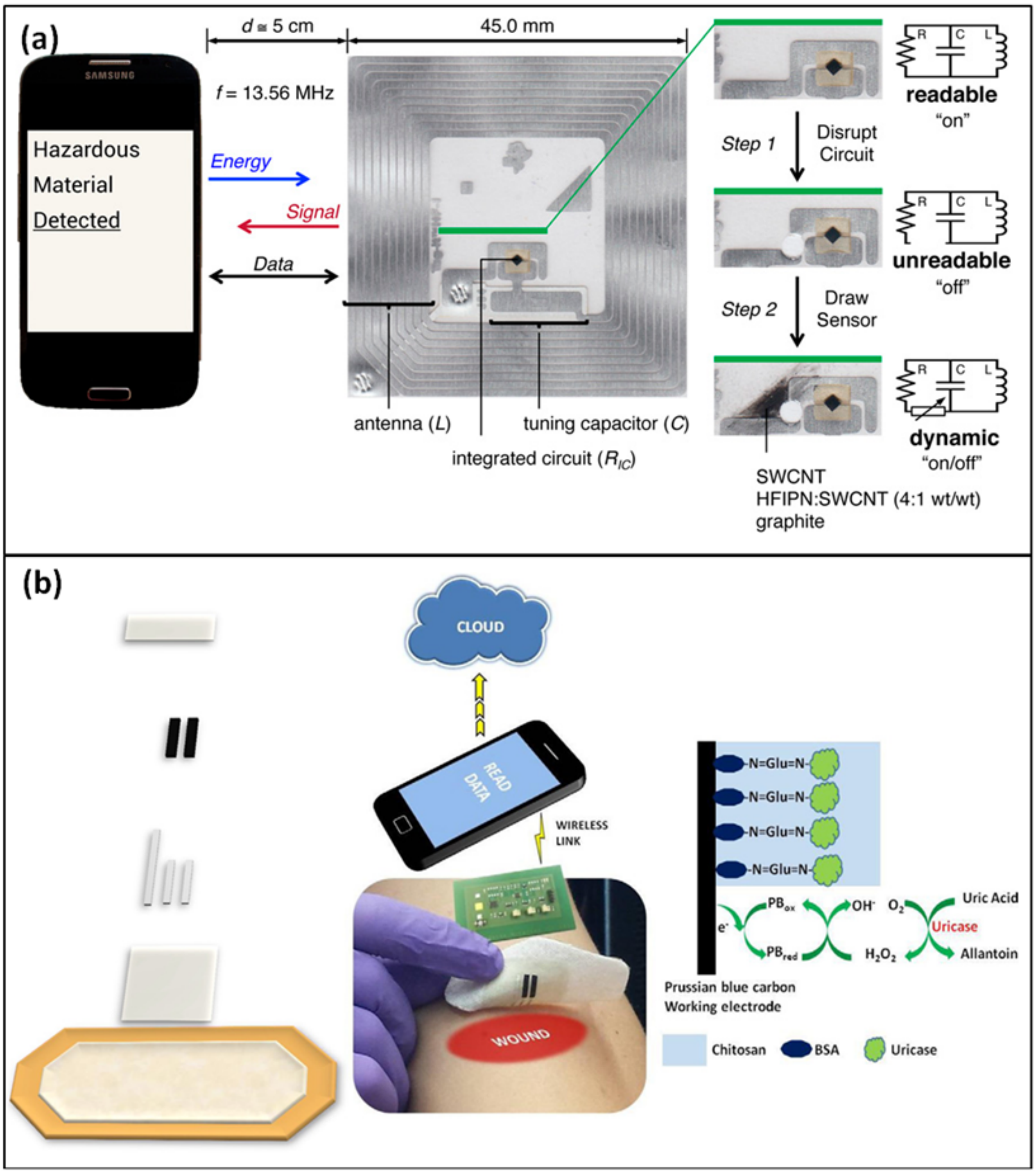

Figure 1.6: The development of smartphone NFC based sensing platforms; (a) working procedure of the NFC based wireless gas sensing scheme, reproduced from [69] with permission from National Academy of Sciences (United States) and (b) demonstration of NFC based smart bandage for wound monitoring, reproduced from [71] with permission from Elsevier.

technology which can communicate through NFC tags. NFC powered devices can work both as a NFC reader or as a NFC tag; it can send energy to a nearby NFC tag and read the emitted signal. An NFC tag does not require any external power source, it is integrated with in-built resonant circuit that can couple phone energy for readout. Since, most of the modern smartphones are embedded with NFC, therefore, it has provided a new scheme of wireless sensing with smartphone. Azzarelli et al. have demonstrated the first ever use of embedded NFC technology in smartphones for wireless gas phase chemical sensing [69]. In this work, they have converted a commercial NFC tag to a programmable chemically actuated resonant device (CARD) by replacing a portion of the resonant circuit with single-walled carbon nanotubes (SWCNTs) as shown in figure 1.6 (a). The interaction of hazardous chemical gases such as ammonia and hydrogen peroxide with the SWCNTs increases electrical resistance which leads to decrease in feedback signal from the NFC to the mobile phone and therefore, presence of these particular gases can be detected reliably. Using similar detection mechanism Zhu et al. have demonstrated smartphone NFC based oxygen sensors by replacing the SWCNTs demonstrated by Azzarelli et al. with Fe(II)-Polymer Wrapped Carbon Nanotubes (P4VP-SWCNTs) [70]. Kassal et al. have demonstrated the usability of smartphone NFC technology for development of smartphone bandage wound monitoring [71]. Figure 1.6 (b) shows the working procedure of the developed NFC based smartphone bandage. Recently, Kollegger et al. have demonstrated the usability of the NFC in strip based blood potassium measurement [72].

1.3.4 Smartphone USB based sensing platforms

The modern smartphones are charged through mini USB port which has also been used for connections with additional accessories for example a pen-drive. This USB port can act both as a host as well as a connector for peripheral device, therefore, it can be used to control and simultaneously power an external device through USB On-the-Go protocol. The embedded USB port can also be used in data communication from an external device such as an electrode using custom developed mobile applications. The ability of controlling and receiving electronic signals through USB port makes smartphone ideal for many electrochemical

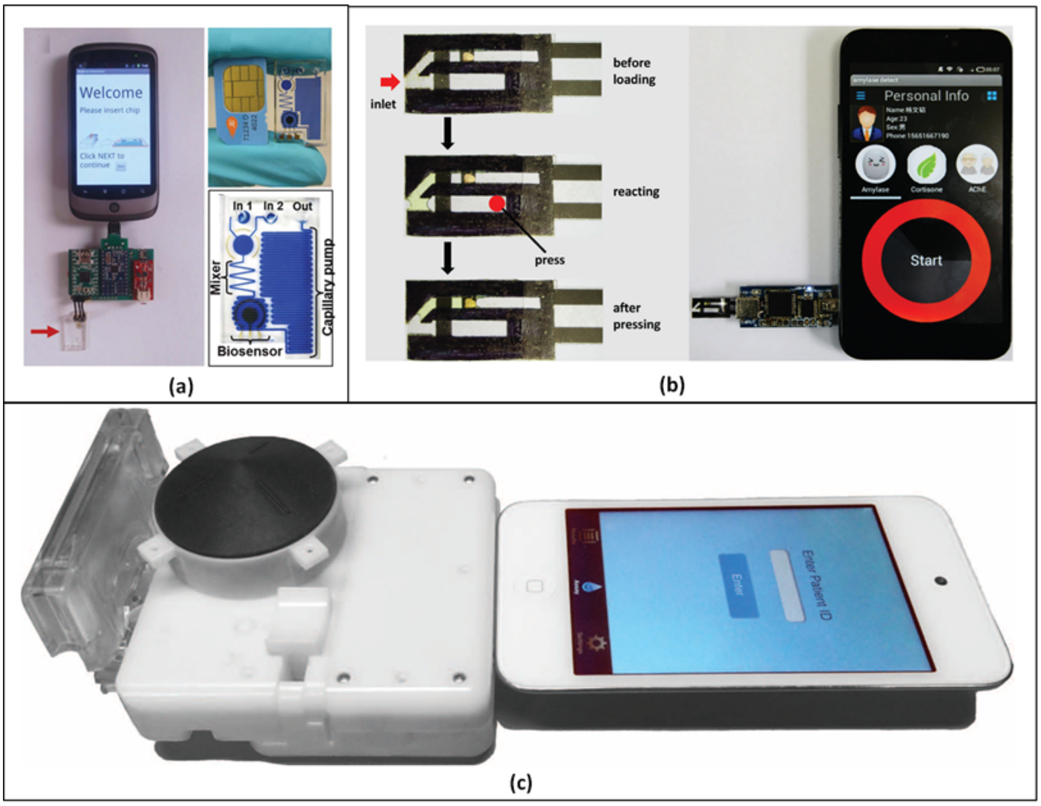

Figure 1.7: The development of smartphone USB based sensing platforms; (a) electrochemical detection platform, reproduced from [73] with permission from Royal Society of Chemistry, (b) demonstration of smartphone based potentiometric biosensor, reproduced from [74] with permission from Royal Society of Chemistry, and (c) demonstration of smartphone USB based dongle for diagnosis of infectious diseases, reproduced from [76] with permission from American Association for the Advancement of Science.

sensing applications. Lillehoj et al. have demonstrated a rapid electrochemical detection platform using mini USB port of the smartphone [73]. The same USB module was used to measures voltage and current signals generated in the microfluidic chip for a particular assay, sending the accumulated data to the smartphone. Zhang et al. have demonstrated a potentiometric biosensing platform using smartphone USB module and a customized smartphone application [74]. The developed platform was used to determine salivary α amylase for personal psychological measurement in POC applications. Similar, USB based electrochemical detection platforms were developed by many other research groups and their usability have been demonstrated for detection of clenbuterol [75] and infectious diseases [76]. Figures

1.7 shows example of different USB powered electrochemical platforms developed in smartphone.

1.3.5 Smartphone audio jack based sensing platforms

Similar to the USB, the embedded audio jack can also be used to interface external devices to the smartphone. The audio jack can work as a data communication function between devices. Audio jack can generate audio signals which can find

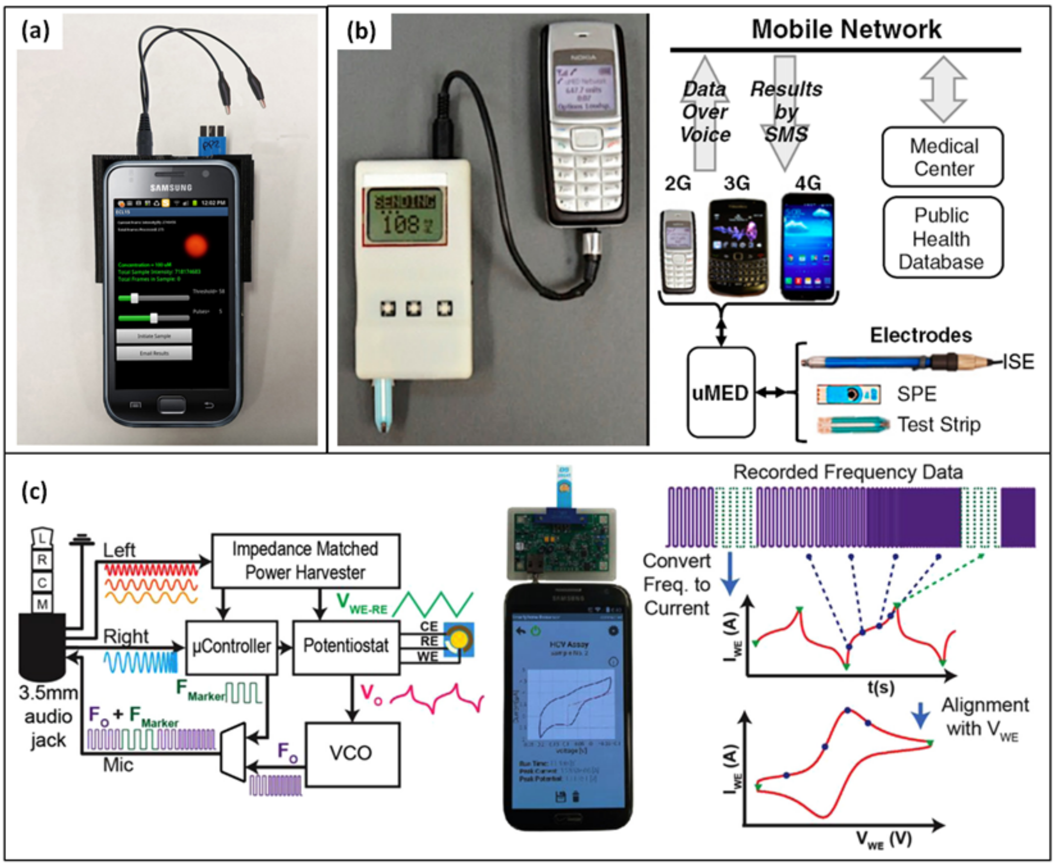

Figure 1.8: The development of smartphone audio jack based sensing platforms; (a) Demonstration of embedded audio jack of the smartphone as a potentiostatic control for ECL based applications, reproduced from [77] with permission from Elsevier, (b) audio jack based universal mobile electrochemical detector for POC applications in resource poor settings, reproduced from [78] with permission from American Association for the Advancement of Science, and (c) audio jack based potentiostat for cyclic voltametric applications in a smartphone platform, reproduced from [80] with permission from Elsevier.

its usability in many sensing applications. Delaney et al. have demonstrated the usability of smartphone audio jack to emit electro-chemiluminescence (ECL) signal from a electrochemical reaction by controlling and polarizing an external electrode via playing an appropriate sound file [77]. The emitted ECL signal was recorded through the smartphone camera to quantify the analyte content. Nemiroski et al. have demonstrated a universal smartphone based electrochemical sensing platform, uMED using the standard audio cable [78]. The uMED platform can be interfaced with different generations of mobile phones to perform different electrochemical sensing through commercialized electrodes. Using similar functionality of smartphone audio jack, its usability has been demonstrated in many electrochemical sensing applications such as detection of different biomarkers [79], Hepatitis C core antibody [80], and detection of nitrate in water [81]. Figure 1.8 shows the examples of different smartphone based electrochemical sensing platforms developed by using the embedded audio jack.

1.4 Statement of the research problem and research motivation

The usability of the smartphone based sensing platforms have been extensively demonstrated as an affordable and reliable alternative over lab confined instruments with reference to remote and resource poor regions [14,82]. Many smartphone based POC devices can be found in the market itself [83]. Most of the biochemical assays and detection methods used for diagnostic as well as environmental assessments are based on optical techniques such as spectrophotometry and microscopy. The in-built camera of the smartphone has been extensively used to demonstrate it as a potential counterparts for the lab confined standards tools [25,38,46]. Though, smartphone camera based optical platforms can significantly help by providing low cost and field deployable tools in low resource settings, however, due to the presence of the IR cutoff filter, the CMOS camera is sensitive only to the visible spectrum (wavelength range: 400 nm to 700 nm). Along, with the IR filter, the presence of the Bayer CFA in the pixels reduces the overall sensitivity in the optical detection process [84]. As demonstrated by McCracken et al. [85] spatial lighting gradients and variance can also affect the overall performance of the camera.

The embedded ALS provides an excellent alternative over smartphone camera based sensors. The ALS in the smartphone is responsive over a wide spectral range from 350 nm to 1000 nm. Short-wave near infra-red (SW-NIR) regime (700 nm to 1100 nm) has been extensively used for many important biological as well as agricultural sensing investigations [86-89]. Therefore, smartphone ALS provides an excellent alternative to develop sensing platforms in the SW-NIR spectral regime which is not possible with the smartphone camera. Another advantage of using smartphone ALS is that it can provide a better dynamic, range 0 Lux to 20000 Lux with a resolution as small as of 0.01 Lux [59]. Thus, it finds its applicability in many sensitive analytical applications. The intensity data can be read from the ALS and display the same by using a custom built smartphone application with reduced processing power as compared to camera based image processing methods which eventually would reduce the overall battery power consumption of the smartphone. Till date, considerably less works have been reported on the application of smartphone ALS in optical sensing applications. Though, the functionality of ALS has been reported in a small number of biosensing applications [61-64] however, no proper optics design has been considered to reduce noises from the external environment and to enhanced the sensitivity. For in-field applications proper encloser is required for completely shielding the device from the external luminance. Along with the hardware issues, there are many software related problems in the demonstrated works which should be addressed for a broad future implementation of the ALS based sensing platforms in consideration to resource-limited settings. In all the reported works no proper signal processing algorithms have been implemented to reduce the error in intensity measurements which may occur due to the internal heating of the smartphone over time. Moreover, in many environmental sensing applications the in-field calibration, real-time data sharing, and reporting are required. None of these features were demonstrated in all ALS based optical platforms reported so far. Therefore, there is a huge scope for necessary improvements for smart ALS based sensing schemes.

Finally, it has been observed that the usability of the smartphone based optical platforms were limited to only biochemical, environmental, and diagnostic applications. There are still many optical methods available beyond spectroscopy and microscopy which can be developed using smartphone in order to have a broader prospects of its applications. For example, optical interferometry is one of the most commonly used techniques in optical metrology. The requirement of sophisticated computational platform to process interference fringes, rigorous opto-mechanical components, and need of sophisticated detector such as CCD or CMOS camera have restricted its applicability for field based sensing applications. Due to the availability of high megapixel count camera module and high-end GPU; onboard detection and complex image analysis can be possible within the smartphone itself. Also, the availability of advanced 3D printing technology, it possible to develop mechanical components required for necessary optics holding [90]. Therefore, there remains a huge scope for the development of more sophisticated optical instruments which again may find its applicability in many optical metrological applications.

1.5 Scope of the thesis and thesis contribution

The embedded ALS of the smartphone has a great potential in many optical sensing applications but surprisingly very less works have been reported till date. The primary goal of this thesis is to foster the applicability of the ALS in different optical sensing platforms by developing rigorous hardware as well as software platforms. Different optical techniques such as direct absorption, evanescent wave absorption, and light scattering principles have been used to develop smartphone based optical tools and the usability of these tools have been demonstrated for sensing of various chemical and physical parameters. Since, the embedded ALS can work as a detector for both visible as well as NIR spectral regime; therefore, the present thesis aims to demonstrate the usability of the developed tools for sensing applications in NIR regime which can not be possible with rear camera of the smartphone. Due to the growing need of safe drinking water, the usability of the designed smartphone sensors in this thesis are primarily demonstrated in measuring of important water quality defining parameters. Considering the adaptability of the proposed tools by the people from these remote and resource poor regions who may not have sufficiently scientific expertise, the optical design and the user interface of the smartphone application have been kept as simple as possible while developing these tools. Moreover, to conceptualize the designed platforms as a truly field portable tools for various in-field applications. In the present thesis work, either the in-built LED flash or an external LED which has been powered from the smartphone battery has been used as a light source. The ambient lighting condition may severely affect the measurement process for in-field applications; therefore, in this thesis utmost precautions are taken to eliminate the influence of the surrounding environment by blackening the cradles from both the sides. Moreover, the thesis work aims to develop required smartphone applications (smart apps) so that all the required computation can be performed onboard within the smartphone itself.

Beyond exploring ALS based sensing systems, the thesis also aims to demonstrate the usability of smartphone in developing optical systems for interferometric applications. Herein, the camera of the smartphone is used to record the interference fringes generated from a 3D printed compact optical system. The on-board fringe processing, fringe counting, and data analysis capability of the smartphone is demonstrated with required smartphone apps. Also, the usability of the interferometric system has been used for measurement of small angular variations.

Herein, the thesis contributes to the development of rigorous smartphone sensing platforms based on embedded ALS to cover a wider spectral sensing range and smart apps for better signal processing. Also, the thesis contributes to the development of smartphone based stand-alone interferometric system which opens the scope for a broader usability of the smartphone for sensitive measurement purposes. Based on the outlined objectives and challenges, the present thesis has contributed in the field of sensing in the following ways:

1. In the first step of this thesis, brief technical details of the embedded sensors and functional components of the smartphone which were used to develop the considered sensing systems have been discussed. Moreover, a detailed discussion about the computational platform used to develop the smartphone applications (smart apps) and algorithms used to develop the smartphone applications has been carried out.

2. In the second step of the thesis work, a smartphone platform photometric system has been designed by using its ALS as a detector and the LED flash as

a light source. The usability of the designed platform has been demonstrated for detection of fluoride level concentration in water samples. Since, the primary motive of this thesis is to find technological solutions which are meant to be used for resource poor region, therefore further optimization has been done in the designed system in terms of its optics design. In the second phase of the present work an external LED has been used as light sources which were powered by the internal battery of the smartphone through USB-OTG protocol. Using external LEDs, the usability of the designed platform has been demonstrated for sensing investigations both in visible and NIR spectral regime by measuring iron and phosphate concentration in water samples. The performance of the developed photometric platforms has been compared with the standard laboratory grade spectrophotometers.

3. Turbidity in water is considered as one of the important water quality defining parameter. In the third step of the thesis work a compact optical set-up has been developed which is based on the ISO 7027 standard for development of nephelometers for turbidity measurements [91]. Here, the ALS has been exploited again as a detector and an external LED with peak emission wavelength 870 nm (recommended by ISO 7027 method) has been used as a light source. A compact optical set-up has been designed by integrating optical components on a plastic nylon cradle which can be attached to the smartphone. The scattered light from the turbid medium has been received by the ALS at 90° as required by the standard method. The performance of the designed smartphone system has been compared with that of a standard laboratory grade turbidity meter by measuring turbidity level of field collected water samples from different places.

4. The fourth work is based on the development of optical platform for salinity measurement in drinking water. To determine the salinity level in water, the fiber optic evanescent wave based sensing principle has been used which is found to be sensitive in low salinity levels in water. The fiber optic sensing system has been integrated with the smartphone for development of the proposed sensing system.

5. Beyond designing, smartphone based sensing systems for monitoring of dif-

ferent water quality parameters; effort has been made to develop the smart optical systems for optical metrological applications. In the last step of the thesis work, using simple optics design, the smartphone has been converted into an interferometric system which has the ability to record and process interference fringes within the smartphone itself. Rapid 3D printing technology has been used to develop the opto-mechanical components and custom designed application has been used to process and analyze the interference fringes. The usability of the developed interferometric system has been demonstrated for monitoring of change in optical phase difference in an interferometric process and measuring of small angular rotation as small as 0.02^0 with high accuracy and reliability.

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