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A Review on Technology-Based Contact Tracing Solutions and Its Application in Developing Countries

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Abstract— To mitigate the spread of the Coronavirus disease 2019 (COVID-19) caused by severe acute respiratory syndrome Coronavirus 2 (SARS-CoV-2), a plethora of technology-based contact tracing (CT) applications have been proposed, designed, and deployed by private and government entities in various countries globally in order to return society to some semblance of normalcy. Although most of the modifications done on the underlining protocols mostly focus on the privacy and ethical concerns of these solutions, pragmatic applications within developing countries are not considered, as applications in most cases are considered to be ubiquitous. This disparity leads to a design-reality gap as the involved entities fail to pay attention to the local conditions in which these systems could be deployed. In this work, an in-depth analysis of state-of-the-art technology-based CT protocols is discussed while considering the compatibility of these designs with the reality of lopsided levels of digital divides and other structural inequalities in developing countries. In addition, a number of existing solutions implemented in developing countries are delineated. Furthermore, pragmatic applications that consider social and technological infrastructures to bridge the gaps in these infrastructures are discussed as well as possible recommendations that could be implemented to effectively mitigate the spread of pandemic outbreaks in developing countries.

Keywords— Contact tracing; Covid-19; Developing countries; Technology-based contact tracing.

1. INTRODUCTION

In a bid to stop the widespread of the Coronavirus disease 2019 (COVID-19) pandemic, private and government entities have arduously worked together to develop systems, which would enable them to identify infected individuals and curb the spread of the pandemic [1]. A key procedure used by these entities in identifying an individual who is infected or has been in close contact with an infected individual is known as contact tracing (CT) [2]. In the past, this process was primarily carried out by two procedures. The first involved training a plethora of personnel to protect themselves from the outbreak as well as questioning and obtaining localization information from infected individuals. The second part involved using the information obtained to follow-up on individuals the infected person recalled to have been in contact with for certain duration [3-5]; for COVID-19 this is about seven to fourteen days [6]. Although this procedure has been adopted in the past to mitigate the spread of a number of pandemics, it was discovered not to scale well in situations where the rate of infection was incredibly high. In addition, it has been identified to be time-consuming and capital intensive [3, 5]. To address this, private and government entities considered a technology-based CT system. This technology-based process has been introduced, not as an alternative to phase out the manual CT process but to augment it. On this premise, multiple

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solutions built atop technologies such as Bluetooth, global positioning system (GPS), ultra-wide band (UWB), and several other technologies have been introduced as a technology-based solution to mitigate the spread of the outbreak [2, 7]. However, the design of these solutions is built using developed countries such as Singapore, United States, South Korea, and other developed nations as a benchmark for this technology-based process. This yardstick, which has been used as a non-official standard for the development of these solutions, defeats the purpose of applicability in developing countries such as India, Vietnam, Nigeria, South Africa, the Philippines, and others [8]. A primary reason behind this is that the level of technological integration in developed societies is different from that in societies or countries that are developing. Looking at this from a wide range of solutions - that have been proposed and implemented in several works - a keystone, which influenced this disparity can be traced to the early rollouts of technology-based CT solutions. The early rollouts of these technology-based solutions focused on usability rather than privacy [3, 8]. To address this concern, subsequent versions worked on improving the technical limitations of the system while addressing privacy and ethical concerns. Though multiple solutions addressing this challenge has been proposed and implemented in several works, a major concern is that these solutions are developed on the assumption that their application, as regards implementation on a global scale, is ubiquitous. Though this is not the case in all cases; however, this perspective could lead to unintended challenges, especially in developing countries with lopsided levels of digital divides and other structural inequalities [8].

1.1. Contact Tracing

This process involves locating an infected individual and those individuals that have associated with him in order to curb the spread of an outbreak [2]. Successful containment of the disease rests on the ability to identify and isolate infected individuals from the general public [5]. The manual process of carrying out this procedure involves training several medical personnel and then using those trained personnel to identify individuals that are contact risks, as well as individuals who are latent contact risks [3]. However, failing to identify individuals who are infected or have been in contact with infected individuals can cause the disease to silently spread. This can be challenging especially for diseases where the symptoms are not detected until after a number of days. For instance, about 70% of the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) transmissions occur before a person is identified as infected [9]. In instances such as this, it has been discovered that the manual process would not scale well in situations where the spread of the outbreak was very high. As a means to mitigate this drawback, technology-based CT was introduced to augment the manual CT process. The technology-based CT solution uses a variety of technologies that considers factors such as proximity awareness, location-based services, proximity duration, automated decision making, geospatial technologies and machine learning algorithms to scrutinize the digital footprint of infected individuals so as to trace those who are latent contact risks and enforce specific health protocols [9]. Although the technology-based solutions have been used by societies to combat the ongoing COVID-19 pandemic, there is minimal adoption of these solutions by individuals in developing countries [8]. A review of existing technology-based CT solutions in developing countries is discussed in section 3.

1.2. Contribution of this Review

Most of the works that review technology-based CT discuss the solutions proposed and implemented around privacy and ethical concerns, system architecture, impact management and user adoption - primarily in developed countries. A number of studies [3, 8-10] have briefly highlighted that solutions should be adapted to developing countries, with the closest study to this work being the work of [8], which focuses on Africa. However, this paper goes further to review existing technology-based CT solutions in developing countries and further considers structural inequalities, which account for the lopsided levels of digital divides in these countries. On this premise, this work discusses technology-based CT solutions with underlining concerns related to developing countries, while recommending possible solutions that take into consideration the local conditions of these countries. The technological solutions reviewed in this literature focus on solutions built atop technology features in mobile phones.

1.2.1. Comparison of this Review with State-of-the-Art Surveys and Reviews

A comparison of this review with other survey and review literature is summarized in Table 1. From this review, the key considerations under which this review is compared with others in Table 1 are primarily influenced by the consideration of social and technological divides that influence the application of technology-based CT solutions in developing countries. These are discussed later in section 4.

Table 1. Comparison of this review paper with existing COVID-19 contact tracing reviews and surveys.

Reference	Year	Discussed technologies used in CT	Discussed adoption rates	Addressed digital divides in implementation	Open challenges
[7]	2020	Yes	No	No	Yes
[2]	2020	Yes	No	No	Yes
[11]	2020	Yes	Yes	No	Yes
[4]	2020	Yes	Yes	No	Yes
[12]	2021	Yes	No	No	Yes
[13]	2021	Yes	Yes	No	Yes
[14]	2021	Yes	Yes	No	Yes
[15]	2021	No	Yes	No	Yes
[3]	2021	Yes	No	No	Yes
[16]	2021	Yes	Yes	No	Yes
[9]	2021	Yes	Yes	No	Yes
This review	2021	Yes	Yes	Yes	Yes

In the work of [7], the survey reviewed several technologies used in CT. The authors focused on Bluetooth low energy (BLE). The BLE-based approaches were discussed from a server side and a client side. This disparity outlined the risk that impacts these solutions. Following this, the authors discussed several limitations of the approaches as well as several cryptographic solutions that could be used to secure approaches built atop BLE.

The work of [2] discussed in detail the impact of the COVID-19 outbreak on various aspects of society and offered medical insight on the COVID-19 outbreak. Following this, the authors discussed several technology-based interventions that were researched, designed and/or implemented to curb the spread of the pandemic outbreak.

The review in the work of [11] provided an analysis of some existing wireless communication technologies used in CT as regards their methodologies. In addition, the authors discussed the challenges of technology-based CT and the impact of these challenges on the adoption rates of technology-based CT.

An analysis of the security and data protection of technology-based CT solutions was studied in the work of [4]. The work studied several adversarial models and presented insights and directions to be considered for future developments of technology-based CT initiatives. Regarding the rate of adoption, the authors focused on European countries. In addition, the authors selected Google play store to obtain the number of applications downloaded in order to estimate the users' adoption per country.

The work of [12] focused on internet of things (IoT) tools for CT. The authors discussed CT applications used by different countries for COVID-19. These solutions focused on wireless communication features that are present in smartphones. In addition, the summary delineated the pros and cons of using them. Furthermore, the work discussed hybrid solutions and future directions that could enhance the effectiveness of these tools in IoT space.

From 96 literatures obtained from Scopus and Web of Science, only 25 studies were used in the work of [13]. The key consideration in this review was centered on cultural context and individual characteristics. As discussed later in subsection 4.4, the work of [13] discusses cultural context from the perspective of CT application adoption. The discussion on the subject of cultural context generally centers on the perception of users on the subject of privacy. In addition, how this perception influences the rate of adoption is also considered. Individual characteristics, on the other hand, primarily focused on variation in acceptance and social diversity.

In the work of [14], the adoption rate of CT applications in European countries was delineated. Following this, the adoption rate of the application was analyzed based on engagement, functionality, aesthetics and information. Simulated best case adoption rates (BCARs) were simulated to show the percentage of adoption needed to make technology-based CT solutions an effective tool.

The work of [15] discussed the privacy of COVID-19 CT and exposure notification applications. In this work, the summary of technology-based CT applications was focused on the solutions implemented in developed countries. The primary challenge discussed centered on factors impacting adoption rates.

The work of [3] primarily focuses on the security and privacy issues of CT applications. The authors discussed privacy issues and security attacks such as bluesnarfing, enumeration, etc., and how these attacks impact technology-based initiatives. An advanced encryption standard (AES) and random cloud storage were recommended in [3] for protecting the collected data.

The work of [16] aimed to recommend the best practice guidance needed to design the ideal technology-based CT application. The authors, which cut across various disciplines agreed on six key considerations needed to achieve their set goal.

The work of [9] gave a systematic review of technology-based CT papers from January 1, 2020 to March 31, 2021. The work focused on the effective reproductive number and works that reduce this number. The authors also reported on the adoption rate and compared technology-based CT with manual CT procedures. Following this, the work compared the ability of both CT procedures to reduce the effective reproductive number.

In contrast to the surveys and reviews summarized in Table 1, our review jointly discusses the technologies used in technology-based CT solutions, adoption rates primarily in developing countries, digital divides in implementing technology-based CT in developing countries and open challenges. It is important to note that this field is a highly dynamic research field. Therefore, at the time of writing this paper, new and related research, which might include other key considerations as regards developing countries, might not be captured in Table 1.

1.3. Organization of this Review

Concerning the rest of this paper, an overview of wireless communication features in smartphones that are used for technology-based CT is discussed in section 2. In section 3, an overview of technology-based CT solutions that are utilized or proposed in developing countries is discussed. Taking Nigeria as a case study, section 4 focuses on the key challenges that limit the permeation of the technology-based approach in developing countries. A succinct overview of possible recommendations to address the challenges outlined in section 4 is discussed in section 5. Finally, this paper is concluded in section 6.

2. OVERVIEW OF WIRELESS COMMUNICATION FEATURES USED FOR TECHNOLOGY-BASED CT

Before the COVID-19 pandemic thrust technology-based CT into the limelight, the technology had already been quietly explored for this purpose for over a decade [17]. In one of the earlier accounts, the author in [17] alongside other researchers explored the potential of the technology in 2009. Although reception towards the concept was lukewarm at the time, the work proposed a Bluetooth-based solution as a viable way of curbing a budding outbreak in a small social network. This study laid part of the key foundation needed to use a technology-based approach to determine an individual who came into close contact with another during a period that met the requirements for the individual to be considered a contact risk.

To give a quantitative metrics to this, earlier works like [18-20], used the received signal strength indicator (RSSI) measured between the transmitter and the receiver of paired devices for distance estimation and localization of devices. This obtained information - which can be used to determine if an individual is a contact risk or not - was adapted as a non-official standard for using its subsequent variants as a CT aid. However, a major drawback of Bluetooth was that it required a connection to be established between devices involved before exchanging data. The added complexity involved in establishing a connection between devices impeded the efficient exchange of messages. In addition, the signals were prone to attacks by malicious individuals, since the devices advertise themselves [7, 21]. As the interest in technology-based CT grew, private and government entities have discovered that the most effective technology-based CT approaches thus far are those that utilize known and newer wireless communication features that are built into smartphones [2, 9]. Delineated in the following subsections are other smartphone features upon which technology-based CT solutions are built.

2.1. Bluetooth Low Energy

Among the wireless communication technologies adopted for CT, BLE has had the highest rate of adoption, as most CT solutions implemented across the globe have most of their solution built atop BLE [9]. BLE is a subcategory of Bluetooth [22]. The added term "low energy" refers to the reduction in the energy consumed by the device battery. This extends the battery's lifetime in comparison to the legacy Bluetooth technology. The BLE variant of Bluetooth was released in 2010 as part of the Bluetooth 4 radio specifications. Like the legacy Bluetooth, it operates in the 2.4 GHz ISM band, in which three advertisement channels and 37 data channels are defined [23]. The BLE represents an effective step to expand the ecosystem of Bluetooth to the IoT [21].

Generally, BLE devices can be assigned one of two roles, peripheral or central, and they are identified by a device address. Once connected, a peripheral device and a central device can communicate by exchanging data packets over the BLE data channels [21]. Fig. 1 delineates a basic BLE handshake flow. For a BLE-enabled device, central devices scan for nearby devices by tuning on the peripheral advertisements to scan for advertising services.

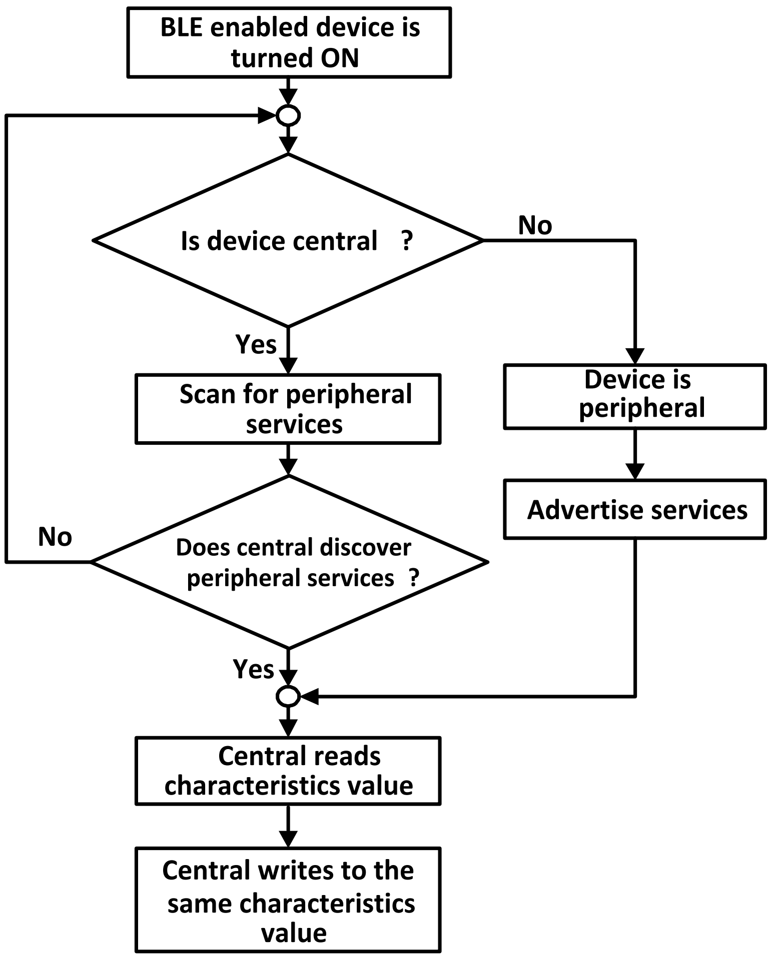

Fig. 1. Conventional BLE handshake flow.

If discovered, the central device reads and writes the value of the characteristics. Though the BLE technology is not designed to measure distance, the distance between two devices can be measured using the RSSI. The primary principle for this measurement follows the inverse square law [24]. As per its application in CT, when the RSS measured is relatively high, it is generally assumed that a contact event has occurred and the reverse is the case for individuals whose devices are far apart [21, 24]. This is used by CT applications to provide a good enough estimation of proximity. Nonetheless, this is not always the case in real-world settings. In these settings, variables such as absorption and device orientation could strongly attenuate the radio signals, while reflection on the other hand could change the signal strength received in indoor environments as shown in the work of [25]. In addition, the significant variation of transmission power over different smartphones affects distance estimation [9]. These errors in measurements could cause either a false sense of safety or a false sense of panic. Within the drawbacks of the BLE-based solution for CT is that it is unable to tell if an obstacle such as plexiglass separates an individual from another. In this case, the BLE-based distance estimation can falsely alert an individual that they might be an infection risk, resulting in unnecessary panic. On the other hand, an individual could build a false sense of security if an infected individual is not running the application at the point of contact or if distance estimation does not successfully register the contact [6, 25].

For the purpose of usability, it is crucial that technology-based CT applications can run in the background. However, the iOS version of the BLE-based app is bound by restrictions that iOS has on background Bluetooth functionality; thereby its proprietary advertisement format is not readable by non-iOS devices [7].

BLE is susceptible to replay and relay attacks, during which malicious users impersonate and rebroadcast the location and history of users, which affects the data collected by the central server. Privacy-friendly schemes such as private set intersection [26], elliptic curve cryptography [27] to name a few, are used to protect the information broadcasted and received between users as well as between users and the central server.

2.2. GPS

GPS is a satellite navigation system used by authorities around the world to monitor the location of GPS-enabled devices. This technique is adopted by countries such as India, Ghana, the Philippines, Thailand, and Norway to monitor COVID-19. A major drawback of using this technology as a CT tool is that it can reveal sensitive information about individuals [11]. In addition, it has low precision in indoor environments. The precision for GPS is about 10m. This decreases in areas with tall buildings. This vertical limitation, that is, for floor detection, signifies that individuals identified within a tall building would register within the margin of error. Furthermore, the battery usage is higher in comparison to BLE [7, 21].

Unlike BLE where the restrictions by Apple's iOS limit the functionality of the application's usage running in the background, the limitations do not affect applications related to location tracking. Therefore, in contrast to other wireless communication features in smartphones that are restricted from running in the background, GPS-based CT applications, whose primary function is related to location tracking can run in the background of iOS devices.

2.3. Wireless Fidelity

Wireless Fidelity (Wi-Fi) is another communication technology that is identified as an effective CT tool [5]. In most uses' cases, this solution works with the assumption that universities, corporate offices and other locations where a high density of individuals tend to spend their day have access to Wi-Fi. On this premise, Wi-Fi based CT could be done from either the device or the network, and in either case, they are used to characterize and model the movement of users. Although its primary application is indoor, it requires an infrastructure that might not be available in all places, especially outdoors. This limits its application as regards CT especially in areas without Wi-Fi coverage. In addition, its use raises privacy and ethical concerns, since the location of individuals can be documented actively and passively when their device is connected to the Wi-Fi network [1]. Furthermore, location estimates are not always accurate, as multiple users can connect to the same access point (AP) from different rooms. Since estimates are primarily based on timestamps of devices connected to an access point, uninfected individuals could receive false risk alerts, which could cause unnecessary panic.

2.4. UWB

The newer generation of smartphones such as the iPhone 11 and the Xiaomi Mix 4 are equipped with UWB wireless communication capabilities [28]. In order to address the challenge of accurate distance estimation and localization using the conventional BLE systems, UWB uses a low energy level for short-range, high bandwidth communications over the radio spectrum. Furthermore, UWB has less noise interference, which makes it a suitable technology-based CT approach for indoor applications [12]. Although it provides higher accuracy (<0.5m) [9] with a low error of margin of about 0.1m [12] than BLE for both distance estimation and localization, its major drawback is the technology's incompatibility with smartphones not equipped with this technology. Unlike GPS, Wi-Fi and QR codes, privacy concerns are low.

2.5. Quick Response Code

Quick response code (commonly referred to as QR codes) is a machine-readable visual label that contains data. The data embedded in the QR codes enable the technology to function as an identifier, tracker and locator [29]. This method of CT requires an individual to take photographs of the QR code at various locations. A mobile application automatically reads the locations encoded into these QR codes and populates the central database with the user's information. If a user is tested positive, the information updated can be used to alert contacts who had interacted with the same QR code within the duration of concern. China has a high adoption rate for this approach. The data obtained was used to assign color codes (green, yellow and red) to users. This color-coding generally influenced the citizen's degree of movement [15]. However, the movement of individuals is non-deterministic; therefore, its efficiency as regards its application is highest within the same room/floor of a building. If the QR codes are positioned outdoors, the direction of individuals that may have interacted with the same QR codes, would not have necessarily followed the same direction or be in close proximity at the time of interaction [11]. This could cause a false sense of panic. Like the BLE-based CT process, QR codes also processes and match local grouping information. However, privacy preservation is low [30]. Table 2 summarizes the different wireless communication features in smartphones that are used for technology-based CT.

Table 2. Summary of the different wireless communication features in smartphones used for technology-based CT.

Technology	Location/ Proximity Accuracy	Running in background (iOS and Android)	Infrastructure required	Privacy concerns	Target environment
BLE	Outdoors (<2m) Indoors (<2m)	No, yes	No	Low	Outdoors, indoors
GPS	Outdoors (10m) Indoors (Extremely low)	Yes, yes	No	High	Outdoors, limited indoors
Wi-Fi	Outdoors (Depending on APs) Indoors (<1m)	No, yes	Yes	Low	Limited outdoors, indoors
UWB	Outdoors (Depending on UWB transmitters) Indoors (<0.5m)	No, yes	No	Low	Limited outdoors, indoors
QR Codes	Outdoors (Building level) Indoors (Room/floor level)	No, yes	Yes	High	Limited Outdoor, indoor

3. OVERVIEW OF EXISTING TECHNOLOGY-BASED CT SOLUTIONS IN DEVELOPING COUNTRIES

Works such as [4, 12, 14, 15] - which discuss the present tools used for technology-based CT - offer a sizeable range of information on the CT solutions implemented around the globe. As regards adoption and usage, these works delineated the rate of adoption of various technology-based CT applications and the number of downloads from Google Play store, respectively. However, most of the information on the adoption rates and the number of downloads are for developed countries with little to no information on technology-based CT solutions in developing countries. To build around the latter, information concerning technology-based CT solutions that were designed and/or implemented in developing countries were obtained from Google Scholar. This information was used to streamline the number of countries to sixteen. However, not all solutions had details concerning their system architecture, trust model, technology, adoption rate and information on the number of downloads from Google Play store. However, for countries listed, information found on any three of the five details earlier mentioned was included in Table 3. Primary details of the factors considered for the CT applications are discussed in the following sub-sections.

3.1. System Architecture

There are generally two types of system architectures engaged in the development of technology-based CT applications. The applications could either be centralized or decentralized in approach [5].

In the underlining framework of the centralized architecture, a central authority manages personal data collected from the technology-based CT applications [5]. Although there are arguments which state that the centralized approach of technology-based CT is the most effective and easy solution, there have been concerns surrounding the data gathered by this approach [5, 14]. The large-scale collection of information gathered by entities involved in handling the information uploaded by individuals that use technology-based CT applications has sparked concerns about how this data would be handled post-COVID-19 [14]. To address this, a decentralized approach that prioritizes the end-users privacy was developed. Technology-based CT solutions designed based on the decentralized approach give individuals the control to either share the data collected through their devices over a certain duration to a central server or not. This approach generally protects the personal identities of the infected and non-infected individuals from the central authorities. The central authorities are only aware of the pseudo identities of individuals and these can be used to alert individuals who are potential contact risks. However, there are concerns that this would fail if a large number of individuals who are alerted to be contact risks refuse to act accordingly [5].

To strike a balance between both approaches, a number of researchers have proposed and implemented a hybrid approach that enables the health authorities (HAs) and infected individuals to operate both architectures at different stages of the technology-based CT infrastructure. The infected individuals' information could be used to obtain information concerning whom the infected individual had come in contact with while preserving the identity of the individuals with whom the infected individual did not come in contact.

3.2. Trust Model

Concerning the trust model and security proofs, centralized servers are trusted. However, the protocols are designed in a way that the information leakage to the servers is still acceptable as in the case of a passive (semi-honest) server corruption [31]. Since there is no absolute certainty as to whether the dealer or administrator of the servers would be honest or not, system architectures are further enhanced by using cryptographic techniques [32] to secure information of users from malicious outsiders and insiders alike. In essence, if the protocol is secure against active adversaries and communication complexity is optimized between involved devices - such that the administrator does not collude with either party and it is secure against attack from malicious outsiders - then the protocol is trusted or honest; else, it is semi-honest or honest-but-curious [33].

3.3. Users Adoption

The summary of CT mobile applications (commonly referred to as apps) delineated in Table 3 highlights apps utilized or proposed in developing countries. From the list of countries, the number of downloads identified in Google Play store as at the time of this writing could only be obtained for India, Vietnam, Columbia, South Africa, Saudi Arabia, Indonesia, Thailand, Philippines, Turkey, Malaysia, and Latvia. Due to location restrictions from Google Play store, data on the number of downloads for countries such as Pakistan and Ghana were not accessible. However, the number of downloads from Bulgaria was retrieved from the work of [4]. In addition, there was no information present on Google Play store on the KDTRACE app discussed in the work of [34], neither was there any data on the user's adoption rate. However, it was identified in the work [32] that the app was still in development by the state's government.

Table 3. Summary of existing contact tracing apps in developing countries.

App	Country	System architecture	Technology	Trust model	User's adoption (%)	Number of downloads from Play store
Apturi COVID	Latvia	Decentralized	BLE	-	5.24	100, 000+
Arogyu Setu	India	Centralized	BLE, GPS	Honest	7.40	100,000,000+
Bluezone	Vietnam	Centralized	BLE	Honest	10.42	10, 000, 000+
Corona App	Colombia	Centralized	GPS	Semi-Honest	20	10, 000, 000+
Covid Alert	South Africa	-	BLE	-	1.68	1, 000, 000+
Covid-19 Gov PK	Pakistan	Centralized	-	-	-	-
Tawakkalna	Saudi Arabia	Centralized	GPS	-	29.2	10, 000, 000+
E7mi	Tunisia	Centralized	BLE	Semi-honest	0.85	100, 000+
GH COVID-19 Tracker	Ghana	Centralized	GPS	Semi-honest	-	-
Hayat Eve Sigar	Turkey	-	BLE	-	0.1	100, 000+
KDTRACE	Nigeria	Centralized	BLE	Honest	-	-
MorChana app	Thailand	Centralized	BLE, GPS	Semi-honest	7.15	5, 000, 000+
Mytrace	Malaysia	Centralized	BLE	Semi-honest	30.5	10, 000, 000+
PeduliLindungi	Indonesia	Centralized	BLE	Semi-honest	3.70	10, 000, 000+
Stay Safe PH	Philippines	Centralized	GPS	Semi-honest	0.9	1, 000, 000+
VirusSafe	Bulgaria	Centralized	GPS	Semi-honest	0.2	10, 000+

- signifies that the information was not found

The estimated user adoption rate for each country was obtained by dividing the number of downloads by the entire country's population. In addition, the calculation was based on the information obtained from Google Play store and does not include the number of downloads from outside sources such as Apple store.

A major reason for the low rate of adoption of technology-based CT solutions among individuals in these countries has to do with their perception of privacy issues concerning the usage of information generated by these apps [28, 35]. While these solutions are proposed to curb the spread of the outbreak, its effectiveness is mutually inclusive to its rate of adoption. As reviewed in the work of [9], varied adoption percentages have been proposed to increase the effectiveness of these solutions and curb the spread of the COVID-19 pandemic. While 100% uptake of the app by users is ideal to control the spread of a pandemic, the work of [9] identified from reviews that an 80% uptake by smartphone users would need to actively utilize CT apps to mitigate the spread of the pandemic.

4. CHALLENGES OF TECHNOLOGY-BASED CT IN DEVELOPING COUNTRIES

Capturing the dynamic nature of an outbreak can be challenging, as measuring and obtaining every available data that captures both the geographical and temporal extent of the sample space can be difficult. Nonetheless, obtaining an abstract interpretation - while considering the geographical and temporal extent of the sample space - is possible [12]. Despite the difficulty in representing the entire sample space, it has been stated in multiple studies [3, 9, 10, 11, 28] that an increase in the level of adoption would increase the information obtained from a sample space, which in turn would increase the reliability of the system. Though the delineated studies support this approach, the practicability of these solutions, if not well thought out by researchers and government entities could limit its application and adoption in developing countries. Taking Nigeria as a case study of a developing country, factors that limit the practicability of technology-based CT are discussed in the following subsections.

4.1. Low Ownership of Smartphones

Nigeria as a developing country is considered the "Giant of Africa." In 2021, the World Bank reported that before the COVID-19 outbreak, 4 out of 10 Nigerians were living below the national poverty line, and millions more were living just above that line with the possibility of them falling back when shock occurs [36]. With the waves of lockdown and the collapse of businesses, as well as the massive lay-off of personnel, shock occurred. With this as the present reality, a massive number of individuals are more interested in their day-to-day living than owning a smartphone. By social class, the majority of Nigerians are within the bracket of the lower class. The monthly earnings of individuals within this class are within \$80 - \$250 and with the average price of an off-the-shelf smartphone within the range of \$60 - \$150, ownership especially in rural areas is significantly low. With a high number of individuals not technologically oriented, and a number of them identified within the vulnerable group, that is, the elderly, technology-based CT solutions built atop technology-based features of smartphones as downloadable apps might not scale well.

4.2. Erratic Power Supply

About 47% of Nigerians do not have access to grid electricity [37] and those who have access only get an average of 6.8 hours of electricity supplied to them [38]. In the work of [39], a key finding as regards the effectiveness of the proposed technology-based CT solution was to have the Bluetooth turned on instead of randomly at certain times of the day. In addition to the network operations and the functions within smartphones that consume power, adding a technology-based CT application that requires a higher frequency of wake-up functions for more efficient CT would not be favorable, since the state of electricity supply within the country is erratic.

4.3. Poorly Equipped Staffs

At the height of the COVID-19 pandemic, a major complaint amid the trained personnel who served at the frontlines concerned the poor supply of necessary equipment. The cost of this was dire, as a number of frontline workers across the globe became victims of the problems they painstakingly fought to address. The phobia that resulted from this shortcoming caused medical facilities in developing countries like Nigeria and Bangladesh to barely address medical cases for the suspicion of the case being a COVID-19 infection. This resulted in a massive number of patients being rejected from these facilities [6].

4.4. Cultural Framework

The work of [13] discusses the cultural framework from the perspective of application adoption, and as delineated in the work of [16], the discussion on the subject of cultural framework generally centres on the perception of users on the subject of privacy and how this affects the rate of adoption. Although the perception of these frameworks differs with countries, the countries that are primarily discussed within this framework are developed countries. This subsection extends the scope of this framework by briefly discussing how cultural values in developing countries, such as Nigeria affect the adoption of technology-based CT. Communal living is part of the ethos of Nigerians. Due to this, individuals are at risk of being infected as there is little to no respect and in some cases, awareness for barrier gestures such as social distancing and preventive measures such as quarantine during their daily encounters.

5. POSSIBLE RECOMMENDATIONS

Although it is difficult to account for every possible scenario, it is expedient to develop an efficient CT solution that identifies individuals who are contact risks as well as individuals who are latent contact risks in developing countries. On this premise, it is important that designers take into consideration cultural values, social structures, domestic political factors, skills, resources and the reality of users in these developing countries. The information that is gathered from these can be used to design solutions that close the social and technological gap of adapting technology-based CT solutions to mitigate the spread of an outbreak [8]. Discussed below are possible recommendations that can be adopted by designers and government entities.

5.1. Compatibility with Operating Systems Outside Android and iOS

The work of [6] highlighted that 67% of the world's population own a mobile phone, and according to [9], 56% of these mobile devices are smartphones. Putting into consideration the market share of smartphones, a majority of these smartphones operate on

Android and iOS operating systems. However, other non-tactile and tactile smartphones operate on other operating systems such as Blackberry, Symbian OS, Palm/Web OS, and the newly developed Calyx OS. Though their market penetration is not as large as the popularly known Android and iOS operating systems, they are still equipped with the underlining technologies on which technology-based CT solutions are built. To account for this niche of users, designers and government entities need to adopt the technology-based CT solutions to seamlessly operate with operating systems outside Android and iOS operating systems.

5.2. Compatibility with a Fraction of the 44%

As underlined in subsection 4.1, the cost of these smartphones has led to the low penetration rate of smartphones in developing countries. As a result, most individuals opt for mobile phones that are not equipped with most of the wireless communication features in smartphones. A significant number of these users make up the remaining 44% of mobile phone users, and within this pool, a significant number of these devices are equipped with Bluetooth. Since most technology-based CT solutions are built atop variants of Bluetooth, designing Bluetooth-based CT solutions that operate with these mobile phones and are compatible with smartphones would create a more effective network that further bridges the gap of the digital divide.

5.3. Utilizing Cell Towers for Localization and Distance Estimation

A majority of the individuals that populate the rural communities are identified to be within the vulnerable group. The digital literacy of these individuals is low, which largely contributes to the lopsided levels of digital divides. Nonetheless, a significant number of these individuals possess a mobile phone with an active SIM card. In a case where any of these individuals test positive for COVID-19, HAs could work with network operators as proposed in the work of [6] to obtain location data. This data can be used to map out the mobility of the individual over a number of days. In addition, the information could be used to identify individuals who were in close proximity with the infected individual. For this approach to be efficient, enhanced precision as regards localization and distance estimation would need to be addressed, and the individuals would need to have their mobile phones powered on.

5.4. Awareness Campaigns

Awareness campaigns around social and technological requirements during outbreaks could slow the spread of the pandemic. On this premise, initiatives that involve religious leaders, advertisements through local programs on television and radio, and town criers in local communities could enlighten individuals of an outbreak. This approach alongside technology-based CT can be used to gradually bridge the information gap that causes the digital divide in developing countries [8].

5.5. Technology-Based CT should Augment Manual CT

According to the work of [9], there is no conclusive finding that identifies which CT strategy is superior. Although the entities involved are yet to find the balance between the challenges and opportunities in using one of the techniques over another, or to augment the other, it is eventually the responsibility of these entities to navigate through these and ensure that their efforts towards curbing the spread of an outbreak are at its core human-centered. This approach would enable us to navigate this era and better prepare for likely outbreaks that could occur in the future.

6. CONCLUSIONS

Since the outbreak of the on-going COVID-19 pandemic, technology-based CT solutions have been adopted to flatten-the-curve and return society to some semblance of normalcy. However, there are design concerns as regards the adoption of this technology-based solution in developing countries. As the social and technological gap between developed countries varies from that of developing countries, it is, therefore, necessary for private and government entities to consider adapting these technology-based solutions to match the need of the reality of their environments. On this premise, technology-based CT solutions in developing countries should scale beyond the use of technology-based features built atop smartphones. Since their penetration differs significantly across countries, with a remarkably low usage among the vulnerable group, that is, the elderly. These solutions should be cheaper with efficient distance estimation while consuming less power and preserving the privacy of the individuals.

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