Digital Contact Tracing: Mitigating the Impact of the Next Pandemic

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

As of April 2021, there have been around 134 million cases of COVID-19 across the world, of which 2.9 million people have died [16]. Factoring this into the estimated global population of 7.9 billion people yields an infection ratio of close to 1.7%, assuming each case is a different person. Naturally, the spread of the virus is not uniform across the globe and has accumulated in certain regions, such as the United States. The infection ratio in the US is a whopping 9.45% [16]. Although the percentage of cases resulting in death is only around 2% globally and within the US, the impact on most human life in one way or another is almost undeniable, whether it be in terms of social or economic disruption. When an outbreak reaches this scale of magnitude, it is necessary to think about how it can be prevented in the future.

When such a catastrophe cannot be prevented, it is necessary to have measures in place that limit spread and mitigate potential damages. A common method of limiting the spread of a disease is contact tracing (CT): a process that determines who has a disease and who they may have given it to. If all infected individuals and contacts are identified and quarantined, the disease cannot spread. In theory, this method should prevent the spread of a disease if executed properly, but due to an assortment of social, ethical, and technical issues this technique is traditionally difficult to perform well. However, like in many other fields, technological innovations present new capabilities that assist and automate the process. Digital contact tracing (DHT) is a novel method of tracking the spread of a disease, which relies on wireless, internet-connected devices that many people carry today. No matter what implementation is used, CT involves collecting and processing extremely sensitive health and social data: who has contracted a disease and who they interact with. It is therefore necessary for DCT applications and traditional means of CT to protect this information at all costs while functioning properly. If a proper balance between privacy and effectiveness is established, CT can prevent disease from spreading to domestic, national, and global levels, while respecting an individual's rights and liberties. It is vital to explore the applications, ethics, and pitfalls of modern smartphone CT applications, and answer the question: can digital contact tracing applications be leveraged and adopted into widespread use to mitigate the impact of the next pandemic?

Literature Review and Technical Framework

In a time when society is becoming increasingly interconnected and globalized, people are constantly circulating the planet. People bring along with them news, ideas, trading goods, and animals. Both humans and animals also bring microscopic organisms and viruses with them. In the case of the Spanish Conquistadors who carried the smallpox virus, it helped them conquer the Aztecs and wipe out 40% of Tenochtitlan in a single year [14]. In the case of SARS-CoV-2, it most likely spread in a zoonotic spillover from an animal population – possibly the horseshoe bat (96% genome match) or the pangolin (85-92% match) - to a currently unknown intermediary animal host, and then to humans in Wuhan, China [10]. Before it could be contained, it spread across the country, continent, air, and water all over the world, infecting and killing millions.

Ecologically speaking, humans made the expansive spread of the highly infectious coronavirus easy, due to living spaces located close to domesticated animal farming populations, and low biodiversity of such populations [15]. In addition, governments and public health administrations took a reactionary approach to slowing the spread, rather than a preventative one. Unsuccessful countries such as the US did not have technology-powered reconnaissance and surveillance systems, robust outbreak investigation systems and did not take swift, science-based public health actions. Specifically in the US, public health experts speculate public health infrastructure is undercut by $4.5 billion [13]. State and local public health departments lacked a sufficient workforce to conduct mass contact tracing, and the federal government left states to fend for themselves [11]. By the time the next pandemic occurs, US states and international countries should have a sophisticated contact tracing system in place. While governments could funnel enormous sums of money into hiring any army of human contact tracers, traditional CT like this is very expensive to carry out in terms of time, money, and labor. Additionally, human contact tracers can potentially misuse health information and erroneously encode record. If DCT technology is perfected and accepted by authorities and the public, it will automate the process of tracing while improving effectiveness. However, it comes with an array of obstacles - ethical problems concerning privacy, security, and equity, and perfecting the technology itself.

Contact tracing has been essential for communicable disease control in public health for dozens of years. While it is a common conception that smallpox was controlled through universal immunization, extensive contact tracing played a major role in limiting the spread of the disease. After identified as being infected, infected individuals were quarantined, and the surrounding community and contacts at-risk were notified, which greatly inhibited the spread of the virus. Although contact tracing is most often used for controlling diseases, it is also used to investigate the traits of diseases, such as infectiousness, when the capabilities of a disease are unknown. Contact tracing can be used to determine links between cases of a disease, and to determine if secondary transmission is taking place in a certain region. Contact tracing is also used in the airline industry during larger pandemics, and for partner care, which involves notifying the sexual partners of an infected individual. Although contact tracing can aid in addressing an infectious disease, is not always the most efficient method. In areas of high disease concentration, focused testing can be more effective. In areas without testing, contact tracing is not possible. There continues to be problems in successfully executing contact tracing, but the progression of technology has enabled more possibilities.

There are several modern technologies that make contact tracing possible. Case management software is frequently used in public health to keep records of cases. This information is usually stored in a database with the ability to notify people who have been in contact with a disease carrier. Today's smartphones can use GPS, Bluetooth, or Wi-Fi to determine when people have been in contact with each other and receive messages over the internet when a contact has been infected. Databases are required to keep track of who was infected, when, and who their contacts were. It is possible to store this information in a deidentified format using cryptographical methods and a decentralized architecture. Locational data can also be important for determining hot spots and general spread of a virus but is not inherently necessary. Potential contacts can be alerted in less than 15 minutes after a positive case is reported, whereas traditional CT may take hours to days. Furthermore, DCT captures hidden contact between strangers, which may account for 25-40% of transmissions. Traditionally, contact tracers are limited to only notifying people who positive individuals know.

After COVID-19 became widespread, regions around the world started implementing their own DCT applications. DCT applications allow a user to report his or her positive case of coronavirus after testing with public health and alert devices that were recently near them. While it would be ideal for there to be a universal app for contact tracing that enabled tracing across borders, this is not possible due to the nature of health systems and regulations across the world and within the United States. Rather, over the course of several months following the inception of COVID-19, several countries (and U.S. states) rolled out applications based on different technologies.

A few countries quickly produced GPS-based applications and tracked movements of users. In China, Alipay and WeChat released an application and as part of the “Health Code” system which determines a color code (green, yellow, or red) based on a person’s exposure risks and freedom of movement based on factors such as travel history, time spent in risky areas, online transactions, and relationships to potential carriers. Citizens are required to provide personal information, including name, national ID, and physical health condition. Citizens must also register with facial recognition, update physical conditions every day, and check into businesses through the app. Russia released a contact tracing application to 60,000 Muscovites, and 30% were subsequently fined for violating quarantine restrictions. Both in Russia and China, facial recognition AI is used in combination with hundreds of thousands, if not millions, of cameras to track citizens, and played a role in their implementation of DCT.

Other countries opted to use Bluetooth to protect the privacy of users and not track location. In April 2020, Apple and Google released a software framework for building COVID-19 iOS and Android applications. Developers can now utilize the Google/Apple Exposure Notification (GAEN) system to create contact tracing applications that use Bluetooth Low Energy (BLE) wireless radio signals and cryptography. The framework is based on the Decentralized Privacy-Preserving Proximity Tracing (DP-3T) protocol. Devices generate a daily key to generate an ephemeral identifier in every message, encrypted using AES-CTR and HMAC-SHA256. Devices in proximity transmit BLE signals including the time, ephemeral id, and signal strength. The data for each transmission is stored in a list on each device. When users confirm a positive case with a health authority, they are given a code to enter in the app and upload their case and ephemeral id to the central server. Devices regularly download a list of all positive device identifiers from the server and compare them to their local list of stored ids to search for a contact. A contact pair is two devices that are deemed to have been within 1.5 meters for at least 15 minutes based on Bluetooth signal strength and timestamps, where one of the paired devices has tested positive. If a contact is found, the device indicates an exposure notification, which does not include who the contact was or when a transmission may have occurred. One issue with apps that use the system is that some people opt out or forget to input the code this into the app, which prevents contacts from being alerted.

Although technology exists for contact tracing, it is not perfect. Bluetooth requires main processors to be turned on and can quickly drain battery power unless apps are restricted to short listening periods. However, apps using the GAEN framework can interact directly with native smartphone operating systems to improve performance. Repurposing Bluetooth from its original communication function poses serious technical difficulties. At Trinity College in Dublin, researchers found Bluetooth can perform poorly when a phone is in the presence of reflective metal surfaces — in one experiment on a bus in Sweden, a mobile application built using the GAEN system did not trigger exposure notifications even though the phones were within 2 meters of each other for 15 minutes. In addition to false negatives, false positives occur commonly when noise causes signal strength to be much less than it is, indicating close proximity. Another problem is that Bluetooth Radiofrequency Electromagnetic Fields (RF EMFS) can pass through walls and surfaces, whereas viruses most likely do not. While GPS signals might solve this in some respects, they use device location and pose a major privacy issue. Additionally, GPS accuracy would most likely not be capable to determine distances between two phones at the scale of 1 to 2 meters, and do not work perfectly indoors. GPS, however, could be used in combination with Bluetooth to store the distance of every message transmission. Without location, GAEN has no way of indicating where transmission occurred, and public health officials could use this information to measure geospatial disease spread and concentration.

Beyond the technical challenges faced, all contact tracing apps suffer from the same general problem: unless a certain percentage of the population installs an app, it will not work effectively. People will not opt in unless they believe in the public-health strategy behind an app and in the personal advantages they can hope to gain from it, which poses a major challenge. Researchers at the University of Oxford modeled the coronavirus's spread through a simulated city of 1 million people and found that 60 percent adoption is needed to stop the pandemic and keep countries out of lockdown, although lower rates of adoption are still helpful. Most countries did not come close to this number. According to Abuhammad in a study of people in Jordan, 71.6% of people accepted to use COVID-19 contact tracing technology. However, the percentage of people who were using this technology was 37.8. The cause of this gap was discovered to be due to ethical concerns such as privacy, voluntariness, and beneficence of the data. Across the globe where using contract tracing apps is optional this appears to be the case. European countries such as Germany, which had some of the best results of any country in containing the virus, only reached about 40% adoption. The US did not reach 10% and only 22 states produced a DCT application.

The lack of downloads is strongly related to the privacy paradox. Americans say they are deeply concerned about privacy on the web and their cellphones, and do not trust Internet companies or the government to protect it. Yet they keep using the services and handing over their personal information. Additionally, people hold onto misinformed beliefs about contact tracing technology even after reading about how the app works and believe the app tracks location. As a result, no significant number of downloads occurred around the world. In

Singapore, where 80% downloaded a DCT application, only about 1% was infected and 31 people died, demonstrating the DCT potential when used in coordination with robust health systems.

An additional obstacle is that some people do not have smart phones. It is estimated that only 65% of the French population has smartphones. 80% of Americans have smart phones, but only 60% of the elderly have them. The elderly population is at greatest risk for infection but receives the least equity from DCT. Furthermore, people sometimes leave their phone at home or do not carry it on them. Metcalfe's Law shows that the number of unique possible connections in a network of n nodes is proportional to n^2. In a large society network, 20% of people not owning smart phones, and many people not downloading DCT applications can have profound negative effects on recording potential contacts.

Methodology

The potential technical project could involve designing and developing a DCT application based on the GAEN system. This prototype could be useful for states that do not have one in place, as only 22 states currently have them. A state's health system could be mocked, as well as the central server used in the DP-3T protocol. Furthermore, new techniques of data transmission and signal processing could be investigated to improve on the imperfect accuracy of Bluetooth technology.

Results and Discussion

Challenges with contact tracing can arise related to issues of medical privacy and confidentiality. Public health practitioners are usually mandated reporters, responsible for containing a disease within a population and for warning individuals of their exposure. At the same time, infected individuals have a right to medical confidentiality. Public health teams are obliged to disclose the minimal amount of details that can meet the goals of contact tracing — contacts are only informed that they have been exposed to an infection, and the source of the exposure is left unidentified. Additionally, some health providers believe that contact tracing may discourage people from seeking medical treatment for fear of loss of confidentiality, particularly in cases of sexually transmitted diseases. The goals of contact tracing must be balanced with the maintenance of trust and sensitivity to individual situations, although privacy puts a limit on effectiveness.

Tracking COVID-19 patients and contacts' activities with mobile applications introduces more privacy issues. Safeguarding privacy is the core concern of health systems, however, an individual's privacy has not been considered for some preliminary contact tracing applications. Some DCT applications impinge on people's privacy as they collect, analyze, and have access to personal health data such as health behavior, status, travelling history, household coordinates positions and location. DCT apps should instead enforce the privacy of data from contacts, snoopers, and third-party health agencies. Privacy concerns also present a major issue in increasing download percentages: The higher the perception that user privacy is protected, the more people will adopt a contact-tracing app, but stronger privacy protections place limits on the effectiveness of the tool in tracing the spread of the virus, thus slowing the spread of the app. Although it would be helpful if an app warned users that individuals with whom they were thinking of getting together with were infected, or was incorporated into social media, this would put risk at an individual's privacy.

The goal of the STS research was thus to investigate how a balance between privacy and adoption can be achieved, which can increase download percentages and effectively combat the next pandemic. From preliminary research, it appears that the GAEN framework enables iOS and Android applications to automate contact tracing, while limiting personal-identifiable data, and working directly with native hardware for BLE signaling and encryption. A major overlying issue, however, is that the companies who produce the smartphones most people use are not trusted by the public. Applications relying on Google and Apple, or even state health authorities who contract developers to make DCT applications on top of the GAEN framework, are met with skepticism. As a result of this, concerns about health privacy in general, and flaws in Bluetooth signaling technology itself, DCT applications failed to make a substantial impact on the COVID-19 pandemic.

Conclusion

When dealing with a deadly pandemic such as COVID-19, it is necessary to value both the lives of people and their privacy. In response to this ethical dilemma, Google and Apple released an Exposure Notification system that presents a secure method of implementing contact tracing applications, without collecting personal data or using location services. The protocol was designed to minimize data collection about users and ensuring anonymity, while successfully tracing and alerting people who may have been exposed to an infected individual. However, download rates of existing contact tracing applications demonstrate a problem, as they are far lower than Oxford University's estimated 60% for stopping the pandemic. More than half of the United States do not have contact tracing applications in place, presenting an additional issue. Before the next pandemic, it is necessary to perfect the underlying signal processing technology of DCT applications, establish robust health system infrastructure in every state, and most importantly get the public onboard using DCT applications.

References

[1]Y. Park et al., "Contact Tracing during Coronavirus Disease Outbreak, South Korea, 2020", Centers for Disease Control and Prevention, 2020. [Online]. Available: https://wwwnc.cdc.gov/eid/article/26/10/20-1315_article. [Accessed: 26- Oct- 2020].

[2]S. Jian, H. Cheng, X. Huang and D. Liu, "Contact tracing with digital assistance in Taiwan's COVID-19 outbreak response", International Journal of Infectious Diseases, 2020. Available: 10.1016/j.ijid.2020.09.1483.

[3]N. Ahmed *et al*., "A Survey of COVID-19 Contact Tracing Apps," in *IEEE Access*, vol. 8, pp. 134577-134601, 2020, doi: 10.1109/ACCESS.2020.3010226.

[4]E. Mbunge, "Integrating emerging technologies into COVID-19 contact tracing: Opportunities, challenges and pitfalls", Diabetes & Metabolic Syndrome: Clinical Research & Reviews, vol. 14, no. 6, pp. 1631-1636, 2020. Available: 10.1016/j.dsx.2020.08.029.

[5]J. Hsu, "The Dilemma of contact-tracing apps: Can this crucial technology be both effective and private?", IEEE Spectrum, vol. 57, no. 10, pp. 56-59, 2020. Available: 10.1109/mspec.2020.9205550.

[6]L. Garg, E. Chukwu, N. Nasser, C. Chakraborty and G. Garg, "Anonymity Preserving IoT-Based COVID-19 and Other Infectious Disease Contact Tracing Model", IEEE Access, vol. 8, pp. 159402-159414, 2020. Available: 10.1109/access.2020.3020513.

[7]S. Abuhammad, O. F. Khabour, and K. H. Alzoubi, "COVID-19 Contact-Tracing Technology: Acceptability and Ethical Issues of Use ," Patient Preference and Adherence, vol. Volume 14, pp. 1639–1647, 2020.

[8]H. Cho, D. Ippolito, and Y. W. Yu, “Contact tracing mobile apps for COVID-19: Privacy considerations and related trade-offs,” arXiv [cs.CR], 2020.

[9]"Contact tracing", En.wikipedia.org, 2020. [Online]. Available: https://en.wikipedia.org/wiki/Contact_tracing. [Accessed: 26- Oct- 2020].

[10]B. Roche, A. Garchitorena, J. F. Guégan, A. Arnal, D. Roiz, S. Morand, C. Zambrana-Torrelio, G. Suzán, and P. Daszak, “Was the COVID-19 pandemic avoidable? A call for a ‘solution-oriented’ approach in pathogen evolutionary ecology to prevent future outbreaks,” *Wiley Online Library*, 31-Aug-2020. [Online]. Available: https://onlinelibrary.wiley.com/doi/full/10.1111/ele.13586. [Accessed: 10-Apr-2021].

[11]M. C. Lu, “Perspective | Future pandemics can be prevented, but that'll rely on unprecedented global cooperation,” *The Washington Post*, 17-Apr-2020. [Online]. Available: https://www.washingtonpost.com/health/future-pandemics-can-be-prevented-but-thatll-rely-on-unprecedented-global-cooperation/2020/04/16/0caca7b8-7e6d-11ea-8013-1b6da0e4a2b7_story.html. [Accessed: 10-Apr-2021].

[12]M. Lu, X. Wang, H. Ye, H. Wang, S. Qiu, H. Zhang, Y. Liu, J. Luo, and J. Feng, “Does public fear that bats spread COVID-19 jeopardize bat conservation?,” *Biological conservation*, Feb-2021. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7837179/. [Accessed: 10-Apr-2021].

[13]N. Maani and S. Galea, “COVID-19 and Underinvestment in the Public Health Infrastructure of the United States: Milbank Quarterly,” *Milbank Memorial Fund*, 16-Jun-2020. [Online]. Available: https://www.milbank.org/quarterly/articles/covid-19-and-underinvestment-in-the-public-health-infrastructure-of-the-united-states/. [Accessed: 10-Apr-2021].

[14]R. Gunderman, “How smallpox devastated the Aztecs – and helped Spain conquer an American civilization 500 years ago,” *PBS*, 23-Feb-2019. [Online]. Available: https://www.pbs.org/newshour/science/how-smallpox-devastated-the-aztecs-and-helped-spain-conquer-an-american-civilization-500-years-ago. [Accessed: 10-Apr-2021].

[15]R. T. Corlett, R. B. Primack, V. Devictor, B. Maas, V. R. Goswami, A. E. Bates, L. P. Koh, T. J. Regan, R. Loyola, R. J. Pakeman, G. S. Cumming, A. Pidgeon, D. Johns, and R. Roth, “Impacts of the coronavirus pandemic on biodiversity conservation,” Biological conservation, Jun-2020. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7139249/. [Accessed: 10-Apr-2021].

[16]“CDC COVID Data Tracker,” Centers for Disease Control and Prevention. [Online]. Available: https://covid.cdc.gov/covid-data-tracker/?CDC_AA_refVal=https%3A%2F%2Fwww.cdc.gov%2Fcoronavirus%2F2019-ncov%2Fcases-updates%2Fcases-in-us.html#cases. [Accessed: 10-Apr-2021].

[17] T. M. Persons, CONTACT TRACING APPS. [Online]. Available: https://www.gao.gov/assets/710/708405.pdf. [Accessed: 16-Oct-2020].