Effectiveness of digital contact-tracing applications on COVID-19 pandemic

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ABSTRACT

Currently the entire globe is affected by the COVID-19 pandemic. The virus keeps spreading and governments tighten their safety measures. Many app designers have tried to develop an mobile application in order to execute contact tracing more efficiently. The World Health Organization recommends a combination of measures: rapid diagnosis and immediate isolation of cases. However, there are likely many cases of undetected SARS-CoV-2 infection. Several mobile applications have been proposed to the Dutch government, yet one fits the expectations. In this article, we explore the effectiveness of such contact-tracing apps and explain how to reach the highest possible effectiveness such applications.

CCS CONCEPTS

• **General and reference** → **Cross-computing tools and techniques**; *Verification*

KEYWORDS

ACM proceedings; SARS-CoV-2; Coronavirus; COVID-19; Effectiveness; Contact-tracing.

INTRODUCTION

The issue capturing global attention in the recent months is the COVID-19 pandemic, causing great disruption throughout the world in terms of health care and economy. Many governments have since the outbreak opted for an approach to combat the virus through limiting all social interactions within society (commonly referred to as a lockdown), putting a halt to the spread of the virus at the cost of national economy. In the long term, this approach is not sustainable. However, leading to the need to find ways to reduce restriction on social interaction in all aspects of society without losing grip of the spread of the virus. To this end, the Dutch government has suggested the nation-wide deployment of an application designed to predict/detect persons infected with the Coronavirus, Enabling them to accurately manage the virus' impact on society without the need for a dramatic type of lockdown. The need for such an app is still being questioned, since it brings a lot of difficulties with it, regarding the violation of the Dutch privacy legislation. In [10] is explained that we need a mobile contact-tracing app to urgently support health services to control the COVID-19 transmission, target interventions and keep people safe.

The focus of this article therefore lies solely with the effectiveness of such contact-tracing apps. The objectives of the article will be to determine through literary research what the relevant requirements are to the problem and what exactly the desired effectiveness of the application is in order to meet its requirements. Finally, the objective of practical research done thereafter will be to determine what type of implementation of the app satisfies the requirements set by the results from literary research.

In this article we present our insights on the effectiveness of digital contact-tracing applications in context of the COVID-19 pandemic. These insights lead to several recommendations on how to reach the highest possible effectiveness when discarding influenceable factors like privacy. The state-of-the-art applications' values will be reviewed together with the developers' views on their product. Simulation models will be analysed in order to compare and give structured critique on them to conclude what could be missing in these models. Together with knowledge gained from related works, the article will present a well-structured argument.

We expect the findings of the article to bring us a well-structured list on how to achieve the highest effectiveness of a digital contact-tracing application in context of the COVID-19 pandemic. The article contributes to (i) an understanding of optimal effectiveness for digital contact tracing apps and (ii) to the problem of designing a functional digital app in order to combat the COVID-19 pandemic.

RELATED WORKS

In order to give clear and reliable conclusions the findings need to be compared with already existing knowledge. We have gained knowledge on the following topics: effectiveness of contact-tracing; application of technology; simulation models and state-of-the-art mobile apps. This knowledge will help us focus on the critical aspects of the applications' effectiveness and create a well-structured view on what is necessary to reach this objective.

Effectiveness of contact-tracing applications

The effectiveness of contact-tracing has several coherent factors. The mobile application which will be launched should work properly to begin with. The app will therefore need to reach certain benchmarks.

One of these benchmarks is the app adoption rate [8] which the application will need to achieve. The adoption rate is the percentage of the population which is required to properly use the app in order to suppress the epidemic [11]. According to [12], if 70% of the population uses smartphones (assuming that there is no app use there for children aged under 10 and the fact that people aged over 70 have a low smartphone use), and epidemic like COVID-19 can be suppressed with 80% off all smartphone users using the digital contact-tracing app, which is equal to 56% of the total population. Contact-tracing using smartphones can be beneficial even with a partial adoption among the population [12]. In order to contain the spread, the adoption rate should at least be higher than 60% [8]. The developers of DCTS [9] think this percentage must be even higher, the DCTS (Digital Contact Tracing System) needs a broad acceptance among the population, which would be more than 70% in order to have an impact.

Whenever an person has been in contact with an infected individual, the application will send a message to the possible infected individual about the situation [9]. This message should bring insights to the user and provide it of clear advice and instructions. In order for this method to be as effective as possible, a psychologist should be consulted about the exact wording and information of the notification, in order to achieve the desired effect [9]. This should highly increase the probability of the user succeeding in what the notification tells them, which is crucial for reducing the spread of the virus.

When looking at the effectiveness of contact tracing, the latent period (the time interval between when an individual is infected by a pathogen and when he or she becomes capable of infecting other susceptible individuals [13]) needs to be taken into account. According to [14], whenever the detection time of an infected person is fixed, a too large latent period (larger than the detection time) results in a situation where every infected person is detected before transmitting the infection, so tracing need not prevent any transmission. Effectiveness may therefore be very sensitive to the latent period, especially with little variation [14]. The sensitivity may be large in the case of single-step tracing [10, 15, 16]. This could be solved in means by introducing a variable detection time [14]. The DCTS [9] proposes to apply second order tracing. The DCTS is being evaluated together with intervention strategies, and these results are being crosschecked using both deterministic and Monte Carlo based approach models [17]. Based on these models, applying only first order contact tracing might not be enough. Therefore, [9] wants to enable both first and second order tracing. "Tracing second order contacts increases significantly the number of traced potentially infected people. If every direct and indirect contact stayed in quarantine, a huge percentage of the population would be affected" [9].

Because the digital contact tracing applications are often installed on the user's mobile phone, there occur several limitations [8]. Errors may occur due to the assumption that the distance can be estimated from the measured attenuation. Smartphones might share certain hardware components. Next to that, the smartphone might not be carried on the body, it could be stored in a purse, or left in the car.

Application of technology

The main focus of a digital contact-tracing application is tracing the user and collecting data on contacts within the social distancing barriers. There are several technical possibilities in order to realise this, which will be discussed. Which approach is best applicable for the highest effectiveness and what are the possible limitations?

Contact tracing requires the device on which the application is installed to track the user's location, or at least, detecting every individual contact with another user. Several solutions have been proposed. Solutions included Wi-Fi MAC address sniffing [20], GPS [8, 9, 20, 21, 22], cellular network geolocating [23, 24] and using mobile network data [9]. Due to the fact that it is supposed to work indoors as properly as outdoors, these solutions are not reliable [9]. Many believe that Bluetooth tracing is the most suitable and has also been demonstrated effective for proximity detection [4, 18]. Because Bluetooth has an effective range of round 25 metres, the use of signal strength can identify whenever another device is within the 2-metre rule according to social distancing measurements [4, 18, 25]. Therefore, many papers [1, 2, 3, 4, 5, 6, 7, 8, 9, 18, 19, 20] propose the use of Bluetooth for proximity detection.

The use of Bluetooth can be split up in two main methods. Several papers propose the use of Bluetooth BR/EDR [1, 2, 3, 18] whereas others propose the use of Bluetooth Low Energy (BLE) [4, 5, 6, 7, 8, 9, 19]. BLE seems to take the upper hand because of its benefits. BLE should make sure that the battery is drained by no more than 5% by performing contact tracing, and that in a situation with 100 devices in close range [9]. The probability of the devices detecting each other successfully within 10 seconds is close to 100% [9]. In its essence, BLE is designed for continuously scanning the background [8],

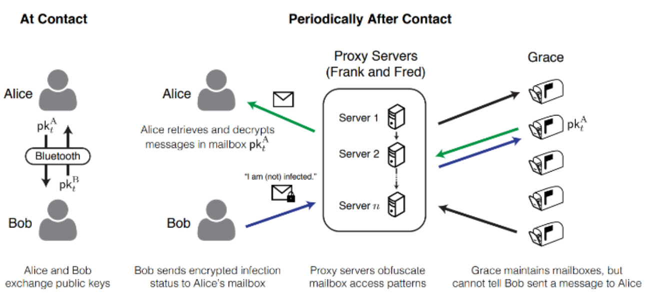

Figure 1: Overview of contact tracing based on private messaging systems. When Alice and Bob are near each other they exchange public keys as tokens. They then periodically encrypt (using each other's public key, followed by the public keys of the proxy servers) a message indicating their infection status, and send it to the proxy server. They also periodically query the proxy server for messages posted to the mailboxes corresponding to their public keys to find out whether they have been exposed to the virus [1].

TraceTogether [1] is currently the best possible example of a working digital contact-tracing application. It makes use of Bluetooth BR/EDR and shares decryption keys whenever a nearby device is located. This key will be able to decrypt an encrypted message about their infection status. Before such a message is sent, it is first delivered at the proxy servers (see Fig. 1), which is to improve the privacy of the user. This message is then send to the person who he or she has been in contact with. The individuals who receive a message are able to decrypt the message by using the key they receive earlier and are able to view the infection status of the other anonymous individual. In this case, the proxy server is added in order for preserve the privacy of the infected individuals from the government (see Fig.1).

In [9], the authors propose the Digital Contact Tracing Service (DCTS). The DCTS is based on the phones emitting and scanning for Bluetooth signals, and thereby exchanging so called Temporary Contact Tokens (TCNs) [9]. The approach uses BLE, mainly because of its continuous scanning in the background. The DCTS will activate BLE and generates a key, which it uses to generate a random TCN, the token which will be given to nearby phones. The TCN will be continuously advertised for other phones, however it will be updated after a certain amount of time to prevent re-identification [9]. When a device spots another device's advertised TCN, it will be stored and phones will exchange their tokens. Whenever an user is confirmed infected, he or she is able to upload the advertised TCNs and keys to a server. This server collects all newly uploaded TCNs. When a match occurs with a TCN on the server and a stored TCN on your device, the users will receive a notification. In order to compare the TCNs on the server with the locally stored TCNs on the device, the database from the server can be downloaded (see Fig. 2). In order for the DCTS to allow second order tracing [9], the user who gets notified because they have been in contact with an infected individual also uploads their TCNs on the server.

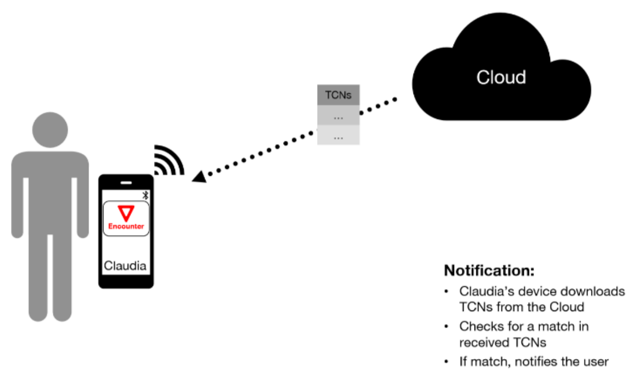

Figure 2: Overview of checking encounters. Every device can check its recorded TCNs against the reported TCNs on the server. If a device finds a match, it notifies the user [9].

The DCTS makes use of a decentralised approach [9], in order to lower the risk of re-identification of affected persons. In a decentralised approach, the personal data collected through the app is stored locally with the user. In a centralised approach, the personal data is controlled by the government authority [28]. There is a strong growing trend globally, and especially in Europe, which shows that the decentralised approach would be preferable [27, 28].

Bluetooth however does have several limitations. When situated in a crowded scenario where multiple phones are present, the application will use larger delays than specified in the BLE approach, which will lead to six times the energy consumption [8]. The device might need to run other Bluetooth related tasks, like wireless headphones, in parallel. Because the device can only carry out one task at a time, Bluetooth scheduling is needed [8], which limits the continuous transmission of beacons. Also when sitting on the couch while using a mobile device, the signal may reach through the walls at which the couch is located, whenever another device is in reach of the Bluetooth signal on the other side of the wall, it will identify the situation as if the individuals carrying the devices have been in close contact with each other. However, this is not correct.

Simulation models

A simulation model is one of the methods that is commonly used in Operational Research. Operational research (OR) deals with the application of advanced analytic models to help make better decisions. A simulation model represents the real situation that occurs in a system and tests multiple scenarios based on different behaviour [32]. Simulation models can be useful to obtain more of an understanding about a current system by testing scenarios using specific software tools [32]. It can be seen as an incorporating time that reflects to any changes that occurs over time [32].

Because of the COVID-19 pandemic, the government has to come up with a set of policies to contain the virus. Multiple simulation models are used to see what effect certain policies have on society. The mobile contact-tracing app is one of these policies which can be tested with the simulation models.

The ASSOCC model (Agent-based Social Simulation for the COVID-19 Crisis), is a simulation model that has specifically been designed and implemented by European researchers from Umeå University, TU Delft, Malmö University, Utrecht University, Caen University and Stockholm University to address the societal challenges of the COVID-19 pandemic [29]. This model studies the individual and social reactions to containment policies and it is a tool that can be used by decision makers (such as the government) to explore the different scenarios with their effects. The ASSOCC model does not generate predictions, however, it simulates the behaviour of a synthetic population given a set of policies (for example the contact-tracing app) [29]. The model enables to study the possible effects on the spread of the virus, how people can be expected to react to the policies and the socio-economic effects of the policies [29]. ASSOCC is built in NetLogo, which is a multi-agent programmable modelling environment [33]. It is based on a set of artificial individuals which each have a set of given needs, attitude towards regulations and risks, and demographic characters [29]. Each artificial individuals decides at each time what they should be doing. These decisions are based on the individual's profile, state and social, psychological and physical needs [29]. An action is selected by an individual by first making a list of all possible places it can go to with different motivations, which is called an action [29]. It then calculates the global expected effects on the needs of these actions and it lastly selects the action which satisfies the highest number of needs [29].

The ASSOCC model has looked at the effects of implementing the contact-tracing app policy into society. In this scenario, a perfect app aligned with all functional, legal and ethical requirements is assumed [30]. The effectiveness of such an app was researched by performing three experiments. First, the effect of the app depending on different percentages of population (0%, 60%, 80% or 100%) using the app was studied. According to the ASSOCC model, using the app does result in a lower infection peak, however, these differences are not significant and increasement of app users results in a sharp increasement of needed testing [30].

Next, the effect of using the app was compared with random studied of a percentage (0% or 20%) of the population. According to the ASSOCC model, random testing raised the awareness of infection, even when the artificial individuals had no reason to suspect infection and is more effective than the app [30].

Third, The effect of the app depending on the percentage of risk avoiding individuals that use the app (0%, 30% or 60%) was studied. According to the ASSOCC model, the effects of risk averse people were not significantly visible [30].

It can be concluded from the model that the effectiveness of contact-tracing apps on lowering the rate of infected individuals is limited and lower than that of random testing and that the app makes no significant contribution to the spread of the virus [30].

The Dutch government based their decision of implementing a contact-tracing app on the COVID-19 agent-based model (ABM) with instantaneous contact tracing. It was developed to simulate the spread of COVID-19 in a city, and to analyse the effect of passive and active policies [34]. The demographics of this model are based upon UK national data for 2018 from the Office of National Statistics [34]. The ABM model is based on a set of artificial individuals which are categorized into nine age groups by decade. Each individual is part of a structural and transient network and is part of a household, which is an important part of their daily activities. Every day, each individual interacts with a random subset of their connections and has random connections. The status of the infector, the susceptibility of the infected person to infection according to age and the type of interaction determine the rate of transmission of the virus [34].

The active policy of digital contact-tracing was studied in this model. When contact-tracing, a random number of interactions is assigned to the model. The usage of the app is just as the model age-dependent. According to the ABM, contact tracing is vital to control the spread of COVID-19 for infections with high levels of pre-symptomatic transmission [34]. The ABM allows to explore this policy and its effects and contains the option for recursive tracing of contacts of contacts [34].

Both the ASSOCC model and the ABM are agent based simulations. This means they are able to handle with the uncertainty and variability of the system [29]. Both models are however constructed differently, which leads to different results of the effectiveness of a contact-tracing app. In this paper, these two models are analysed and compared to each other to give advice about the effectiveness of contact-tracing apps.

State-of-the-art mobile apps

3 RESULTS AND DISCUSSION

Technology application

For contact tracing, solutions such as WiFi MAC address sniffing, GPS, and cellular network geolocating have hall been proposed. However, the most suitable for use in CTA is often believed to be Bluetooth tracing. Many point to the effectiveness for proximity detection, that has already been demonstrated [4, 18]. They also claim that while Bluetooth has an effective range of around 25-30 metres, signal strength can be used to effectively identify whether another device is within the 1,5-metre rule promoted as a component of social distancing [38].

However, the original Bluetooth BR/EDR protocol, while it was designed for primarily "pairing" phones with other devices such as computers, Bluetooth speakers, or keyboards for the purpose of data communication, it was a non-time sensitive process. It was not designed to have a reliable and sustainable contact tracing, as what currently is looked into as a solution for this pandemic. In the traditional pairing process, if the pairing is not successful then the user has to reset one of the devices and try again. This manual intervention is not sustainable in the context of contact tracing, where two or more phones are always expected to "pair" reliably.

In comparison, the Bluetooth Low Energy (BLE) protocol, has been designed for continuously scanning in the background and is therefore the main choice for proximity tracing on smartphones. The main reason why contact tracing apps choose for continual transmission and listening instead of continuous is energy [8]. The energy costs would be higher when using continuous transmission and listening.

There is however a problem that arises with the use of BLE. It can namely travel through a wall, just like any other Bluetooth signal. Even though the more objects there are in between the devices, the less overall range a device will have [37], it can lead to some troubling scenarios.

One of these scenarios is tracing through your neighbour's wall. Imagine your neighbour, who you do not come in contact with, tests positive for the virus. Both phones, yours and theirs, connect with each other via Bluetooth through the wall (false-positive contact detection), it can lead to possible quarantine for you, even though you have not come in contact with each other. This leads to some problems especially in heavily populated areas, such as in cities and apartment complexes.

One solution that we propose, would be the use of sound or sonar technology in combination with this BLE. While the BLE detects the phones at a continuous pace, the sound application could act as a safe switch to check whether there is an object such as a wall in between both phones. SONAR-X [26] claims to be more accurate than BLE due to less false-positives. Their technology could be combined with the reliability of BLE and lead to an even more reliable solution.

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