Methods and Directions of Contact Tracing in Epidemic Discovery

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***Abstract*—The contact tracing process is a mitigation and monitoring strategy that aims to capture infectious diseases to control their outbreak in a practical time. Various applications have been proposed and developed contact tracing process; most of these applications utilize the smartphone technologies to record all movements of contacts and send notifications to the expected infected ones, either high-risk or low-risk. On the other side, several challenges limit the functionality of contact tracing applications and processes; these limitations include (1) privacy concerns, (2) lack to fully identify contacts, and (3) delays in identification. In this paper, we survey the functionality of the contact tracing process, how its works, open directions and challenges, applications, and its domain of use.**

***Keywords*—Contact tracing; routes analysis; epidemic discovery; big spatial health applications**

I. Introduction

In December 2019, the would witness an unprecedented outbreak disease struck Wuhan's city, China [1]. This mysterious disease reveals itself to the globe as Coronavirus disease 2019 (COVID-19). This contagious disease dramatically spread and affected millions of people world wide [2]. This threat leads the World Health Organization (WHO) to trigger an international emergency warning to this unprecedented virus [3]. At the time of writing this paper, WHO reported that the number of people lost their lives is over 500 thousand, and over 10 million others are still struggling and fighting for their survival. This virus is extremely infectious, where it can easily pass from person to person. Hence, to cope with the coronavirus's spread, authorities around the world implemented lockdown measures for months. However, these measurements have significantly affected global economic and social activity.

Governments started to find alternatives to ease the socio-economic catastrophes, the authorities have gradually started to partially left the lockdowns. However, they are still struggling to find efficient techniques to monitor the mobility of potentially COVID-19 infected patients and who have been in contact with a virus infected person. Since people in close contact with someone who is infected with the virus are at higher risk of becoming infected themselves, and of potentially further infecting others, closely monitoring these contacts can prevent further transmission of the virus. This process of this monitoring is known as contact tracing.

The contact tracing process is a mitigation and monitoring strategy that aims to capture infectious diseases to control their outbreak in adequate time. The contact tracing process's main objective is to prevent the onward transmission of infectious diseases by examining the infected individuals and then identifying and examining each individual's contacts. Contacts are defined as all individuals who made direct physical connections to the infected ones; thus, all next-generation suspected cases will be controlled. Various applications have been proposed and developed to serve this process, the majority of these applications utilize the smartphone technologies to record all contacts mobility and send notifications to the expected infected ones, either high-risk or low-risk. On the other side, several challenges limit the functionality of contact tracing applications and processes. These limitations include (1) privacy concerns, (2) lack to fully identify contacts, and (3) delays in identification.

In this paper, we survey the functionality of the contact tracing process, its mechanisms, open directions, challenges, applications, and its domain of use. The survey reviews an extensive collection of models adopted based on the contact tracing process output and serves this domain. Mainly, the contribution of this paper is presenting an integrated view of the contact tracing process as a whole, which will help the researchers understand the functions of the process, identify the challenges and open issues, and inspire them to develop new applications, methods, and models in this domain.

The articles mentioned in the survey have been carefully collected to reflect the impact of applying contact tracing in controlling the spread of epidemics. The main keywords in the search have been formalized to select articles that focus on the definition of contact tracing, the applications of contact tracing in epidemics, the usage of contact tracing to developing statistical models that can predict the spread of the epidemic, and the technologies of contact tracing. These keywords include contact tracing, epidemics, Covid-19, infectious diseases, and epidemic models. The targeted articles have been published between 2003 and 2020. Also, publishers with high reputation have been targeted, such as IEEE, Springer, BMC, and journals of medical internet research (JMIR).

The rest of the paper is organized as follows. Section II presents the standard definitions of contact tracing according to different perspectives. Section III highlights the importance of contact tracing and main applications that use contact tracing. Section V tries to shed the new directions of contact tracing and the main challenges that face these directions. Section VI presents the typical models that have proposed to simulate the outbreak of epidemics and the impact contact tracing in preventing the spread of epidemics.

II. Definition of Contact Tracing

This section explores several definitions of the contact tracing process and highlights the different functions that must exist in this process.

In [4], authors define the COVID-19 contact tracing as the process that controls and manages the prevention of the onward transmission of COVID-19 disease by accurately determine and evaluate individuals that had direct physical contact with COVID-19 patient during the past period.

In [5], the authors define the contact tracing process, as the strategies that ensure and confirm the monitoring and controlling of the infectious disease. In [6], [7] authors define the contact tracing process is the process of following and capturing the course of infectious disease, this process starts from investigating the diagnosed cases that confirm their infection to all other individuals that were in physical contact with the patients in the recent past. In [8], authors define contact tracing as an essential procedure needed to fight the outbreak of infectious diseases; like the COVID-19 epidemic.

In [9], the authors define the contact tracing as a process of following up with the contacts that recently reacts with infected people physically. Also, the authors considered the contact tracing process as a mitigation methodology to controls the spread of infectious diseases by identifying, examining, and taking precautions the next-generation cases in a timely fashion.

In [10], the authors define the contact tracing process as a robust disease control strategy that contains and controls the disease by preventing and reducing the disease from transmissions from individual to another. In this regard, this strategy is working by following up infected cases reported, and suspected ones, then isolate them. In addition to, tracing all contacts that come into close physical contacts with theses cases; either infected or suspected. Fig. 1 presents the contact tracing process. This process traces all contacts that deal with an infected patient. Then, the process categorizes these contacts into two categories: (1) infected and (2) not infected. After that, the infected patients are classified into two categories: (1) high-risk contacts; which are contacts that are exposed to death and need special care, and (2) low-risk contacts.

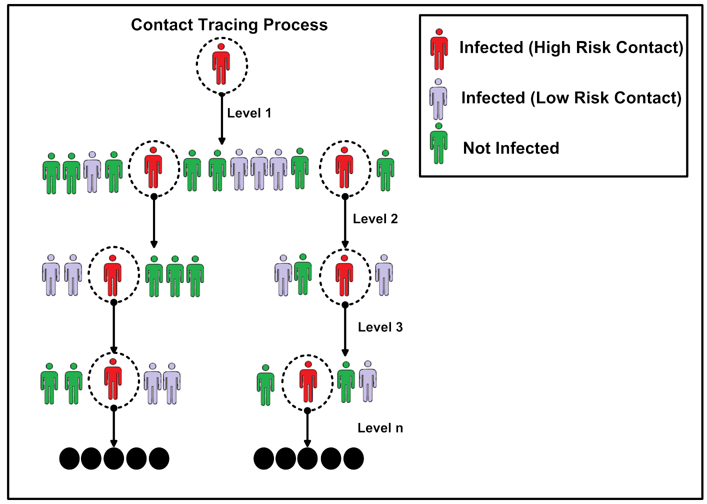

Fig. 1. Contact Tracing Process

III. Importance and Applicability

This section presents the importance of contact tracing in preventing the spread of epidemics and recent applications of this technique.

Authors in [11], [12], [13] explore various methods for contact tracing including pairwise-approximation and fully random simulations methods to tackle and investigate the infected and suspicious cases. Therefore, these methods start by examining the network of contacts that belongs to the infected and suspicious cases. Particularly, This research focus on the significance of studying well the disease-transmission pathways for each person and how to model the contact tracing approaches accurately based on disease-transmission pathways information. In the end, results show that there is a strong relationship between the accuracy of modeling the contact tracing and reproductive ratio of the disease by alert and deal with the infected and suspicious cases by either immediate treatment or isolation.

In [4], the authors highlight and investigate community surveillance roles and guidelines to reduce and prevent the spread of COVID-19 disease. Besides, the authors study how to apply the contact tracing and quarantine for COVID-19. Overall, the spread of COVID-19 disease from individual to another through nasal or oral spray or exhalation or cough of COVID-19 infectious persons. The authors mentioned the importance and criticality of contact and this for performing the quarantine in a good manner and timely fashion. Additionally, the authors classified the contacts that deal with a COVID-19 infectious human into two categories: (1) high-risk contacts, and (2) low-risk contacts. The high-risk contacts are persons that made direct physical contact with COVID-19 infected person or live with the with COVID-19 infected person in the same house. The lower cases are persons that are with COVID-19 infected persons in the same workplace or same environment or travel with the patient through any means of transportation such as; train or bus. Furthermore, the authors highlight the significance of quarantine to prevent and limit the spread of COVID-19 disease, quarantine is the process that restricts the movement of individuals that deal with COVID-19 patients in the past period. The quarantine duration of the COVID-19 identified by the World Health Organization is 28 days. Finally, the authors mentioned challenges that limit the contact tracing process in general. These challenges include: (1) the tracing difficulty of contacts who are traveled via bus or train or any other means of transportation, (2) the inability to track and remember all contacts that deal with COVID-19 patient in the last 14 days, (3) it is difficult to track and find all people that directly contact the COVID-19 patient, particularly if the patient visited wide gatherings like marriage or religious gatherings or market, and (4) the common fear between the health care staff to trace contacts, as they are thinking they will become infected.

In [14], the authors studied the Ebola virus and concluded that the virus is transmitted from individual to another via physical interaction with the infected patients such as body fluids. Additionally, authors in [15], introduced a study that investigates the Ebola virus contact tracing process, this study aims to perform surveillance for persons that were in exposure for infected patients during 21 days. For this purpose, in [9], the authors propose and develop an Ebola transmission model that adopted contact tracing. This model investigates the perfect timing for contact tracing actions to be done. Also, the authors differentiate the contact tracing delays into three types: (1) initiation delays, (2) contact identification delays, and (3) hospitalization delays. Results showed that quick contact identification and hospitalization can lead to decreasing the spread of the epidemic to 50% compared to delayed identification. In this regard, the authors concluded that starting the contact tracing process at an early stage is a must.

In [16], [17], the authors shed light on using social networking sites (SNS) for contact tracing activities. Additionally, the authors ask the official health sectors and specialized authorities to adopt SNS for controlling and monitoring the evolution of diseases. The authors pay the attention for using SNS because SNS is considered as a significant source of data and knowledge, also the growing popularity of these sites and enriching on several easy portable devices such as; smartphones and tablets, this will provide great opportunities for health sectors to perform the contact tracing in a well-manner.

Mainly, the contact tracing process depends on studying well the contacts network of proximity interactions between persons during the Epidemic period spread. Several attempts have been done to obtain the knowledge of these physical interactions to be investigated. For example in [18], authors get a large scale Facebook data of the interaction between individuals, authors investigate this data to clarify and present the disease dynamics in the community. Additionally, in [19] authors employ wireless sensors to capture face-to-face interactions. In [20], authors describe these attempts as a costly and resources used can be not available or limited to be owned for the majority of people. For this purpose, authors a model for contact tracing based on a mobile phone, and describe the mobile phone as a powerful tool to capture communication traces for the contacts with the proximity interactions. Authors conclude that effective contact tracing can significantly reduce the impact of the Embedic outbreak. Moreover, the contact tracing becomes more effective at the beginning of the Embedic outbreak because the number of contacts that need to be traced is much less than contacts need to be traced after the Embedic evolution. Finally, the authors mentioned that the use of mobile phones to trace contacts can be a valuable option to stop the Embedic outbreak.

In [21], the authors purpose two models for reducing the spread of HIV, these models consider the stochastic screening and contact tracing strategies, these models include (1) differential infection model (DI), and (2) staged-progression model (SP). Overall, the DI model focuses on the individuals' differences during the disease transmission, while the SP model focuses on more on the time differences for the same infected person. The authors define the stochastic screening and contact tracing as intervention strategies to fight the spread of disease transmission. In this study, the authors formulate various formulas to generate reproductive numbers and identify the equilibrium points during the embedic outbreak. Then, the results produced from either the stochastic screening or the contact tracing are compared in both models. Results showed that in the DI model, the contact tracing strategies are powerfully effective tools to determine and bound the superspreaders of the diseases, and therefore this can assist in reducing the final size of the embedic. This feedback is also consistent with the feedback provided in the following studies [22], [23], [24], [25]. On the other side, the authors highlight that in the SP model the stochastic screening is more effective and has a large effect than contact tracing in limiting and slowing the spread of the disease. Finally, the authors conclude that the effectiveness of the intervention strategies can be determined mainly by the underlying reasons for disease transmission.

In [26], [27] authors presents that due to the incubation long period of Ebola virus, which is 11 days, a massive number can come to physical contacts with infected case and the spread of the disease will grow rapidly. For this purpose, in [10], the authors propose a model that incorporates the contact tracing for prediction and monitoring the reproduction rates for Ebola infection diseases. The purposed model considers various control scenarios, to perform a perfect analysis for Ebola disease characteristics and investigates how these characteristics affect on the effectiveness of the contact tracing process to control the Ebola outbreak. These characteristics include: (1) Ebola disease characteristics, (2) surveillance protocols for infected and suspected cases, (3) reporting time of the infected cases, (4) epidemic incubation period, and (5) intervention time to handle reported cases. Additionally, the authors purpose formula to highlights the critical cases from contacts that are traced to obtain reproduction number (R_e) less than one. The formula is as follows: $R_e = k\frac{1-q}{q} + k_m$, where k represents the count of infected contacts that determined in the second iteration per un-traced contacts identified in the first phase, k_m represents the count of infected contacts that determined in the second iteration per traced contacts identified in first phase, $\frac{1-q}{q}$ is the odds that probabilities that the reported contact is not traced. To conclude, R_e production number represents the observation of reported cases per number of contacts traced (observed cases/total number of contacts traced).

Table I summarizes the main papers with their purposes and description in this direction.

IV. Domains of Use and Applications

This section presents the importance of contact tracing in preventing the spread of epidemics and recent applications of this technique.

To construct an effective contact tracing application that can identify contacts of infected individuals, the system should be loaded over handheld devices. Mobile phones are used by most people, so developing a mobile application for individuals will enable authorities to effectively identify contacts. Fig.

TABLE I. Importance and Applicability (Summary)

Paper	Rational	Information Sources	Study Selection	Keywords	Year
Contact tracing and disease control	introduced methods for contact tracing including pairwise approximation and fully random simulations methods	Sexual relationships in Manitoba, Canada that contain sexual partnerships between 82 connected individuals together with the presence of chlamydia and gonorrhea infection (A model to predict the spread)	Importance and applicability of Contact racing	tracing efficiency; transmission networks; pairwise approximations; stochastic simulation	2003
Modeling the impact of random screening and contact tracing in reducing the spread of HIV	Purposed two models for reducing the spread of HIV, these models consider the stochastic screening and contact tracing strategies, these models include (1) differential infection model (DI), and (2) staged-progression model (SP)	Synthetic dataset	Importance and applicability of Contact racing	AIDS; Mathematical modeling; Epidemic modeling; Screening; Contact tracing; Reproductive number; Endemic equilibrium; Sensitivity	2003
A high resolution human contact network for infectious disease transmission	Employed wireless sensors to capture face-to-face interactions	US 2009 absentee data because of the influenza (H1N1). The dataset covers CPIs of 94% of the entire school population, representing 655 students, 73 teachers, 55 staff, and 5 other persons, and it contains 2,148,991 unique close proximity records	Importance and applicability of Contact racing	disease dynamics; network topology; public health; human interactions	2010
Dynamics and control of diseases in networks with community structure	Investigated a large-scale Facebook data to clarify and present the disease dynamics in the community	Synthetic dataset	Importance and applicability of Contact racing	dynamics of infectious diseases spread; immunization interventions	2010
1) Social Networking Sites as a Tool for Contact Tracing: Urge for Ethical Framework for Normative Guidance. 2) Using Social Networking Sites for Communicable Disease Control: Innovative Contact Tracing or Breach of Confidentiality?	Investigated using social networking sites (SNS) for contact tracing activities to control and monitor the evolution of diseases.	None	Importance and applicability of Contact racing	disease control and surveillance; Social media applications	2013
Modeling contact tracing in outbreaks with application to Ebola	Proposed a model that incorporates the contact tracing for prediction and monitoring the reproduction rates for Ebola infection diseases.	Data collected from the West Africa (Sierra Leone and Guinea) Ebola outbreak	Importance and applicability of Contact racing	Contact tracing; Ebola; Epidemiology; Mathematical modeling	2015
Quantifying the impact of early-stage contact tracing on controlling Ebola diffusion	Developed an Ebola transmission model that adopted contact tracing. This model investigates the perfect timing for contact tracing actions to be done	Synthetic dataset (A model to predict the spread)	Importance and applicability of Contact racing	Contact tracing; Ebola; activity-driven network; compartmental model; epidemic model	2018
Contact Tracing and Quarantine for Covid 19: Challenges in community surveillance	Highlighted and investigated community surveillance roles and 109 guidelines to reduce and prevent the spread of COVID-19 disease	None	Importance and applicability of Contact racing	Quarantine; Contact Tracing	2020

2 shows an example of an effective framework that uses an application loaded over individuals' mobile phones. An individual mobile application can automatically connects with another application in case they are in a specific distance. This can identify the contacts of each individual. The application sends these data to the server to store such data. In case an individual is identified as infected with Covid-19, the contacts of this person will be notified to isolate themselves and to have medical attention. Also, the systems gives the statistics of the spread of Covid-19 for decision makers to decide whether to force quarantine, isolation, or lock-down for specific regions, identified by the application.

On 20-March-2020, the government of Singapore published an application named TraceTogether which uses Bluetooth to track and trace contacts. The TraceTogether application works when two users who use the application are nearby, and a user alerts that he is a COVID-19 patient, the application starts to notify the Ministry of Health to identify the network of contacts logged to be near to them. Additionally, the application communicates with those contacts and reports them with the proper follow-up actions [28].

In [29], the authors utilize the power of smartphone application technology and develop a novel peer-to-peer smartphone application that performs the contact tracing process effectively. The authors sheds the light on the significance of the contact tracing as it is an essential process that restricts the transmission of COVID-19 pandemic. The main objective behind this study is developing a smartphone application that performs the contact tracing and similarly preserves user privacy by not collecting any personal information or any location data. The method adopted in this study that performs contact tracing with preserving the privacy mainly depends on a novel data structure named transmission graph, which consists of nodes and edges, the nodes represent the contact points between the persons, while the edges represent the transmission vectors between contact points. Specifically, each contact point is represented by a node and captures the physical interaction between two or more persons at a particular time and location. Finally, the transmission graph has created a network of interactions between persons and preserves user privacy at the same time.

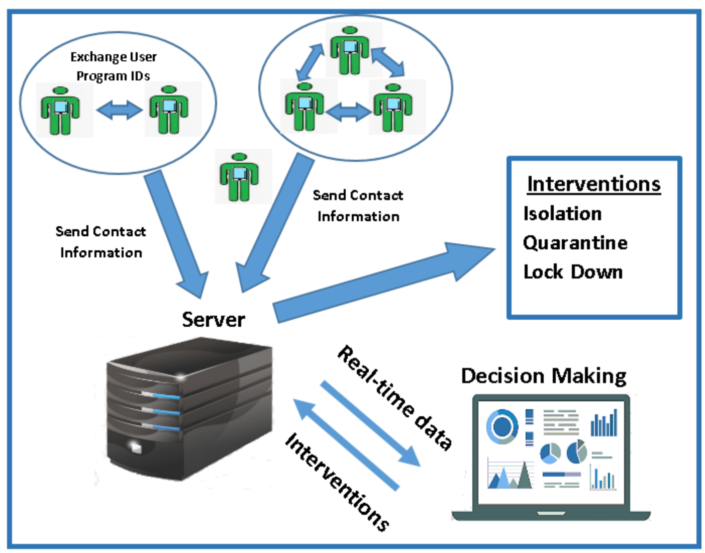

Fig. 2. A Depiction of Contact Tracing Framework based on Real-Time Monitoring of Individuals

In [30], [6], the authors describe several procedures for performing the contact tracing process. These procedures include (1) first-order tracing, (2) single-step contact tracing, (3) iterative contact tracing, and (3) retrospective contact tracing. The first order tracing procedure identifies the individuals that make an immediate direct physical connection with the patient, these individuals require self-isolation and specific medical care handle. Furthermore, the first order tracing procedure does not care about tracing the contacts of the contacts and leave this to happen in the next step "second-order" after the first order has been done successfully. The single-step contact tracing procedure identifies all individuals that contact with the confirmed infected person, and all these individuals are considered as infected, also their contacts are identified and the procedure continues. The Iterative contact tracing procedure, this procedure performs diagnostic tests for all individuals in an iterative way, these tests include symptom screening, and the purpose of this is to discover the infection before its occurrence. The last type is retrospective contact tracing procedure, it follows the same steps of the single-step or iterative procedures, additionally, it investigates the recent past of the infected person and operates in a reverse way to identify all individuals that the patient makes a contact with them. The retrospective contact tracing procedure aims to identify who was the infected person by the disease.

The Australian government has released an application named COVIDSafe. This application aims to control the spread of COVID-19 epidemic, by communication with the expected individuals who are exposures for the infection. the application notifies these individuals and alerts them to take all required immediate precautions [31], [32].

The following studies[5], [29], [33] summarized that the effectiveness of the contact tracing approaches must consider the following: (1) contacts identification, (2) contact notifications, (3) utilizing mobile applications technology for performing automatic contact recording of the movements and direct physical communications, and (4) narrowcast communication via messages.

During the period between 2014 and 2016, the Ebola virus disease (EVD) outbreak has a dangerous effect on the following countries in Africa; such as Liberia, Guinea, and Sierra Leone. As a result, 28,000 cases are reported as infected and above 11,000 deaths as per the study introduced in [34]. In [35], authors developed a smart-phone application named Ebola Contact Tracing application (ECT app), to monitor and trace infected individuals by Ebola in Sierra Leone. This application is integrated with an alert system to report symptomatic individuals and their districts to the response center.

This study [36], discusses how contact tracing is employed by the Liberian authorities to prevent the spread of Ebola during (2014-2015). They uses the official reports of number of cases, provided by the counties, to evaluate the efficiency of the method. Authors build a model that classified the cases into: potential cases to represent cases that had previous symptoms, recovered or died, and Positive Predictive Value (PPV) to represent traced contacts. It applies their analysis over 25,830 contact tracing records of suspected cases during the period from June 4, 2014 to July 13, 2015. These cases represent 26.7% of total EVD cases. Contact tracing showed its ability to detect 3.6% of new cases during its operational time.

Authors in [37] study the spread of the severe acute respiratory syndrome *(SARS)* in Hong Kong in 2003. The authors apply contact tracing over index-cases that have been in hospitals based on questionnaires. Nurses run these questionnaires to identify contacts of index-cases to inform them to isolate themselves and to have medical care. Also, the questionnaires were used to identify the transmission paths to index-cases. Analyzing the questionnaire results allows the authorities to cluster index-cases using multiple criteria, such as demographic (housing and working locations), age (friends and schools), and workplaces. These data allow the authorities to locate the hot-spots to quarantine them and to prevent the spread of the epidemic.

Authors provide a case study analysis for the spread of the Severe Acute Respiratory Syndrome CoronaVirus 2 (SARS-CoV-2) in Wuhan, China. The paper analyzes a dataset of patients in the Shenzhen provenance to identify the efficacy of applying the contact tracing in preventing the spread of the epidemic. The study focuses on applying the contact tracing to detect transmission paths and prevent new infections. The Shenzhen Center for Disease Control and Prevention (CDC) applies contact tracing to track the contacts of infected individuals. Results shows that the prediction of new cases based on contact tracing was very similar to those cases found through traditional surveillance and from hospital records [38].

In [39], the authors provide a study for different non-pharmaceutical interventions (NPI) to mitigate and suppress the spread of Covid-19 epidemic. They classifies the NPIs into two classes: mitigation and suppression interventions. The mitigation interventions aim to reduce the need of healthcare system by protecting people from severe infection. The mitigation interventions include: isolation, quarantine, and social distancing. The suppression aims to minimize the number of new cases and keeps that situation for a long time. Examples of the suppression interventions are: school and university closure and social distancing for long time. The authors provide a study for the impact of each NPI on the spread of Covid-19 and the impact of combining multiple interventions. The authors conduct the study over data collected from China, United Kingdom, and United States. Results show that combining multiple interventions can have a substantial impact in preventing the spread of the epidemic. These interventions affect the economy of the countries on both short and long terms, so countries should choose carefully the suitable NPIs for them.

A. Sexual Disease Monitoring

The Human Immunodeficiency Virus (HIV) is a serious virus that damages the immune system. It damages and kills the CD4 cells, which makes the patient body vulnerable to get infected with different infections and cancers. The HIV can be transmitted thou rough body fluids, such as blood, semen, breast milk, and rectal fluids [40]. The early detection of the HIV gives a higher probability of patients to get treated.

Dennis et al. [40] propose an integration between contact tracing and phylogenetics to control the spread of HIV in North Carolina (NC). They initiate a routine public screening test for HIV. These tests allow the authorities to identify individuals with acute HIV infection (AHI) [41]. After identifying the infected individuals, they will be investigated to construct networks of suspicious individuals to identify transmission paths and warn infected contacts to get medical care. This enables the authorities to control the outbreak of the epidemic. Contact tracing enables the authorities to construct a spatiotemporal clustering of infected individuals, which resulted into identifying the increase of AHI among Men that had sex with Men in two regions in NC.

Lin et al. [42] proposed another application of contact tracing in controlling the spread of sexual diseases. They employ contact tracing to identify infected individuals with HIV in Taizhou Prefecture, Zhejiang Province in China. They study collected the data in the period (2008–2010). Data were gathered from volunteers that were subjected to the HIV test. Individuals that have HIV-positive are subjected to surveys to construct a network about their contacts using surveys. The study enables the authorities to identify 463 new HIV-infected cases. The contact tracing starts with 398 as index-cases to construct their network using surveys. Tracking the 398 index-cases results into tracking 1,403 sexual contacts. The early identification of HIV-infected individuals enables the authorities to inform suspicious individuals to have medical care, which decrease the number of late diagnosis that may acquire immunodeficiency syndrome (AIDS).

B. Social Networking

In [43], the authors discuss how to construct an efficient model that can simulate the dynamics of an epidemic spread in large social contact networks (SCN)s. Large SCNs need huge computation capability to run the simulation algorithms. The authors proposed applying parallel models to simulate huge SCNs to get results in an affordable time. The authors use the high performance computing clusters to run their model in parallel. Running algorithms in parallel needs the SCN to be partitioned. The main problem of SCNs is the distribution skew in these networks as there are some nodes, which are connected to multiple nodes (hubs) and normal nodes connected to a small number of nodes. To partition the hubs, the authors propose splitting the hubs (malls and metros) into fixed splits to run the algorithm over each split in parallel. Also, they propose partitioning the agents (visitors) to mimic the dynamics of the network. The authors test their method over multiple datasets and result show the efficiency of the method.

In [44] the authors propose constructing a model that can simulate the spread of an epidemic. They focus on the social networks of contacts and how can an epidemic propagate in such networks. They consider the heterogeneity of social networks and do not give the same probability to all social network members to get infected at the beginning of the epidemic. They consider the “crowding” or “protection effect” in their model. They develop an Infected-Susceptible-Infected-Recovered (ISIR) model to simulate the spread of an epidemic. Results show that only networks with multiple links have high probability to get infected. Also, they evaluate four immunization strategies and find that the high-degree set and critical set immunization strategies are the best techniques to prevent the spread of the epidemic.

Mainly, to ensure that all contact tracing applications working effectively, they must pass through four stages. Fig. 3 summarize these stages.

The next section describes the new directions of applying contact tracing and the challenges that faces these directions.

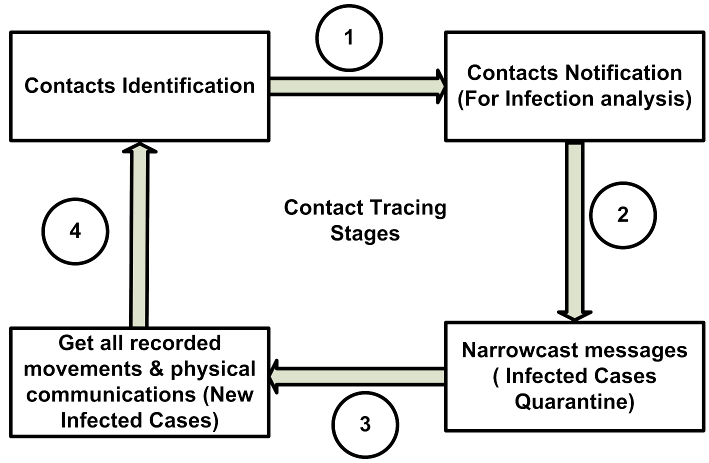

Fig. 3. Contact Tracing Stages

V. Open Directions and Challenges

This section highlights the main challenges of applying contact tracing for real-life applications.

In [8], the authors highlight the privacy concerns as the constraints that limit the functionality of contact tracing applications, and they analyze the implications of these concerns and discussed the ways of improvements. The authors summarized the privacy concerns as following: (1) protection of contacts privacy form the snoopers, (2) ensuring the privacy from contacts, and (3) ensuring the privacy from authorities.

The authors in [45], [46], [47], discussed as classified the challenges in contact tracing process as follows: (1) Inability to fully identify contacts, (2) the lack in reporting systems that adopted on papers, (3) incomplete contact lists, (4) inefficiencies in data collection, (5) transcription errors during the early-stage of the contact tracing, specifically during the contact’s identification, and (6) delays in identification and isolation of the suspected individuals from these contacts.

In [48], the authors highlight some challenges that face the contact tracing process such as; the need to involve large labor to trace the contacts efficiently and accurately. For example, (1) the Canadian Health Sector opens the door for a volunteer workforce to perform the tasks of contact tracing and other relevant tasks [49], (2) In South Korea, the governments employed a huge number of medical staff and other workers at the peak of COVID-19 disease outbreak to trace contacts and controls this epidemic [50].

In [51], the authors classify the individual contact tracing methods into two categories: static and dynamic contact tracing methods. Fig. 4 shows a categorization of contact tracing devices according to contact tracing methods. The authors consider that static individual contact tracing to include: questionnaires and surveys. Although these methods have been effective in dealing with sexual diseases [52], [52], they have certain drawbacks that can be summarized into: (1) not giving an online assessment of the epidemic spread, (2) need of labor force (3) time consuming, (4) need to find contacts one by one. Online versions of these methods, such as online questionnaires and online surveys have been proposed to provide an online assessment of the spread of an epidemic [53], [54],

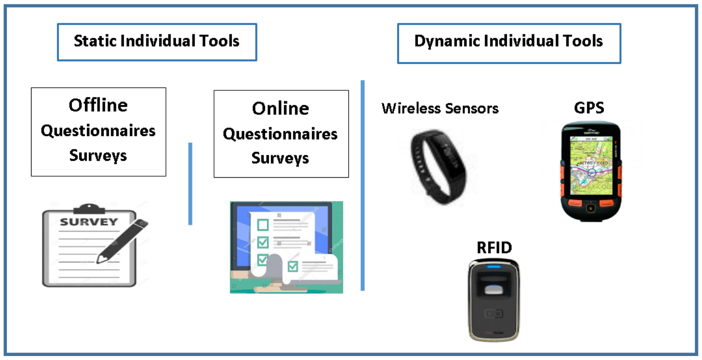

Fig. 4. Categorization of Devices used in Contact Tracing

[55]. Despite of their advantages, the authors consider that the online methods still do not give a real-time information for decision makers and users sometimes fill them with incorrect information [56]. Considering the dynamic contact tracing methods, the authors focus on mobile applications, wireless sensors, and GPS [57], [58], [59], [60], [61], [62], [63]. They identify different challenges of these methods. Considering mobile applications, the battery of mobiles represent a great challenge as it has a limited life-time. The wearable sensors are expensive to track a huge number of people and participants do not like to wear them because of privacy issues. The Radio Frequency Identification Devices (RFID)s have a limited range for sending and receiving data. Even the Global Positioning Systems (GPS) devices have limitations as they are not effective to be used in closed areas, such as schools and universities [51].

VI. Models

This section discusses how researchers can construct models that can describe the spread of epidemics and the impact of applying contact tracing in limiting the outbreak of epidemics.

Models are developed to predict the spread of epidemics, they can be classified into two categories: deterministic and stochastic models [64]. The deterministic model is formulated as a system of differential equations, which generates the same solution each time in case the conditions and parameters' values are the same. The main advantage of deterministic models is their ability to show how the initial conditions can affect over the behavior of the model. A stochastic model can be constructed based on differential equations. It has at least one probabilistic parameter, which makes the output changes each time the model is run [64].

In [65], the authors introduce conceptual models to simulate the outbreak of COVID-19 in Wuhan, these models consider the reaction of human behaviors and actions needed from the governments. The objective of these models is to distinguish and understand the future trends of the outbreak and predict the future ratio. Finally, these models can catch the COVID-19 paths and logged all anticipated future trends of the outbreak. The authors use important information about the COVID-19 to build the model correctly. These information include incubation time, time from onset to discharge from hospital or die. Fig. 5 shows the important stages of each person when he gets an infection until he becomes non-infectious again.

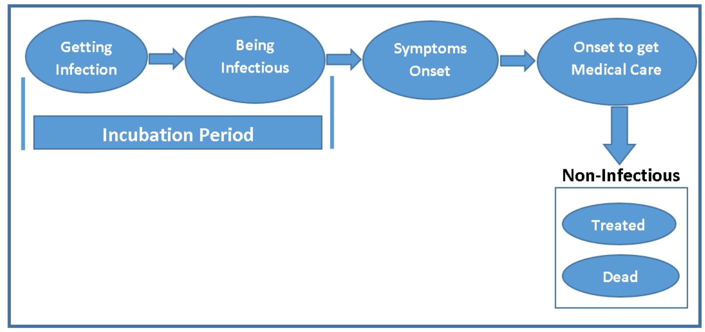

Fig. 5. Infection Progress of Covid-19

In [66], the authors propose an epidemiological model that depicts reality. This objective of this model is to describe and control the evolution of the diseases and predict individuals with high-risk exposures. The authors admit that the leverage of this model lies in generating the prediction results within a short time and how this will be useful in emergency response systems.

In [67], the authors propose an epidemiological model named "Susceptible-Infectious-Recovered-Dead (SIDR)" model, this model is designed to monitor the evolution of COVID-19 epidemic. The monitoring of the COVID-19 epidemic outbreak is done by providing and predicting the following estimates: (1) estimates about infection cases, (2) estimates about mortality, (3) estimates about recovery rates, and (4) estimates about basic reproduction number. These estimates are generated daily. The objective behind this model is to expect the outbreak evolution of the COVID-19 epidemic three weeks ahead before it happens.

In [30], the authors investigate how the effectiveness of contact tracing can limit the evolution of infectious diseases. The authors investigate a contact tracing model that is appropriate for most infections. Several cases are investigated using this model and result concluded that: (1) the variability of detection time leads to an effective contact tracing, and (2) the iterative tracing can increase the effectiveness, and (3) in general, there is no specific formula to predict the proportion that will be traced.

In [68], the authors focus on constructing a stochastic network-based simulator that can predict the spread of the Covid-19 epidemic. They develop the simulator based on the data gathered from Republic of Kazakhstan, taken as case study. The simulator is based on Susceptible-Exposed-Infectious-Recovered (SEIR) model to represent the transition of individuals among different infection states. To verify the efficacy of the model, authors run the simulator over data collected form Lombardy (Italy). Different parameters have been tuned and the simulator was helpful in predicting the duration and number of infected individuals during the spread of the epidemic.

In [69], the authors develop a stochastic model based on the susceptible-infectious-removed to discuss the effect of applying contact tracing to mitigate the spread of the epidemic.

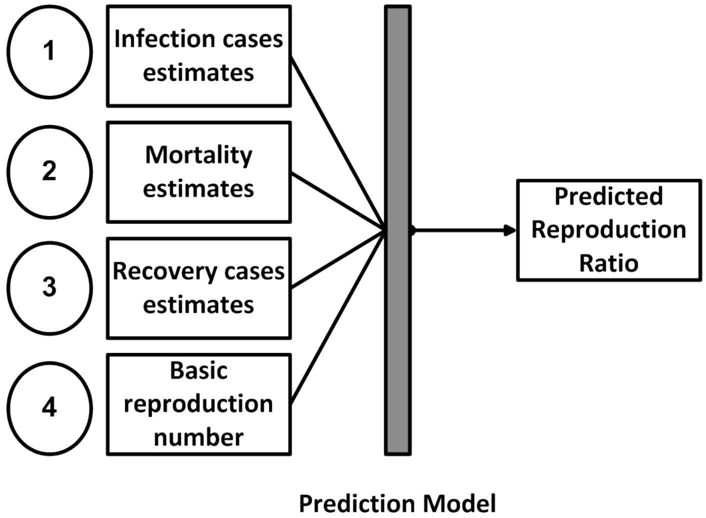

Fig. 6. Prediction Models (Reproduction Ratio)

They represent the spread of the epidemic in social networks with a graph. This facilitates the task of contact tracing in identifying new suspicious individuals. The model shows the effectiveness of contact tracing in stopping the exponential growth of the epidemic, especially in medium states. Also, the model shows the effectiveness of random screening of individuals in limiting the spread of the epidemic.

In [70], the authors provide a statistical model to evaluate the severity of Covid-19 based on the data collected from Wuhan, Hubei. The data was collected from national and provincial health commissions in Wuhan. They extend their work by including the data of 37 countries to study the fatality of Covid-19 in these countries. The data has been used to provide an estimation for important characteristics of the epidemic, such as time from onset to death or to discharge from hospital, and case fatality ratio. The model applies first over the data collected from China, then the model is applied over the data gathered from other countries. Results shows that the estimations generated from model were very similar to real data collected from the authorities in China and other countries.

In [64], the authors focus on developing a stochastic susceptible-infected-recovered (SIR) model that combines contact tracing to analyze the effect of contact tracing in controlling the spread of epidemics. The methods used the tree structure to simulate the spread of the epidemic. The authors derive equations that can describe the spread of the epidemic and the effect of the intervention tools over the spread rate. These equations are then applied over non-tree contact graphs.

In [71], the authors present an analysis of different models, proposed to simulate the spread of two epidemics: SARS and Middle East Respiratory Syndrome (MERS). The authors defines and discusses the important parameters that can affect on the efficiency of the models, such as the basic reproduction number, incubation period, latent period and infectious period. Also, they extend their work to study the effect of the intervention techniques in mitigating or stopping the spread of the epidemic, such as quarantine, isolation, and contact tracing.

Basically, the output of the contact tracing process includes the following: (1) infection cases, (2) mortality cases, and (3) recovery cases. These outputs can be considered as an input for any prediction model that anticipates the reproduction ratio of the infection. Fig. 6 concludes inputs and outputs for prediction models that try to predict the production ratio of infection.

VII. Conclusion

The contact tracing process is a mitigation and monitoring strategy that aims to capture infectious diseases to control their outbreak in adequate time. In this paper, we reviewed various applications developed contact tracing process, discussed in great detail the challenges that limit contact tracing applications, such as privacy concerns, lack of identifying contacts, and delays in identification fully. In this survey, we have shown how researchers can construct models that can describe the spread of epidemics and the impact of applying contact tracing in limiting the outbreak of epidemics. Finally, We have surveyed and listed open directions, applications, and its domain of use.

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