Lockdown Exit Strategy: Use Big Data to Learn to Fight COVID-19

Insight-driven Leak-proof Risk-stratified Contact Tracing

Andy Zheng Ph.D.

Founder & CEO, Aspiring Citizens Cleantech

Adjunct Fellow, Lee Kuan Yew Centre for Innovative Cities

22 May 2020 (Version 2)

30 Apr 2020 (Version 1)

Executive Summary

With growing research evidence about substantial asymptomatic (and pre-symptomatic) transmissions of COVID-19, epidemic control measures with current manual contact tracing procedure faces serious challenges in speed, scale, and completeness to break the infection chains. Searching for promising lockdown exit strategy and avoiding intermittent lockdowns, nations are recognizing the importance of digital contact tracing to tackle the source of the problems: the virus spread.

Our proposed contact tracing solution addresses some key missing pieces in our current pandemic response. First, data collection via QR code scanning labels each transmission context (type and location of venue), which is key for accuracy (reduce false positives) of identifying close contacts, and for insights about transmissions in different contexts. Second, big data analytics stratifies risk levels of different groups of people (who is more likely to be infected or spread virus widely), to guide targeted and resource-efficient pandemic response (such as mask wearing and viral testing measures). Third, the transmission contact tree analytics provides an accurate, rapid, complete, and systematic approach to reveal asymptomatic infections and reduce tracing leakages, tracing along the contact events from confirmed infection cases.

As a group of citizens, eager to contribute to the success of our united pandemic response, we are prepared to collaborate and provide our FluTrace analytics to health authorities for effective contact tracing, to address challenges from asymptomatic transmission in the contact network. PAIR FluTrace 1.0 has been deployed in taxis in 3 Chinese cities since 10 Feb 2020, monitored more than 1.5 million contact events, and provided instant result to contact tracing requests. As our approach of data collection relies on the QR code posted by business owners of public spaces, near-complete data collection effort is viable by leveraging on existing visitor registration practice in office premises and enforcing on the business owner side. We are glad to see that QR code contact tracing solutions, SafeEntry and PGCare, have been rolled out for most public indoor spaces recently.

We acknowledge and thank Dr Lim Chon Phung, Senior Advisor to Aspiring Citizens Cleantech, for his contribution to developing PAIR FluTrace and making the solution available in ASEAN. We also thank Poon King Wang, director at Lee Kuan Yew Centre for Innovative Cities, for his valuable feedback during drafting this report.

Table of Content

1. A Global Problem of Unprecedented Scale and Difficulty

Without vaccine in the near term, what would be our best hope for lockdown exit strategy? After city-wide lockdown substantially reduces the infection rates, how do cities keep the infection rates low when reopening economic activities[1]? Increasingly more nations[2] are recognizing the importance of digital contact tracing to tackle the source of the problems: the virus spread.

Singapore's pandemic response has been adjusting to new facts. Rising number of unlinked cases is an indicator of community spread; asymptomatic infection transmission requires mask wearing for both unwell and well residents. How can insight-driven leak-proof risk-stratified contact tracing provide the needed big data insights to guard our communities during reopening economic activities?

Unlinked cases, not linked to identified clusters or identified infected people[3], suggest that there are undetected infection sources in the community. These undetected infected people, likely due to delay and leakage in manual contact tracing, may transmit infection to more people, leaving it to luck for completely breaking the infection chains. Can we digitize contact tracing[4] to be less labor-intensive, more complete, and faster? Can we use risk-stratified contact tracing data to prioritize viral testing and mask wearing for more resource-efficient pandemic response? We can also apply targeted social distancing measures (denied access to crowded public spaces such as subway station) to different risk groups of people, so that our society keeps running efficiently while minimizing risk of large-size spread events.

Unlike SARS[5], COVID-19 is found to present asymptomatic (together with pre-symptomatic) infection transmission[6]. Becoming infectious before symptom onset makes symptom-based screening measures ineffective and makes mask-wearing by only unwell people inadequate. However, any infected person (node) has at least one contact event (link) with another infected person (a neighboring node) in the contact tree. Can we apply big data analytics to systematically locate, test, and isolate asymptomatic infection cases, tracing from any confirmed infection case? We can also use the contact event data to calculate the Incubation Period and infer the Latent Period, useful for fine-tuning contact tracing strategies.

Although the government has daily updates about confirmed infection cases, the public has little knowledge about the common and risky transmission contexts (the type and location of venues): the virus is transmitted via the suspended respiratory droplets[7] during direct contact or touching the same surface[8] during indirect contact. Can we process the context-labelled contact event data to inform the public for more targeted and resource-efficient prevention measures[9]? We can also use the traffic data per context to advise cleaning schedule.

Accurate, fast, complete, risk-stratified, and insightful contact tracing is a promising lockdown exit strategy to keep infection rates low, by locating, testing, and isolating layers of close contacts to an infected person. The public will collectively contribute to collecting anonymized data and benefit from generated data insights. If this insight-driven digital solution proves effective and well-supported in a global city, more nations may be encouraged to follow this evidence-based lockdown exit strategy to reopen the regional and global economies.

2. Snapshot of PAIR FluTrace Solution

PAIR FluTrace, an insight-driven leak-proof risk-stratified contact tracing data platform, **provides accurate, fast, complete, risk-stratified, and insightful contact tracing procedure**, for reducing tracing leakages due to asymptomatic patients in the infection transmission network, for stratifying different risk groups of people for resource-efficient epidemic control measures, and for learning about the frequency and risk of different contexts of infection transmission. Figure 2.1 highlights the conceptual model underlying PAIR FluTrace, similar to the instant digital contact tracing proposal in Figure 2.2.

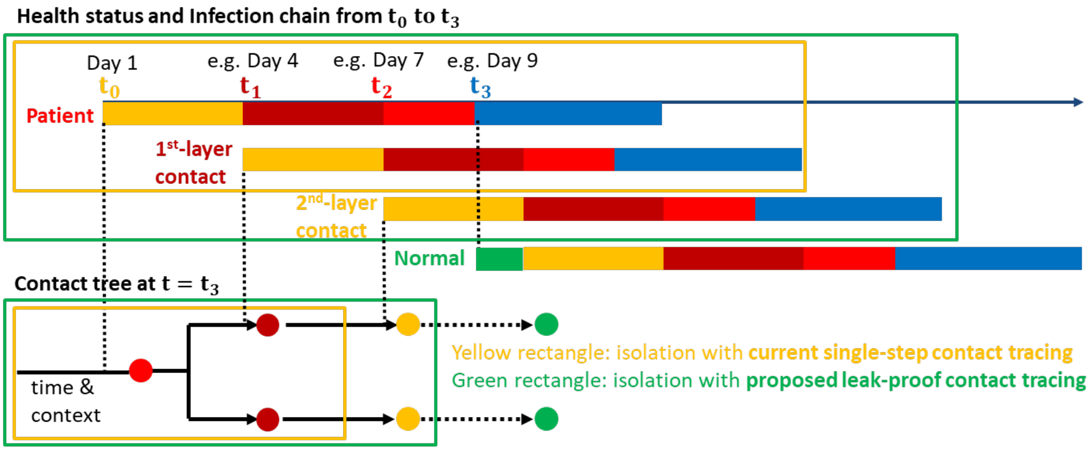
1. Insight about transmission context during contact event: Each line between two nodes in the contact tree (Figure 2.1) represents **a contact event** of pathogenic exposure. The data entry of each contact event contains uid + areaCode + contextType + contextId + timeStamp. To protect personal privacy, the contact event data of normal people (Green risk group) will be stored locally in the user's phone for 21 days or until the user is involved in an infection case; the contact event data is anonymized when stored in the cloud.

2. Leak-proof contact tracing: Assuming the existence of asymptomatic infection transmission, an infected person becoming infectious before symptom onset ($t_1 < t_2$, or x<1.0), **more than the 1st-layer contacts** are identified by PAIR FluTrace analytics to be isolated or stay home. To **reduce leakage (false negatives)** of infectious people in manual contact tracing, PAIR FluTrace analytics trace along the lines (contact events) to include all infected nodes (people) in the contact trees (green rectangular in Figure 2.1), breaking the infection chain and keeping the Reproduction Ratio below 1.0 for sustained epidemic suppression.

3. Systematic procedure to reveal asymptomatic infections: As long as an infected but asymptomatic person is **linked to a confirmed case**, the systematic and fast procedure of locating and testing close contacts in the contact tree will reveal such an asymptomatic patient, reducing **cross-branch tracing leakages** (branch C, D, and E in Figure 2.3).

4. Risk stratification of people for resource-efficient epidemic control measures: Risk stratification uses big data and machine learning models to assess among the close contacts: who are more likely to be infected before testing, and who spread virus more widely if infected. With asymptomatic infection transmission, the health status of an infected person (Figure 2.1) typically changes from susceptible (green) to infected but not infectious (yellow), to infectious without symptoms (dark red), to infectious with symptoms (light red) until being tested and isolated (blue). By the time (t_3) when a confirmed infection case (light red node in the contact tree) being tested and isolated, 1st-layer contacts (dark rede nodes) may have transmitted the infection to 2nd-layer contacts (yellow nodes), causing **downstream tracing leakages**. These 2nd-layer contacts may not be infectious yet, but would infect more people if left undetected. **Identifying all the risky contacts of an infected patient** is crucial to reduce downstream tracing leakages. **Risk stratification** of the contacts, with positive recall optimized according to testing capacity and prevalence, guides the pandemic response team to carry out targeted testing operations and other epidemic control measures, to efficiently mitigate infection risks in the community (Figure 2.4).

Figure 2.1: Contact tracing strategies for breaking infection transmission chain.



Timeline of health status:

$\mathbf{t_0}$ time of pathogenic exposure (contact event)

$\mathbf{t_1}$ time of becoming infectious; **Latent Period** = $\mathbf{t_1} - \mathbf{t_0} = \mathrm{xT}$

$\mathbf{t_2}$ time of symptom onset; **Incubation Period** = $\mathbf{t_2} - \mathbf{t_0} = \mathrm{T}$

$\mathbf{t_3}$ time of being tested & isolated; **Response Period** = $\mathbf{t_3} - \mathbf{t_2} = \mathrm{yT}$

Reproduction Ratio $\mathbf{R_0} = \mathrm{n}[(1 + \mathrm{y} - \mathrm{x})\mathrm{T}]\mathrm{p} = \mathbf{np(1 + y - x)T}$, target value to be **below 1.0**

Figure 2.2: Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing[10]

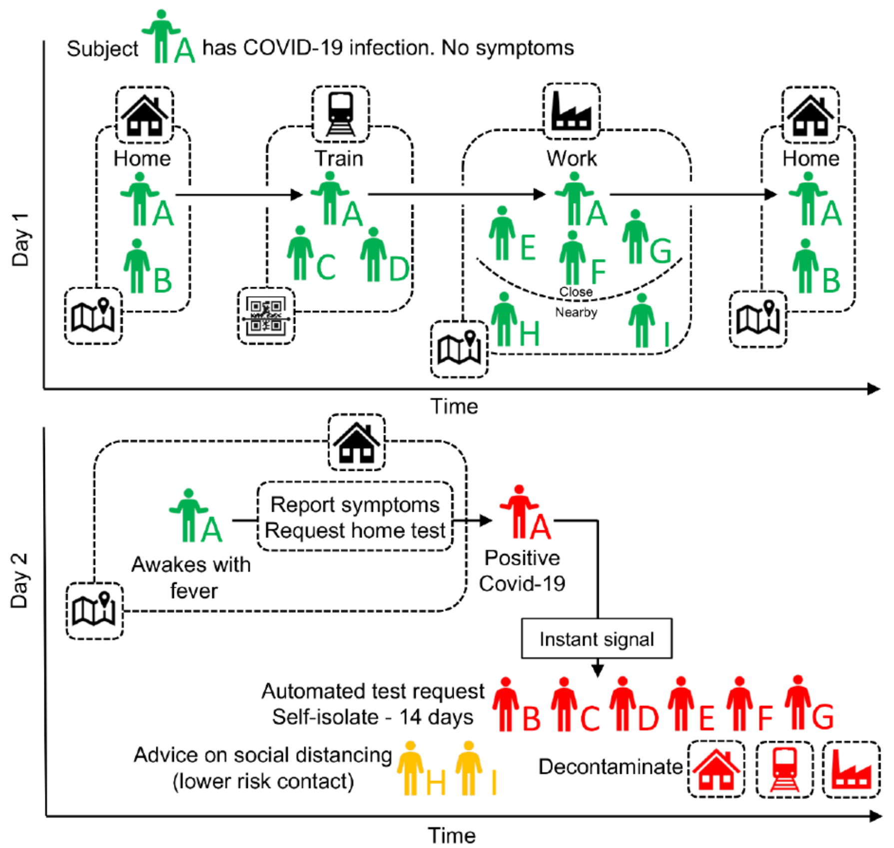


Fig. 4. A schematic of app-based COVID-19 contact tracing. Contacts of individual A (and all individuals using the app) are traced using GPS co-localisations with other App users, supplemented by scanning QR-codes displayed on high-traffic public amenities where GPS is too coarse. Individual A requests a SARS-COV-2 test (using the app) and their positive test result triggers an instant notification to individuals who have been in close contact. The App advises isolation for the case (individual A) and quarantine of their contacts.

Figure 2.3: Comparison of contact tracing effectiveness between SARS and COVID-19. Unlike SARS, COVID-19 is found to present asymptomatic (together with pre-symptomatic) infection transmission. Becoming infectious before symptom onset[11] (40% as estimated by US CDC) makes symptom-based screening measures ineffective, conventional contact tracing prone to cross-branch and downstream tracing leakages, and breaking infection chains challenging.

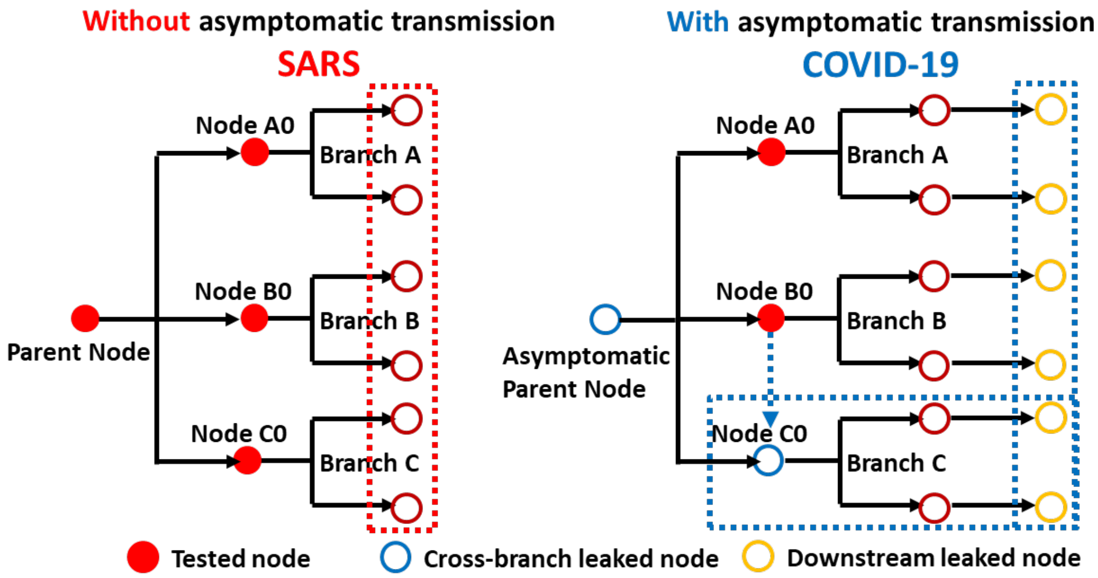
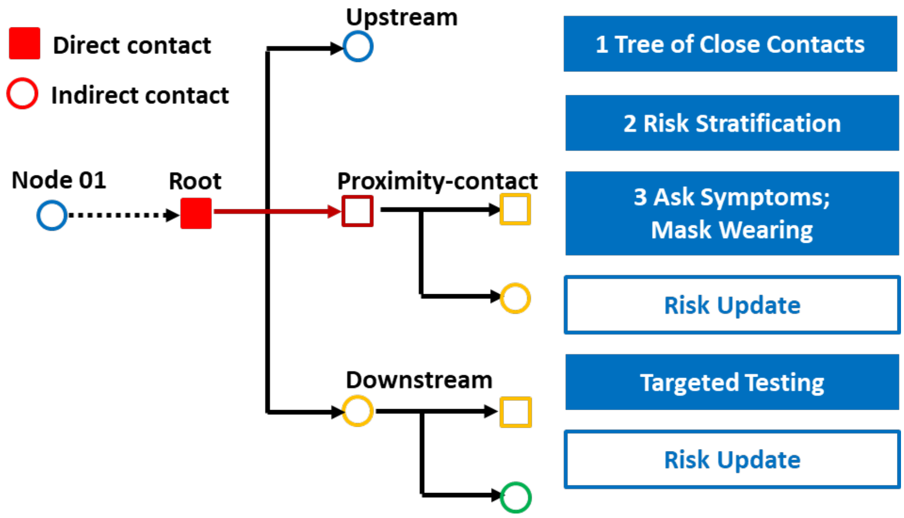


Figure 2.4: Infection risk mitigation workflow: Risk stratification, Symptoms check, & Targeted testing of close contacts. Bluetooth-based approach, TraceTogether, Apple, Google, only tracks proximity contacts.



3. Targeted Epidemic Control Measures for Different Risk Groups

More targeted epidemic control measures for different risk groups help our COVID-19 response to be resource-efficient on mask and viral testing kits, with the Yellow risk group being identified and ring-fenced from the currently healthy group of people.

Table 3.1: Targeted epidemic control measures for different risk groups[12].

Characteristics of infection	**Patient (RED)**	**1st-layer contact (RED)**	**2nd-layer contact (YELLOW)**	**Normal (GREEN)**	**Visitor (YELLOW)**
With asymptomatic transmission; $\frac{1+y}{x} \in [2,3)$	A + C B + D F1	A + C B + D E + F1	A + C B + (D) E + F2	A + C (B) F3	A + C B + D F1 + F3

Epidemic Control Measures:

A. Personal Hygiene (reduce p): Good personal hygiene helps reduce risk of infection p after contact event (pathogenic exposure), especially in the transmission context of touched surfaces during indirect contact.

B. Mask Wearing (reduce p): Mask wearing helps reduce airborne droplets from viral shedding of infected people via sneeze, cough, talk, and breathe[13]. Due to asymptomatic transmission, mask wearing needs to cover not only symptomatic people but also people with contacts with infected patients.

C. Temperature Screening: If the basic symptoms of an infectious person include fever, temperature screening is effective to locate and isolate potentially infectious person.

D. Fast Viral Testing (reduce y): Fast viral testing can test and isolate infected people as soon as possible, ideally reducing the Response Period to almost 0. Viral testing is especially effective if there is no asymptomatic transmission ($x \geq 1.0$). E.g. South Korea adopted viral testing for more than 0.5% of the population to reveal and isolate infected people and their close contacts.

E. Multi-layer Contact Tracing (Number of layers N = rounddown[$\frac{1+y}{x}$]): Contact tracing is used to guide isolation measures in containing the virus spread. Depending on the timeline of symptom development, effective contact tracing should ideally locate minimum number of layers in the contact tree to include the latest infected people, who are not yet infectious. When the Latent Period is short compared with the Incubation and Response Period, e.g. with $\frac{\text{Incubation Period+Response Period}}{\text{Latent Period}} = \frac{1+y}{x}$ larger than 2.0 as shown in Figure 2.1, conventional single-step contact tracing is leaky, missing 2nd-layer contacts due to possible asymptomatic transmission. Fast, complete, and multi-layer contact tracing may reduce the Reproduction Ratio after leakage to below 1.0.

F1. Isolation (reduce n): Confirmed infected people and their close contacts are isolated typically for two weeks to prevent them from transmitting the infection to more people.

F2. Lockdown/Stay-home (reduce n): If a member of a household needs to stay home, all members of the household need to stay home except for essential activities (e.g. grocery shopping). City-wide lockdown freezes social activities in attempt to reduce number of contacts per day n to almost 0. E.g. China applied lockdown measure in the city of Wuhan on 23 Jan 2020, and then in cities nationwide to slow down the virus spread[14].

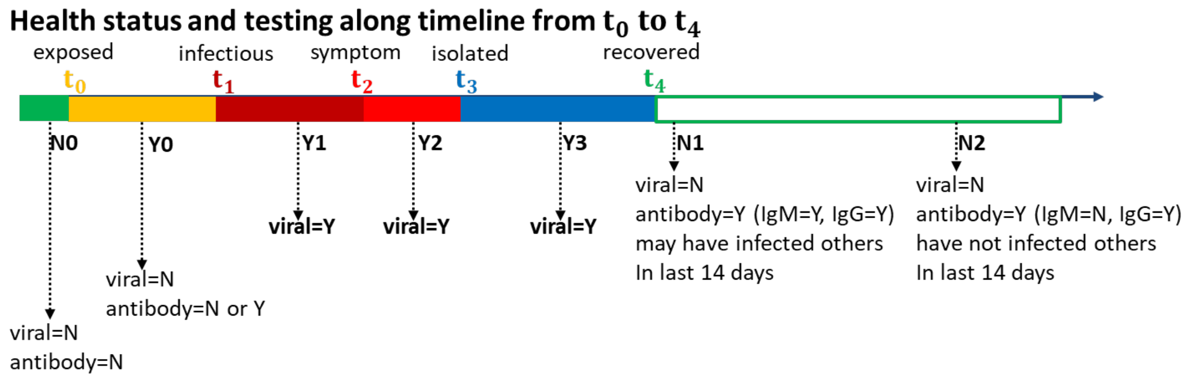
F3. Social Distancing (reduce n): Social distancing measures include keeping a minimum distance between each other in public space and limiting the size of gathering. They may also include denied access to public transport and high-traffic public spaces.

Resource-efficient mask wearing and viral testing:

PAIR FluTrace contact tree, based on contact event data, provides multiple layers of close contacts, suggesting different risks of infection and different stages in symptom development (Figure 2.1). Such risk stratification can prioritize the use of mask and viral testing kit for resource-efficient pandemic response.

For confirmed patient and 1st-layer contacts (Red risk group), they will be viral tested and isolated. For 2nd-layer contacts (Yellow risk group), they will be on watchlist for future symptoms (contacts who later develop symptoms are presumed positive before viral testing), observe stay-home notice, and must wear masks outside home premise. For normal people (Green risk group), they will observe social distancing rules and advised to wear masks (Green* risk group). For incoming visitors (Yellow risk group), they will first undergo viral testing and isolation, and then observe mask wearing and denied access to public transport and high-traffic public spaces during visit.

Figure 3.1: Anticipated result for viral and antibody testing along the timeline



Viral testing (RT-PCR test[15]) and Antibody testing (serological test[16]) are useful to test if someone is infectious or has been infected, respectively.

Automated symptoms self-reporting:

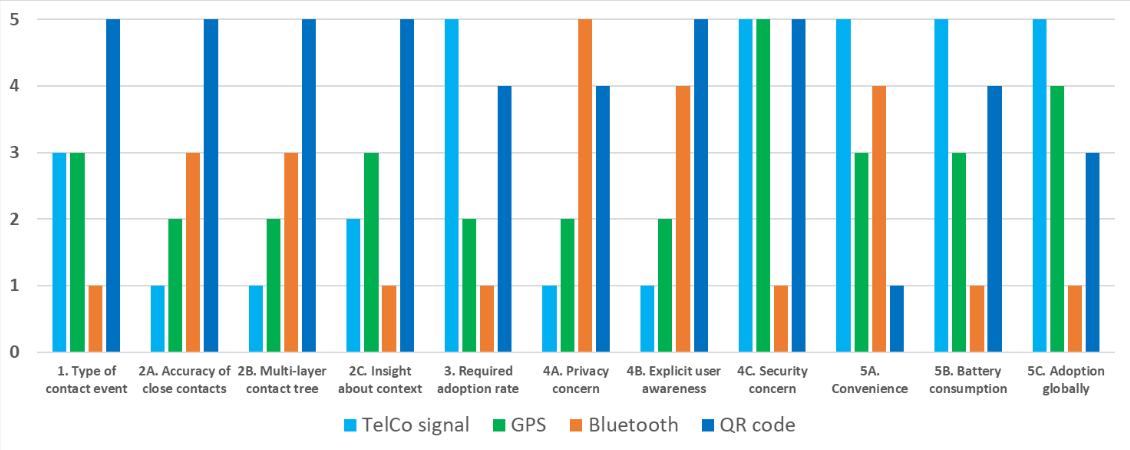
After the risk stratification process (Figure 2.4), a selected number of close contacts will be notified for self-reporting symptoms[17], including loss of taste & smell, persistent cough, chest pain, and fever. If the close contact has any of the 4 symptoms, the symptom onset date will also be self-reported. Together with GPS location, the crowdsourced symptom surveillance data can guide careful assessment of contexts near hot spots of symptomatic users.

Insight-driven targeted contact tracing:

If complete tracing of all contact events is not feasible, insight-driven approach focuses the data collection effort on high-frequency (n) and high-risk (p) transmission contexts. The digital tool can label each transmission context (location and type of venue) in data collection to assess frequency and risk of all monitored transmission contexts. Instead of high overall adoption as required by Bluetooth approach, high adoption rate of QR-code-based contact tracing for high-frequency and high-risk transmission contexts may also reduce the Reproduction Ratio after leakage to below 1.0.

4. Comparison of Tracing Technologies in High-Density Cities

Figure 4.1: Ranking of tracing technologies.



Key attributes of the technology:

Among the 11 attributes in 5 categories (each category with a weightage 3.0), Type of contact event, Accuracy of close contacts & Multi-layer contact tree & Insight about transmission context, and Required adoption rate are 3 most critical categories for accuracy and technical feasibility. The ranking of the 4 contact tracing technologies in favorability score is QR code[18] (64), TelCo signal[19] (50), GPS[20] (41), and then Bluetooth[21] (29). QR code is strong in accuracy, technical feasibility, and overall privacy protection. TelCo signal is strong in adoption and convenience. Bluetooth's security concern may override its strength in not recording location data. Refer to Table 4.1 for summary.

1. Type of contact event: It must include both direct contact, where two people are within close proximity, and indirect contact, where virus may be passed on by touching the contaminated surface.

2A. Accuracy of close contacts: Ranging precision from a building, a location, to a room leads to different accuracy of close contacts; higher precision reduces "false positive" close contacts.

2B. Multi-layer contact tree: With more accurate and smaller number of close contacts, it is more feasible to implement targeted measures to different risk groups according to multi-layer contact tree. Number of 2nd-layer contacts (N) is driven by the square of number of close contacts per day (n).

2C. Insight about context: Insight about infection transmission context (type and location of venues) can inform more targeted data collection effort and identification of close contacts.

3. Required adoption rate: High adoption rate from residents are key for avoiding leakage (false negatives) in contact tracing. QR code approach can be designed to leverage on existing practices of visitor register in commercial premises and cashless payment via QR code. Furthermore, traffic volume can be monitored per registered QR code, for enforcing business owner of public spaces to increase adoption rate in major venues. Based on peer-to-peer detection of close contacts, Bluetooth's contact tracing efficacy (e.g. >50%) is proportional to the square of adoption rate (e.g. >75%), and is only effective with high overall adoption rate.

4A. Privacy concern & 4B. Explicit user awareness: Privacy concern mainly involves personally identifiable location data. Bluetooth approach is best with peer-to-peer detection of human-to-human direct contact. QR code approach contains location data mostly in public space and QR code scanning action indicates user awareness of every entry of location data being collected. Encrypting and storing data in user's phone (for Green risk group) reduces privacy concern, which is computationally difficult for TelCo signal and GPS.

4C. Security concern: The Bluetooth vulnerability poses data security concerns to more sensitive personal data in the phone than the location data collected for contact tracing. QR code approach only uses camera to read parameters embedded in the QR code without visiting any webpage, posing no data security concerns. TelCo signal and GPS do not pose threat of unauthorized data exchange with the phone.

5A. Convenience & 5B. Battery consumption: TelCo signal does not need any user action. GPS and Bluetooth do not require further user action once the app and GPS (or Bluetooth) are turned on, with higher cost to phone battery. QR code is most inconvenient to users as scanning action is required during each contact event, with marginal cost to phone battery over the day.

5C. Adoption globally: TelCo signal, GPS, QR code, and Bluetooth approaches require increasingly expensive mobile phones. Printed QR code is substantially cheaper and easier to deploy than installing WiFi or Bluetooth detecting device.

Table 4.1: Comparison between different tracing technologies

	TelCo signal	**GPS**	**Bluetooth (Singapore BlueTrace)**	**QR code (PAIR FluTrace)**
1. Type of contact event	OK (direct & indirect contact)	OK (direct & indirect contact)	Worst (direct contact only)	Best (direct & indirect contact, context type)
2A. Accuracy of close contacts	Worst (poor resolution & no indoor positioning)	Bad (no indoor positioning)	OK (algorithm based on adoption rate, calibrated distance & arbitrary duration)	Best (based on context-specific & adjustable duration)
2B. Multi-layer contact tree	Worst (largest n)	Bad (large n)	OK (missing 1st-layer indirect contacts)	Best (small n)
2C. Insight about context	Bad (poor positioning)	OK (building-level)	Worst (zero context awareness)	Best (each context is labelled with an ID)
3. Required adoption rate	Best (existing complete data)	Bad (not peer-to-peer detection, but adoption is hardly enforceable)	Worst (peer-to-peer detection' tracing efficacy is proportional to the square of adoption rate)	Good (not peer-to-peer detection, coverage is enforceable via business owner of public spaces)
4A. Privacy concern	Worst (location data stored in the cloud)	Bad (location data stored in the cloud if GPS is on)	Best (data stored locally, no location data)	Good (data stored locally, contexts in public space)
4B. Explicit user awareness	Worst (user turn on mobile phone)	Bad (user often turn on GPS for other applications)	Good (user choose to turn on Bluetooth but it works non-stop)	Best (user choose to scan the QR code)
4C. Security concern	Best (no additional data exchange)	Best (no unauthorized data exchange)	Worst (Bluetooth vulnerability risk personal data in phones)	Best (only data exchange with the specified server using specified APIs)
5A. Convenience	Best (when phone is turned on)	OK (GPS is normally on)	Good (turn on Bluetooth)	Worst (scan QR code every time)
5B. Battery consumption	Best (requires no additional power)	OK (GPS frequency)	Worst (constant scanning)	Good (only when scanning QR code)
5C. Adoption globally	Best (any phone)	Good (smart phone with GPS)	Worst (smart phone with Bluetooth)	OK (smart phone with camera & printed/displayed QR code)

References:

[1] The exit strategy for lockdown. Ending coronavirus lockdowns will be a dangerous process of trial and error. Science news. 14 Apr 2020.
In absence of vaccines and effective contact tracing, intermittent lockdowns are expected into 2022. Projecting the transmission dynamics of SARS-CoV-2 through the postpandemic period. Science. 14 Apr 2020.

[2] East Asia. How Digital Contact Tracing Slowed Covid-19 in East Asia. Harvard Business Review. 15 Apr 2020.
South Korea. South Korea is reporting intimate details of COVID-19 cases. Nature news. 18 Mar 2020.
Singapore. Singapore government to make its contact-tracing app freely available to developers worldwide. Straits Times. 23 Mar 2020.
United Kingdom. UK considers virus-tracing app to ease lockdown. BBC news. 31 Mar 2020.
European Union. Call for single EU tracking app with data protection. BBC news. 6 Apr 2020.
Stanford University. Slowing the spread of infectious diseases using crowdsourced data. COVID Watch. 20 Mar 2020.
University of Washington and Microsoft. UW and Microsoft researchers present a "PACT" for using technology to fight the spread of COVID-19. University of Washington. 8 Apr 2020.
Apple and Google. Privacy-Preserving Contact Tracing. Apple.com. 16 Apr 2020.

[3] Unlinked COVID-19 infection cases in Singapore. News Highlights, Ministry of Health. 11 Apr 2020.
Online models estimating infection rates and reproduction ratio. Temporal variation in transmission during the COVID-19 outbreak. Centre for Mathematical Modelling of Infectious Diseases. 4 Apr 2020.
Data visualization of COVID-19 cases. Dashboard of the COVID-19 Virus Outbreak in Singapore. CO.VID19.sg. 16 Apr 2020.

[4] Technologically empowered human contact tracing team. App-based contact tracing may help countries get out of lockdown. Economist. 16 Apr 2020.
The tradeoff between completeness and manageable workload in contact tracing. The Apple-Google Contact Tracing Plan Won't Stop COVID Alone. The Wired. 14 Apr 2020.

[5] 2 out of 1068 asymptomatic close contacts of SARS patients were tested positive for antibody. SARS-CoV antibody prevalence in all Hong Kong patient contacts. Emerging Infectious Diseases. Oct 2004.

[6] Contact tracing should include period before onset of symptoms due to asymptomatic transmissions in Singapore. 10 patients in Singapore got virus from those without symptoms. Straits Times. 3 Apr 2020.
New York City: 88% of COVID-19 infected pregnant women are asymptomatic. Universal Screening for SARS-CoV-2 in Women Admitted for Delivery. The New England Journal of Medicine. 13 Apr 2020.
Comparing Serial Interval with Incubation Period, 44% of infections are due to pre-symptomatic transmission from the index case. Temporal dynamics in viral shedding and transmissibility of COVID-19. Nature Medicine. 15 Apr 2020.

[7] The droplets from sneeze and cough. The physics of the sneeze. Nature news. 31 May 2016.
The droplets from loud speech can suspend in the air for 8-14 minutes. The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission. Proceedings of the National Academy of Sciences USA. 13 May 2020.

[8] Stability of COVID-19 on different surfaces. Aerosol and surface stability of HCoV-19 (SARS-CoV-2) compared to SARS-CoV-1. The New England Journal of Medicine. 17 Mar 2020.
A video from Japan shows how efficiently virus can transmit via touched surfaces in a buffet style restaurant. Black light experiment shows how quickly a virus like Covid-19 can spread at a restaurant. CNN. 14 May 2020.

[9] Singapore makes mask wearing mandatory. Mandatory for all in Singapore to wear mask when out, except for kids under 2 and those doing strenuous exercise. Straits Times. 14 Apr 2020.

[10] Targeted epidemic control measures by risk groups using digital contact tracing. Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing. Science. 31 Mar 2020.

[11] CDC estimated that 20%-50% of infected patients were asymptomatic (asymptomatic patient) and 40% of transmission occurred prior to symptom onset (asymptomatic transmission). COVID-19 Pandemic Planning Scenarios. US CDC. 22 May 2020.

[12] Color-coded QR codes indicate different health status of healthy (green), close contacts (yellow), and isolated (red). China is fighting the coronavirus with a digital QR code. CNN. 16 Apr 2020.

[13] Surgical face masks could prevent transmission of virus from symptomatic people. Respiratory virus shedding in exhaled breath and efficacy of face masks. Nature Medicine. 3 Apr 2020.

[14] The effect of lockdown measures in Wuhan and other Chinese cities on containing virus spread. An investigation of transmission control measures during the first 50 days of the COVID-19 epidemic in China. Science. 31 Mar 2020.

[15] Positive viral test result indicates presence of RNA from SARS-CoV-2 at concentration above detection limit, and the patient is presumed to be infectious. LabCorp's COVID-19 RT-PCR Test. US FDA. 20 Apr 2020.

[16] Antibody may not be detected at early stage of an infection when the immune response is still building. COVID-19 update: Serological tests. US FDA. 07 Apr 2020.
Stanford researchers sampled 3,330 people in Santa Clara County for serological test, which indicates a population prevalence of antibodies to SARS-CoV-2 at 2.81%. COVID-19 Antibody Seroprevalence in Santa Clara County. Stanford University. 17 Apr 2020.

[17] Self-reported symptoms, via mobile apps, are useful indicators to predict viral testing outcome. Real-time tracking of self-reported symptoms to predict potential COVID-19. Nature Medicine. 11 May 2020.
The Symptom Tracker app, for self-reported symptoms, is endorsed by Welsh and Scottish government and help guide allocating resources for testing and treatment in specific areas. Rapid implementation of mobile technology for real-time epidemiology of COVID-19. Science. 5 May 2020.

[18] Citizens-initiated smart application. Safe Code app for one-click check-in and check-out of SafeEntry QR Code. Aspiring Citizens Cleantech. 22 May 2020.

[19] Telco signal for tracking population flows. Population flow drives spatio-temporal distribution of COVID-19 in China. Nature. 29 Apr 2020.

[20] GPS and Bluetooth for digital contact tracing. Safe Paths: A privacy-first approach to contact tracing. MIT Media Lab. 10 Apr 2020.

[21] Low adoption rate and lack of context lead to unmeaningful data. Why Bluetooth apps are bad at discovering new cases of COVID-19. The Verge. 10 Apr 2020.
Identification of close contacts and Bluetooth vulnerability. BlueTrace: A privacy-preserving protocol for community-driven contact tracing across borders. GovTech Singapore. 20 Apr 2020.
Bluetooth hardware and operating system requirement hinders adoption. 2bn phones cannot use Google and Apple contact-tracing tech. Financial Times. 20 Apr 2020.