Lincoln Laboratory Technical Report
TR-1288

Automated Exposure Notification for COVID-19

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14 February 2023

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This material is based upon work supported by the Dept of Health and Human Services under Air Force Contract No. FA8702-15-D-0001.

This report is the result of studies performed at Lincoln Laboratory, a federally funded research and development center operated by Massachusetts Institute of Technology. This material is based upon work supported by the Dept of Health and Human Services under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Dept of Health and Human Services.

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ABOUT PRIVATE AUTOMATED CONTACT TRACING (PACT)

Private Automated Contact Tracing (PACT[1]) was a collaborative team and effort formed during the beginning of the Coronavirus Disease 2019 (COVID-19) pandemic. PACT's mission was to enhance contact tracing in pandemic response by designing exposure-detection functions in personal digital communication devices that have maximal public health utility while preserving privacy.

PACT was led by the Massachusetts Institute of Technology (MIT) Computer Science and Artificial Intelligence Laboratory (CSAIL), MIT Internet Policy Research Initiative, Massachusetts General Hospital Center for Global Health and MIT Lincoln Laboratory (MIT LL). It included close collaborators from Boston University, Brown University, Carnegie Mellon University, MIT Media Lab, MITRE, the Weizmann Institute, and a number of public and private research and development centers. The PACT team was a partnership among cryptographers, physicians, privacy experts, scientists, and engineers.

The PACT project members viewed the project as cooperative and synergistic with similar projects elsewhere in academia and in industry. Our goal was to advance the science, engineering, and public-health technology to help fight the common virus enemy, rather than to aim for credit to the exclusion of credit to others.

The PACT effort began in mid-March 2020 with the development of the PACT protocol specification, which is a simple, decentralized approach for using personal digital communication devices for automating exposure detection using Bluetooth Low Energy (BLE) signaling. Version 0.1 of the PACT protocol was released on 8 April 2020. [1] The Apple and Google implementation of automated exposure notification (AEN) services are largely consistent with the PACT protocol and were released shortly afterward. Initial proof of concept technology demonstrations were completed by MIT LL around the same time.

PACT had four major lines of effort:

1. **Proximity Detection Efficacy**:

- Collect the experimental data required to demonstrate and evaluate objectively and quantitatively the extent to which BLE can be used to detect when two people have been closer than a medically relevant distance from each other for too long a period of time—i.e., "too close for too long" (TC4TL). Collect BLE data (and related metadata) to find the best way to compute TC4TL and measure TC4TL performance (using receiver operating characteristic curves, decision cost functions, etc.).

- Determine how performance depends on various equipment, user, and environmental factors and measure the impact that different approaches for computing TC4TL have on smartphone battery life and compute resources.

---

[1] When PACT was formed, it seemed to the founders that we were seeking to help automate parts of the contact tracing process. In retrospect, helping to automate exposure notification (a component of contact tracing) is probably a better description of what the PACT team was seeking to achieve.

- Assess the AEN software developed and distributed by Apple and Google. Recommend improvements to the Apple and Google approach where appropriate.

- Share all results openly and explain the implications to public health authorities (PHAs), Apple, Google, and others to inform decision-making. Simultaneously begin investigation of other signaling protocols—e.g., ultrasound, ultra-wideband (UWB)—in case BLE communication is shown to have insufficient efficacy.

2. **Privacy**:

- Advocate for digital exposure detection approaches to contact tracing that preserve individual privacy and civil liberties.

- Develop, publish, and seek feedback on private automated contact tracing protocols.

- Continue to monitor Apple and Google progress on development and deployment of their AEN protocol, whose decentralized architecture is based in part on PACT, to ensure continued Apple and Google adherence to the highest standards of privacy and security.

- Develop improvements to protocols based on theoretical and experimental results.

- Assess the privacy impact of the integration of digital exposure detection within public health systems and study the larger legal and public policy dimensions of the collection and use of contact tracing information. Share all results openly and explain the implications to the PHAs, Apple, Google, and others to inform decision-making.

3. **Integration**:

- Advise PHAs (mainly in U.S. states, counties, and municipalities, but also PHAs in other nations and other types of enterprises) regarding the development of the best system architectures and deployment strategies so that they can be smart designers, buyers, and users of new digital exposure detection functions within operational, integrated contact tracing systems that combine core PHA functions with new private automated contact tracing capabilities.

- For U.S. states, advise one or more state PHAs on the selection of an end-user smartphone app that leverages the Google Apple Exposure Notification (GAEN) service and can be deployed in a manner that meets usability requirements of diverse communities and protects privacy and the public trust.

4. **Public Health Efficacy**:

- Study whether and how automated exposure detection can provide measurable improvements in manual contact tracing efforts to slow infection rates.

- Conduct controlled pilots with public health or other medical officials.

- Form partnerships with PHAs, researchers, and non-governmental organizations (NGOs).

In support of these lines of effort, PACT executed several cross-layer activities that helped demonstrate public health efficacy. These included prototype development and demonstrations; system analysis; data collection and experimentation; and large-scale deployment support.

PACT convened two scientific workshops relating to privacy-preserving AEN: one virtual workshop in April 2020 and a second hybrid workshop in October 2021. This report is an outcome of the second workshop and serves as PACT's final report. It seeks to explain and discuss the use of automated exposure notification during the COVID-19 pandemic and to provide some recommendations for those who may try to design and deploy similar technologies in future pandemics.

PACT personnel authored dozens of reports and briefings, almost all of which are available publicly at PACT's MIT web site: https://pact.mit.edu.

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ACKNOWLEDGMENTS

PACT personnel participated in frequent, periodic meetings with other teams with similar goals around the world, including teams from Singapore, Ireland, Switzerland, the UK, the Commonwealths of Pennsylvania and Massachusetts, the State of Washington and others. Leaders from many of these teams have contributed to this report. We are very grateful for all of these productive relationships.

Funding for PACT was kindly provided by IBM Research, the U.S. Defense Advanced Research Projects Agency (DARPA) and the U.S. Centers for Disease Control and Prevention (CDC).

PACT personnel met and worked with teams from Apple and Google on a weekly basis for more than two years. The amazing exposure notification collaboration between Apple and Google, corporations who are normally fierce competitors, was amazing to observe, and PACT was proud to collaborate with them. We also acknowledge the great teams at Microsoft, MITRE, the Internet Security Research Group (ISRG), the U.S. National Institutes of Health (NIH), the Association of Public Health Laboratories (APHL), and Linux Foundation Public Health (LFPH), without whom exposure notification could not have been so impactfully deployed.

We acknowledge the 70+ in-person and virtual participants in the October 2021 ImPACT 2021 workshop. This final report has been heavily influenced by the discussion at that workshop.

In addition to the named authors and contributors to this report, some of whom were part of PACT and some of whom led teams that collaborated with PACT, we would like to acknowledge the following people who led and contributed so much to the PACT effort since the onset of the pandemic:

- Daniel J. Weitzner holds the 3Com Founders Senior Research Scientist chair at CSAIL, is Founding Director of the MIT Internet Policy Research Initiative, and teaches Internet public policy in MIT's Electrical Engineering and Computer Science Department. Danny guided all elements of PACT.

- Dr. Louise C. Ivers is director of the Harvard Global Health Institute, director of the Massachusetts General Hospital Center for Global Health, and the David Bangsberg MD, MPH Endowed Chair in Global Health Equity at Mass General Hospital. She is a professor of global health and social medicine, and professor of medicine at Harvard Medical School. In addition to her many clinical, teaching, and research responsibilities during the pandemic, Dr. Ivers served as scientific advisor to PACT from its onset.

- Dr. Israel Soibelman and Edward Wack are senior executives and technical leaders at MIT Lincoln Laboratory. They helped guide PACT for more than a year.

- Prof. Yael Kalai of MIT CSAIL, who with Prof. Ron Rivest, first conceived of the PACT protocol.

Contributors to the PACT protocol specification include Jon Callas, Ran Canetti, Kevin Esvelt, Daniel Kahn Gillmor, Yael Tauman Kalai, Anna Lysyanskaya, Adam Norige, Ramesh Raskar, Ronald L.

Rivest, Adi Shamir, Emily Shen, Israel Soibelman, Michael Specter, Vanessa Teague, Ari Trachtenberg, Mayank Varia, Marc Viera, Daniel Weitzner, John Wilkinson, and Marc Zissman.

Major technical and programmatic contributors from MIT Lincoln Laboratory also included Lou Bellaire, Michael Burke, Larry Candell, Brad Dillman, Marie Dow, Paul Fiore, Kylie Foy, Gwen Gettliffe, Dave Granchelli, Gary Hatke, Judy Marchese, Bryan Mastergeorge, John Meklenburg, Bobby Pelletier, Dave Pendall, Doug Reynolds, James Riordan, Chris Roeser, Elliot Singer, Mark Smith, Michael Specter, Joseph St. Germain, Bill Streilein, Jennifer Swanson, Marc Viera, Paula Ward, Jenn Watson, Michael Wentz, and John Wilkinson.

We greatly appreciate all the efforts of this amazing team.

Ronald L. Rivest, Massachusetts Institute of Technology
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EXECUTIVE SUMMARY: FINDINGS, OBSERVATIONS, AND RECOMMENDATIONS

When the COVID-19 pandemic began at the end of 2019, the world was unprepared. As the infectiousness and severity of the disease became apparent, many used their skills and resources to fight back. This report documents the efforts made and lessons learned in one such fight: by those directly involved in automatic exposure notification (AEN).

AEN adapts smartphone and Bluetooth Low Energy (BLE) technology to allow those who have become infected (and tested positive) to notify others they may have been infected, even when those others may be strangers to the infected party. Such notifications allow others to take steps such as quarantining to avoid spreading the disease further. This report describes how such technology can (and does) operate effectively.

The PACT (Private Automatic Contact Tracing) project was formed in early 2020 to facilitate the exploration of such technologies and to facilitate collaboration of those interested in pursuing the specification, design, implementation, deployment, and evaluation of such technologies. This report summarizes what was learned, what questions remain to be answered, and guidance for "next time."

Smartphones can communicate over short distances using Bluetooth, and thus seem potentially well-suited to telling when an infected party is sufficiently near another party to potentially infect this other party. Among other things, this report documents how difficult it has been to realize this vision.

It is necessary that such a system be private: it should not be possible to track an individual using information gathered by such a system. This report shows how the use of random identifiers and cryptography can provide the desired privacy; AEN may indeed be done in a private manner.

The effectiveness of such a system depends on it being widely used: both the infected party and a potential infectee must have suitable software on their smartphones for the infectee to discover that they were near an infected party. The system must have a high level of adoption. In most nations, such a system cannot be mandated; it must be installed and used voluntarily. This report describes the many challenges of achieving a high level of adoption. We learned that achieving an acceptable level of adoption is indeed possible, although more could and should be done to increase adoption.

There are many technical challenges to getting such a system to work at all, much less work effectively. For example, details such as the smartphone operating system and timing discrepancies matter. This report explains these challenges, and the rationale made for some of the design decisions made in some implementations. We learned that the design space for AEN systems is large enough to accommodate necessary trade-offs.

We take the view that AEN systems are not standalone systems, but rather a tool to be adopted, promulgated, and used by PHAs. They need to be understood as another "arrow in the quiver," much like masking or vaccinations. AEN systems need to be integrated with public health activities: in the management of testing (identifying index cases—those who are infected), in the management of databases of random identifiers that were broadcast by the phones of such index cases, and in the provision of guidance to others who receive AENs and want to know what they should do.

The designs fielded tend to be highly decentralized: much of the relevant processing takes place on each smartphone. Yet some centralization is needed as well, since we assume (or at least assumed, at first) that all positive test results would be authenticated by a PHA, and furthermore, that PHAs would be involved in notification follow-up. AEN was intended to support and complement, not replace, conventional contact tracing. Further complexity resulted from the fact that dealing effectively with COVID-19 may require multi-jurisdictional coordination. This report describes the challenges in setting up AEN to work with existing PHAs. While coordination of PHAs with exposure notification technology providers could be improved, AEN systems were successfully rolled out in numerous countries and U.S. states.

In the end, one wants to know, “Does this technology help save lives?”, or retrospectively, “How many lives have been saved by this technology?” These questions are difficult to answer because participation (or lack thereof) is not precisely tallied, many important details (such as what a potential infectee did after receiving an alert) may be unknown, and the methods used to ensure privacy prevent certain kinds of detailed questions from being answered. This report nonetheless attempts to answer the very important question: “What have we learned about the public health impact of automatic exposure notification?”

The design and rollout of AEN technology faced other challenges as well:

- AEN was a *new approach* to using technology; people (particularly those in public health) were unfamiliar with it.
- Regardless of geography, public health has long lacked equitable investment for pandemic response, and the level of information technology (IT) workforce depth in public health has suffered as a consequence.
- Exposure notification had to compete for attention and resources with other worthy approaches, such as vaccinations.
- Exposure notification technology is rather complex; the participation of large technology companies and service providers was essential for a quick rollout.
- Exposure notification was sometimes viewed as a technology for the better-off (those who possessed smartphones), although reducing infection rates helps everyone.

Finally, the issue of governance turned out to be critical. “Who gets to make the important decisions?” was a theme we saw over and over again: PHAs? Technology companies? Large organizations (states, corporations, universities) wanting to use and possibly adapt such technologies? Legislators and regulators? This report provides some initial guidance on framing and answering such questions.

The COVID-19 pandemic is not yet over, so this report may seem premature. However, we hope that this report captures, albeit in a basic and preliminary manner, some of our thoughts and lessons learned. We hope that it has significant utility to those who will be “fighting the next pandemic” (it will happen!).

TABLE OF CONTENTS

ABOUT PRIVATE AUTOMATED CONTACT TRACING (PACT) III

AUTHORS AND CONTRIBUTORS VII

ACKNOWLEDGMENTS XI

EXECUTIVE SUMMARY: FINDINGS, OBSERVATIONS, AND RECOMMENDATIONS XIII

LIST OF ILLUSTRATIONS XVII

LIST OF TABLES XIX

1. INTRODUCTION TO AUTOMATED EXPOSURE NOTIFICATION (AEN) 1

   1.1 References 6

2. DETECTING COVID-19 RELEVANT EXPOSURES 9

   2.1 Motivating Questions 9
   2.2 Executive Summary 9
   2.3 Key Requirements for Detecting COVID-19-Relevant Exposures 10
   2.4 Designs, Implementations and Engineering Trade-Offs 11
   2.5 Technical Gaps and Future Research 17
   2.6 References 18

3. PRIVACY AND SECURITY 21

   3.1 Motivating Questions 21
   3.2 Executive Summary 21
   3.3 Privacy and Security Goals 21
   3.4 Centralized and Decentralized Designs 22
   3.5 Tradeoffs Between Privacy, Security, and Other Goals 23
   3.6 Test Verification 25
   3.7 Privacy-Preserving Metrics Collection 25
   3.8 References 26

4. PUBLIC HEALTH SYSTEMS INTEGRATION 29

   4.1 Motivating Questions 29
   4.2 Executive Summary 29
   4.3 Introduction 30

4.4 Policy and Legal Integration 31
4.5 CI/CT Workflow Integration 32
4.6 Digital Integration 34
4.7 Integration Among Jurisdictions 40
4.8 Suggestions For Future AEN-Type Integrations 41
4.9 References 42

5. ADOPTION, EQUITY, AND PUBLIC ACCESS 45

5.1 Motivating Questions 45
5.2 Executive Summary 45
5.3 Introduction 45
5.4 Event 1: Enabling the Service for a Jurisdiction 48
5.5 Event 2: Turning it On and Keeping it On (Individual Users) 51
5.6 Event 3: Notifying Others (Individual Users) 53
5.7 Event 4: Changing Behavior Upon Receipt of Notification (Individual Users) 57
5.8 Conclusions and Recommendations 58
5.9 References 60

6. PUBLIC HEALTH IMPACT 63

6.1 Motivating Questions 63
6.2 Executive Summary 63
6.3 Real-World Evidence of AEN Performance and Public-Health Impact 63
6.4 Public Health Impact of AEN—General Insights 69
6.5 References 70

7. GOVERNANCE 73

7.1 Motivating Questions 73
7.2 Discussion 73
7.3 References 77

8. DISCUSSION AND CONCLUSIONS 79

APPENDIX A. AEN DEPLOYMENTS INCLUDED IN THIS REPORT 81

APPENDIX B. SIGNIFICANT AEN ADVANCES AVAILABLE IN U.S. AND IMPACT ON ADOPTION 83

GLOSSARY 87

LIST OF ACRONYMS 89

LIST OF ILLUSTRATIONS

Figure No.		Page
1	Overview of GAEN system.	3
2	Attenuation vs. distance in a large indoor space, with varying obstructions.	12
3	Data collection hardware, software, and infrastructure at MIT Lincoln Laboratory.	14
4	Narrower and wider net settings yield very similar options for operating points.	15
5	Probability of alert heat map for Wider Net settings, one body blocking.	16
6	CI and CT procedures at start of COVID-19 pandemic.	30
7	Public health procedures with GAEN integration points.	33
8	Events required to share a positive diagnosis and alert other users of close contact.	46
9	Daily publish requests to U.S. National Key Server.	56

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LIST OF TABLES

Table No.		Page
1	Report Functional Stack	5
2	IT Subsystem and Component Integrations for AEN	37
3	Events Required to Share a Positive Diagnosis and Alert Other Users of Close Contact	47
4	Daily Publish Rate to U.S. National Key Server	56
5	Daily Publish Rate of Four U.S. Jurisdictions in October 2021	57
6	AEN Performance and Impact Data	68

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1. INTRODUCTION TO AUTOMATED EXPOSURE NOTIFICATION (AEN)

Authors: Edouard Bugnion and Marc Zissman

The outbreak of Coronavirus Disease 2019 (COVID-19) was first reported on December 31, 2019, in Wuhan, China. In the weeks that followed, the virus quickly spread around the globe. The World Health Organization (WHO) declared on January 30, 2020, that the outbreak constituted a public health emergency of international concern. On March 11, 2020, WHO characterized the COVID-19 outbreak as a global pandemic due to its levels of spread and its severity [1]. By the middle of March 2020, large parts of the world, including much of the United States, Europe, and Asia, went into lockdown. Given the extremely contagious nature of the disease, worry about the scalability of traditional contact tracing techniques, and lack of immediate pharmaceutical interventions, there was a great sense of urgency to find ways to combat the pandemic.

COVID-19 is highly contagious and may be spread by people who are not showing symptoms (i.e., "asymptomatic") or before symptoms appear ("pre-symptomatic") [2]. As COVID-19 spread among people, causing illness worldwide, the human population had little or no immunity. This allowed the virus to spread quickly from person to person worldwide. Before pharmaceutical interventions like vaccines and treatments were available, nonpharmaceutical interventions (NPIs) were among the best ways of controlling spread of the pandemic. NPIs are actions, apart from getting vaccinated and taking medication to treat the illness, that people and communities can take to help slow the spread of illnesses like COVID-19 [3]. Examples of simple NPIs are hand hygiene, face masking, social distancing, and surface cleaning. More sophisticated NPI techniques include testing for infection, interviewing those found to be infected ("index cases"), tracing and interviewing the contacts of the infected ("contacts"), isolating the infected, and quarantining the possibly infected.

The principal mode by which people are infected with severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2, the virus that causes COVID-19) is through exposure to respiratory fluids carrying infectious virus. Exposure occurs in three principal ways: (1) inhalation of very fine respiratory droplets and aerosol particles, (2) deposition of respiratory droplets and particles on exposed mucous membranes in the mouth, nose, or eye by direct splashes and sprays, and (3) touching mucous membranes with hands that have been soiled either directly by virus-containing respiratory fluids or indirectly by touching surfaces with virus on them. Once infectious droplets and particles are exhaled, they move outward from the source. The risk for infection decreases with increasing distance from the source and increasing time after exhalation. Two principal processes determine the amount of virus to which a person is exposed in the air or by touching a surface contaminated by virus: (1) decreasing concentration of virus in the air and (2) progressive loss of viral viability and infectiousness over time influenced by environmental factors such as temperature, humidity, and ultraviolet radiation (e.g., sunlight) [4].

Case investigation (CI) and contact tracing (CT) involve working with the index case (whether symptomatic or asymptomatic) who was diagnosed with an infectious disease to identify and provide support to contacts who may be infected through exposure to the index case. This process prevents further transmission of disease by separating people who have (or may have) an infectious disease from people who do not. It is a core disease-control measure that was employed by public health authority (PHA) personnel for decades [5]. Backward (or reverse or retrospective) tracing seeks to establish the source of an infection by looking for contacts before infection. Forward tracing is the process of looking for contacts after infection, so as to prevent further disease spread. CI and CT are most effective when they are embraced by the impacted community and are part of a multifaceted response to an outbreak that includes testing those suspected of being infected, isolation of the infected, and quarantine of those possibly infected.

While traditional CI and CT activities are irreplaceable as intimate, nuanced, and trustworthy efforts [6], the short latent period and high presymptomatic infectiousness of COVID-19 showed early on that conventional CI/CT methods would not be enough by themselves to contain the spread of the disease. Because COVID-19 was one of the first pandemics in which the majority of the world population had a programmable, multi-radio, Global Positioning System (GPS)-enabled computer permanently turned on in their pocket—their smartphones running the iOS or Android operating systems—digital applications issued by governments played a large role in the pandemic to notify users, record attendance to public events, limit population movement, verify vaccination or immunity status, communicate test results, and assist in contact tracing strategies. These applications all communicated with servers (often government-run) over the Internet but used different technologies available on phones (e.g., GPS, Bluetooth, cameras to scan QR codes) and different communication protocols.

Automated exposure notification (AEN) aims to use these pervasively-deployed smartphones to (1) enable someone who tested positive for COVID-19 to notify other smartphone users whom they were near recently that they may have been exposed to the SARS-CoV-2 pathogen, and (2) help close contacts who receive such notifications to take appropriate actions. To be effective, an AEN system should work with a representative variety of smartphones, should appropriately preserve individual privacy, should work smoothly with users moving between multiple jurisdictions, should have a clearly defined relationship with the needs and existing systems (such as conventional contact tracing) of PHAs, and should have the potential to scale to worldwide use over all phases of a pandemic. AEN is a supplement to, not a replacement for, conventional contact tracing.

In the context of the COVID-19 pandemic, AEN implementations based on a protocol developed by Apple and Google, hereinafter referred to as Google Apple Exposure Notification (GAEN), saw the broadest adoption. GAEN stands out as a protocol, architecture, and implementation with privacy-by-design consideration at all layers, and it is GAEN that is the primary focus of this report, with some discussion of alternatives. GAEN is a protocol that:

- Leverages Bluetooth Low Energy (BLE) exchanges of ephemeral tokens between pairs of phones to record close contact, designed to ensure privacy-preservation and purpose-limitation through decentralized matching of tokens, ensuring that no central authority can directly use that infrastructure to build a database of social contacts.

- Is made available to public health applications via a privacy-preserving application programming interface (API) implemented in both iOS and Android that ensures that identifiers are kept in an encrypted vault on the phone. Together with other application-level restrictions such as the inability to turn on GPS, this design effectively separated the application from the trusted computing base.

- Was deployed on a massive scale during the COVID-19 pandemic in more than 40 countries, including large, federated, interoperable deployments in both Europe and North America.

- Was implemented jointly by Google [7] and Apple [8] to ensure interoperability between Android and iOS platforms as a *de facto* world-wide standard. The protocol was directly derived from academic proposals that emerged in March 2020, notably the Decentralized Privacy-Preserving Proximity Tracing (DP-3T) [9, 10, 11] effort in Europe and Private Automated Contact Tracing (PACT) [12] in the U.S.

An overview of the GAEN system architecture is shown in Figure 1.

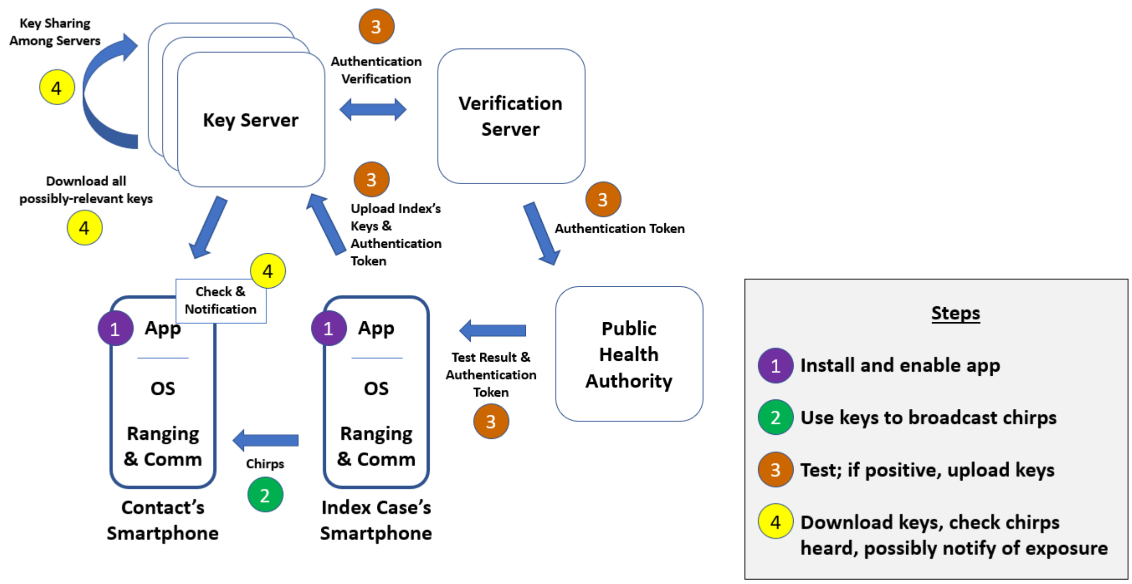

Figure 1. Overview of GAEN system.

The core GAEN protocol operates as follows:

- Between users and their smartphones: Users decide to install and enable an AEN app appropriate for their jurisdiction. (Step 1 in the architecture diagram)

- Between smartphones, via the operating systems: Smartphones randomly generate daily temporary exposure keys (TEKs), from which short-lived rolling proximity identifiers (RPIs or "chirps") are derived via a one-way hash function. In the background, each phone operating system broadcasts its current RPI and retains for a period of time RPIs received from neighboring phones. (Step 2)

- Between index cases and PHAs, via the app: PHAs typically deliver a use-once authorization code or link to index cases, typically following a positive test for COVID-19. Users enter that code in the app, or click that link, to securely volunteer their TEKs from infectious days to trusted PHA servers. (Step 3)

- Between contact cases and their phones, without interacting with PHAs: Each phone application receives a public feed of all index TEKs from the trusted PHA; the operating system can match the TEK feed with the recorded RPI database to extract exposure data. Should the resulting risk model determine that the phone user is a probable close contact, he/she will see a private notification on the smartphone. (Step 4)

- Between PHAs: While each PHA controls critical, region-specific elements, including the risk model, and the management of use-once authorizations, different PHAs can exchange TEKs to ensure cross-border contact tracing. This was notably deployed, for example, by the European Federated Gateway System (EFGS) within the European Union (EU) and European Economic Area (EEA) and by the Association of Public Health Laboratories (APHL) for states within the U.S. (Step 4)

There are now two means of using GAEN. In its first version, GAEN services are available through a specially controlled API on both Android and iOS, allowing governments to develop customized/proprietary smartphone applications. More recently, the operating system (OS) vendors released "Exposure Notification Express" (ENX), an optional, simple, and generic application offered to PHAs, which may lack the requirement or technical resources to create and maintain their own smartphone application. They both use the same underlying protocol, though PHAs using the ENX generic, OS-integrated application have access to aggregate, privacy-preserving usage data providing valuable public health insight not available to the original GAEN applications.

GAEN pragmatically uses BLE, which is a ubiquitous short-distance radio present on nearly all contemporary smartphones in 2020. Through the encrypted encoding of transmission power levels by the sending smartphone, the receiving smartphone can determine the signal attenuation of matching RPI once the Temporary Exposure Key (TEK) is known, which in turn can be used to approximate distance.

The value proposition of AEN in general (and GAEN specifically) to individuals, society, and PHAs is five-fold:

- **Speed**: AEN can lead to faster exposure notification than traditional conventional contact tracing alone.

- **Scope:** AEN can reach persons who are not personally known to an index case.

- **Scale**: AEN can still work when caseloads exceed the capacity of conventional contact tracing.

- **Privacy**: AEN alerts contacts privately and automatically about potential exposure, enabling them to choose how they wish to engage with PHAs. (This is true of GAEN and some of the other related AEN protocols).

- **Adaptability**: PHAs can configure an AEN operating point at different points during a pandemic, so that benefits from AEN detection of true exposures outweigh potential costs from AEN false positives.

GAEN was designed in early 2020 when the Centers for Disease Control and Prevention (CDC) and WHO assumed that COVID-19 was primarily transmitted through distance-limited droplet transmission. In fact, most applications were originally configured to follow the CDC and WHO COVID-19 transmission models to notify contacts that were exposed for at least 15 minutes, within a 2 m (or 1.5 m) radius of index cases, during a 24-hour period. Since then, scientific understanding progressed to conclude that most COVID-19 transmission occurs in closed spaces due to aerosol-based transmission, and transmission is not limited to droplets. PHAs adapted their configuration of AEN systems—and GAEN specifically—as the pandemic evolved, in response to new scientific understanding, reduced costs and wider availability of COVID-19 testing, variations in the level of COVID-19 within their communities, availability of vaccines, and infectiousness of novel virus variants.

This report examines six core areas of AEN design and implementation, looking at what was learned to enable society to prepare better for a potential future pandemic (or for COVID-19 becoming endemic). The report is organized mainly using the functional "stack" in Table 1, although it should be noted that the elements of this stack are not purely orthogonal, i.e., requirements and considerations in one layer are interdependent with the requirements and considerations in other levels.

Table 1

Report Functional Stack

Detecting COVID-19 Relevant Exposures	The requirements for and technology implemented to detect when a COVID-19-relevant exposure between an infectious person and a close contact has occurred. (Section 2)
Privacy and Security	The design considerations and implementation trade-offs made in AEN to preserve privacy and security. (Section 3)
Public Health Systems Integration	The approaches to, and challenges of, integrating AEN into existing and evolving public health systems. (Section 4)
User Interface: Adoption, Equity and Public Access	The barriers to wider adoption of AEN by end users and jurisdictions, and meeting the expectations of those users and jurisdictions. (Section 5)

Two additional sections of the report are cross-cutting:

- Public Health Impact: The measures of effectiveness, costs, and benefits of AEN. (Section 6)
- Governance: The allocation of responsibilities among governments and the private sector and the principles that guide the enabling and eventual disabling of AEN within a jurisdiction. (Section 7)

The report concludes with suggestions for how to prepare to do better AEN in a future pandemic, recommendations for future research, and some final thoughts.

Appendices with additional discussion and data are given at the end of the report.

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2. DETECTING COVID-19 RELEVANT EXPOSURES

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2.1 MOTIVATING QUESTIONS

The most fundamental function of an AEN system is to detect when an exposure between an index case and a close contact occurs in a way that increases the likelihood of the close contact getting infected. In this section, we consider the following key questions relating to the detection of COVID-19-relevant exposures:

- What are the most important technical requirements for systems that seek to detect whether a COVID-19-relevant exposure occurred between two people carrying smartphones?
- How were such systems (especially GAEN) designed and implemented for COVID-19 to satisfy those requirements? What were the key engineering trade-offs? How well did the systems perform exposure detection? What were the most important gaps between what was deployed and what was needed?
- What gaps in how current AEN systems detect exposures should be addressed if AEN is to be deployed in future pandemics?

2.2 EXECUTIVE SUMMARY

The purpose of smartphone-based AEN is to enable an index case to notify recent close contacts that they may have been exposed to the disease, with such notification appearing on the smartphones of the close contacts. The system must determine whether a COVID-19-relevant exposure occurred by taking into account the factors that are most reflective of the risk the exposure had on the contact. These factors include the estimated duration of the close contact's exposure to the index case, the estimated range (i.e., distance from index case to contact) during the exposure, the infectiousness of the index case at the time of the exposure, and various mitigating factors, e.g., usage of personal protective equipment at the time of the exposure, vaccination status of the close contact, environmental conditions during the exposure, etc. Each of these factors figures into the risk that the close contact was infected by the index case during the exposure and so should be considered by the AEN system.

For the AEN systems widely deployed during COVID-19, exposures were detected through the use of BLE signaling, which has the benefit of being supported almost universally on modern smartphones, but also proved to have limited accuracy for distance estimation. PHAs were given the opportunity to set and tune AEN parameters that traded false positive exposure detections against false negative exposure detections, but often lacked the required data and analysis to inform this tuning. Exposures were detected without conditioning on environmental factors (e.g., inside an enclosed space vs. outside an enclosed space), without conditioning on the use of personal protective equipment (e.g., use of masks) and with only "after the fact" conditioning on vaccination status. For all these reasons, there remains significant room for improvement in how exposures are detected should a deployment of AEN be contemplated in future pandemics.

2.3 KEY REQUIREMENTS FOR DETECTING COVID-19-RELEVANT EXPOSURES

Multi-discipline scientific and engineering teams around the world developed an understanding of the requirements for AEN exposure detection within the first few months of the pandemic. Some of this work was independent within each team and some was collaborative across the teams. Design, development, and demonstration of AEN was very much a "tech push" effort; i.e., like many new technical capabilities with hypothesized but as yet unproven benefits, technology was "pushed" to the public health community—the public health community did not request for or "pull" AEN capability. The specifics of the requirements evolved with time, and the resulting AEN systems that were designed, built, and deployed did not necessarily satisfy all requirements. With the benefit of two years of hindsight, AEN requirements can be broadly separated into four categories, each of which is described below.

AEN can be viewed as a supplement to traditional forward contact tracing, in which the exposure notifications to some potential contacts of index cases are provided automatically by the AEN system without a human contact tracer "in the loop." The human-to-human interaction that normally occurs during traditional case investigations and contact tracing interviews are reduced in AEN to a very simple abstraction: Was a contact "too close for too long" (TC4TL) to one or more index cases during times that these index cases were infectious? Thus, ***the first and most fundamental requirement for an AEN system is to alert contacts who were TC4TL to an infectious index case to which they were exposed and to refrain from alerting contacts who were not TC4TL to an infectious index case***; with the definitions of "too close" (within 2 meters or 6 feet) and "too long" (for 15 minutes over a 24-hour period) being specified by local PHAs given the circumstances within their jurisdictions. Because PHAs were already using such simple TC4TL statements in their public safety announcements [1], this abstraction was a readily understood concept to the PHAs, to the public, and to the engineers who were designing, building, and deploying AEN. Infection risk models that are simple step-functions based on exceeding a bilateral TC4TL threshold are overly simplified—e.g., 15 close, 1-minute exposures over a short time period are not necessarily less risky than a single, 15-minute close exposure. As the understanding of COVID-19 evolved during the pandemic, public safety announcements were updated as were AEN configurations.

Because the personal conditions of both the index case and the contact during the exposure impact the risk of infection during an exposure, these conditions should be factored into the decision to issue an exposure alert. Merely specifying a minimum safe distance and a minimum safe time is overly simplistic. For example, even ten seconds of exposure may be extremely risky if during that time an unmasked index case sneezes onto the face of an unmasked contact at close range. Because risk of virus transmission is reduced when individuals are wearing personal protective equipment (PPE) such as masks, usage of PPE during an exposure results in a lower risk than does an exposure without PPE. [2] Additionally, the risk to the health of the contact may be reduced if the contact is vaccinated. So, ***a second key AEN system requirement is to consider personal factors relating to the use of PPE and vaccination status during each exposure when deciding whether to issue an alert.***

The risk associated with a contact's exposure with an index case may indeed be related to the range and duration of exposure, to the infectiousness of the index case, to the use of PPE, and to vaccination status; but there are environmental factors that contribute as well, and these additional factors should be included in the risk assessment performed by AEN. For example, as it became clearer during the pandemic that aerosol transmission was an important vector in the spread of the virus, the nature of the environment, including especially air flow characteristics in which the exposure occurred, was recognized as a factor in virus spread. For example, indoor settings were recognized as generally more risky than outdoor settings.

[3] As such, ***a third key AEN system requirement is to incorporate environmental characteristics present during each exposure in deciding whether to issue an alert.***

Finally, PHAs need flexibility. They need to be able to adjust the exposure notification threshold within their jurisdictions independently of other jurisdictions and as a function of the phase of the pandemic, vaccination rates within the jurisdiction, prevalence of more or less-infectious variants, and evolving understanding of transmission paths and risk. Each of these factors impacts the prior probability that an exposure between an index case and a close contact will lead to infection of the index case. Additionally, PHAs need to consider the relative costs of false negatives and false positives. Failing to alert when an exposure did in fact lead to infection can lead to further spread of the disease with all its associated costs. Issuing an alert when an exposure did not lead to infection has its own costs, including the cost of unnecessary testing and/or unnecessary quarantine. Therefore, ***a fourth key AEN system requirement is the ability to simply and frequently update the parameters and thresholds used to decide whether to issue an alert in a manner that can be decided by and be specific to each public health jurisdiction***.

With the exception of the first requirement described above, which is fundamental, the remaining three key requirements are not listed in any particular order. Each of these three requirements is important, and their relative priorities are open to debate.

2.4 DESIGNS, IMPLEMENTATIONS AND ENGINEERING TRADE-OFFS

As the teams prototyping and deploying AEN around the world came to understand these four key requirements, they faced a number of design and implementation decisions. In this section, we discuss how these decisions were resolved.

2.4.1 Selection of a Ranging and Signaling Waveform

There are a variety of sensor systems that could be used by smartphones to detect when an exposure was TC4TL, but the list of potential options was narrowed quite quickly at the beginning of the pandemic to GPS and radio frequency (RF) ranging, due to the widespread availability of these sensors on smartphones. Other ranging techniques, such as ultrasonic sonar, were considered and explored. [4] Sound-based ranging techniques that required the use of the speaker and microphone of a cell phone were prototyped but not aggressively pursued due to privacy considerations related to persistent access to the phone's microphone. GPS was ruled out for most AEN systems fairly quickly as well, due to the privacy considerations of explicitly tracking AEN users with geographic specificity, the unavailability of GPS while inside most indoor environments, and the concern that even outside, a GPS-based AEN system would not be sufficiently accurate. This left RF ranging, which could be performed using the BLE [5] radios available within almost every smartphone. While BLE hardware is ubiquitous, the protocol was not designed to support highly accurate ranging between two devices. The simplest approach to BLE-based ranging is to broadcast BLE "advertisements" periodically, and to use the received signal strength indicator (RSSI) available on the receiving device and subtract from it the transmitted signal strength as reported by the transmitting device to the receiving device. The difference between transmitted and received signal strength is an indication of how much the signal attenuated on its path from the transmitter to the receiver, and this attenuation is an indication of the distance between the two devices. Where physical obstructions are not present, the BLE signal attenuation is related to the distance between the transmitter and receiver through the inverse square law. For many real-world situations, however, physical obstructions (including human bodies), multipath reflections, poor antenna alignment, and model-specific systemic differences between smartphone transmitters are all factors that degrade the accuracy of this distance estimate. [6, 7] An example of how attenuation is only loosely related to distance between BLE transmitter and receiver is shown in Figure 2. [8]

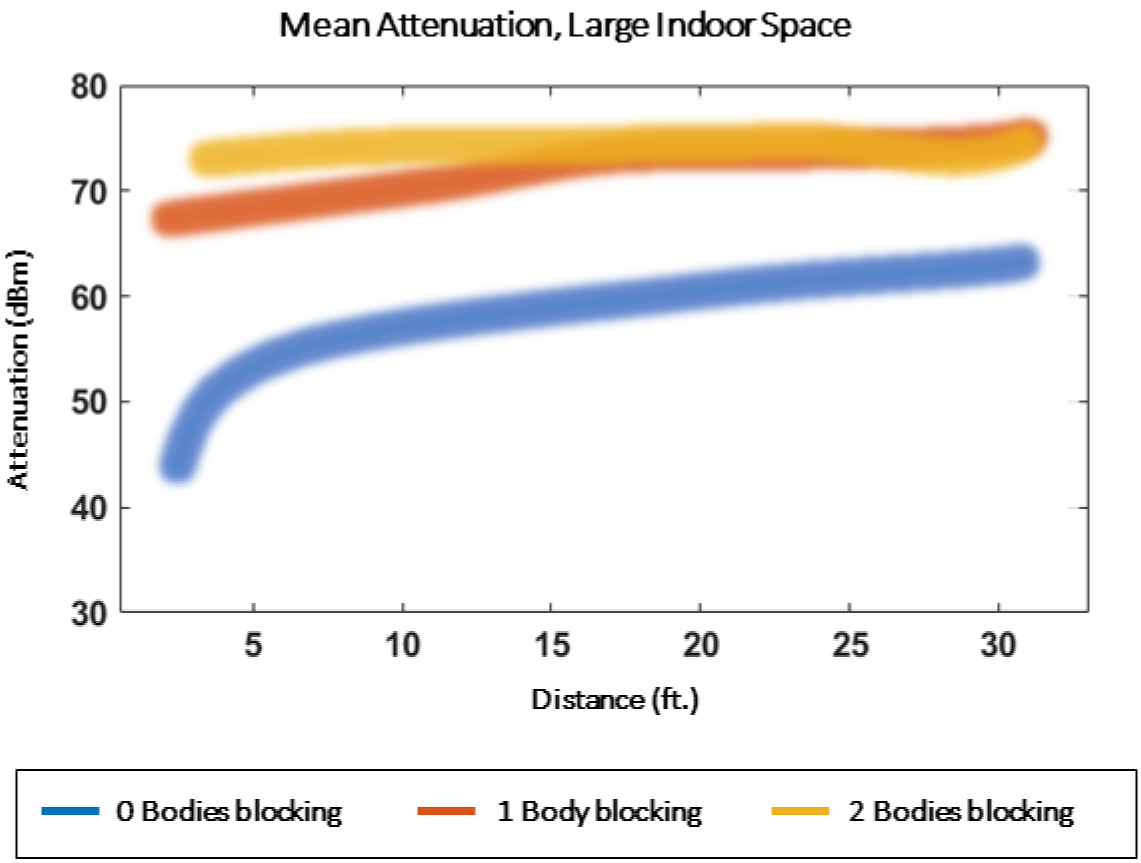

Figure 2. Attenuation vs. distance in a large indoor space, with varying obstructions.

As shown in the Figure 2 graph, attenuation generally increases with distance when there are no obstructions in the way, but interspersing bodies between the transmitter and receiver makes this relationship much weaker. Despite the limitations of signal-strength-attenuation-based estimation of distance, the convenience of pre-deployed hardware (BLE transceivers in smartphones) made BLE-based ranging (for estimating distance) and signaling (for exchanging data) the best option for a rapidly deployable AEN system. For all its weaknesses, given that COVID-19 spreads through aerosols far beyond 6 feet, and given that BLE reception is limited to somewhere between 50-100 feet in most conditions, BLE may be well suited to COVID-19 exposure notification (EN) despite RSSI attenuation being a poor basis of range estimation.

The accuracy of BLE-based range estimates and duration estimates are impacted by the frequency with which BLE signals are transmitted and received. In this context, "frequency" is not the RF frequency of transmission and reception (measured in gigahertz) but the much lower rate (per second or per minute) at which BLE advertisements are sent and received. Higher sampling rates, which lead to more signal-strength measurements between two phones, improve the measurement. In modern smartphones, periodic transmission of short BLE signals is performed by special purpose hardware that is deliberately designed to use very little battery power and that does not require turning on the main and power-hungry smartphone processor. However, reception of BLE signals does require use of the main smartphone processor at significant battery cost. So there is a tradeoff between how often and how accurately distance and duration are estimated vs. how smartphone battery life will be used by AEN. Ideally, smartphones would sample a received BLE signal as many times as possible, but this requires significant energy expenditure, which can drain smartphone batteries.

Other important factors that can cause variability and inaccuracy in RF distance measurements, and that were not included in the decision to issue an alert, included smartphone orientation, smartphone position (in hand, in pocket, in purse, on table, etc.), number of bodies positioned between the phones, physical barriers in the environment, and nature of the multipath environment. While sensors on modern smartphones can help estimate some of these conditions, the data from these sensors did not figure into the AEN distance calculations implemented and deployed during the pandemic.

2.4.2 Non-Smartphone Hardware Tokens

The decision to use BLE for estimating the range and duration of an exposure was influenced most heavily by the ubiquity of BLE on the most common smartphone models worldwide. If new hardware were developed, manufactured, and distributed quickly for very low cost, then better ranging techniques such as ultra-wideband (UWB) RF ranging or custom waveforms could have been considered. For example, UWB and ultrasound ranging can provide repeatable and accurate distance measurements with less than 1 meter error between transceivers, in real-world situations. [9, 10]

Non-smartphone-based AEN systems (such as those employing wearable or carryable hardware tokens) offer opportunities to mitigate many of the privacy concerns associated with using a smartphone, which is often directly linked to a variety of other personally identifiable information. In most public health jurisdictions, the convenience of pre-deployed hardware (i.e., smartphones) was prioritized over the opportunity to develop and distribute specialty hardware. An exception to this trend was the approach in Singapore, where inexpensive hardware tokens were designed, developed, and deployed by the government to the population at no cost to the end user. [11] Designers of future AEN systems might follow the lead of Singapore and develop custom hardware to improve AEN capabilities, tailor the exposure measurements to specific contagions, and reduce the inherent privacy risks. These future solutions could even support the legacy AEN capabilities, such as BLE-based TC4TL detection, to maintain backward compatibility with those who continue to run AEN on their smartphones.

2.4.3 Public Health Authority (PHA)-Specific Exposure Risk Scores

While measurement of BLE attenuation provides the fundamental basis for determining whether devices running the AEN protocol are too close for too long, other factors may be relevant for determining whether that proximity event is indicative of a true COVID-19 transmission event. For example, GAEN computes a risk score that considers the estimated distance between the devices and duration of the proximity event, as well as the relative infectiousness of the index case in deciding whether an exposure event occurred. The risk score computation is conditioned on PHA-selectable parameters, weights, and thresholds, which determine the AEN detection sensitivity. Higher weights or lower thresholds increase sensitivity (i.e., fewer false negatives) at the cost of decreasing specificity (i.e., more false-positives), while lower weights or higher thresholds decrease the sensitivity and increase specificity.

Several sets of recommended GAEN settings were produced by a collective of AEN developers and public health practitioners, through a series of focused "Risk Score Symposium Invitational (RSSI)" meetings coordinated by Linux Foundation Public Health (LFPH). [12] The first RSSI meeting led to the development of "narrower net" and "wider net" settings, which were designed to exhibit lower and higher sensitivity, respectively. A second RSSI meeting updated the recommendations. Public health departments had the ability to implement one of these pre-designed setting profiles or could custom tailor the individual weights and thresholds to meet their needs.

2.4.4 Collection, Accuracy Assessments, and Simulations

The GAEN risk score configuration of weights and thresholds enables hundreds of thousands of potential configurations, and it was not well known how the detector performance of candidate GAEN configurations maps to the actual "too close for too long" standard specified by PHAs. To address this gap, data from GAEN-enabled smartphones were collected at a range of distances, orientations, and placement configurations (e.g., shirt pocket, bag, in hand), using RF-analogous robotic substitutes for human participants (See Figure 3). Exposure notification data were collected along with the smartphones' actual distances and durations of exposure. Data from this collection were shared and incorporated into AEN-related models and public health exposure notification deployment decisions. [8] Assessments of exposure detection performance for a variety of conditions were computed and distributed (see Figure 4 for an example).

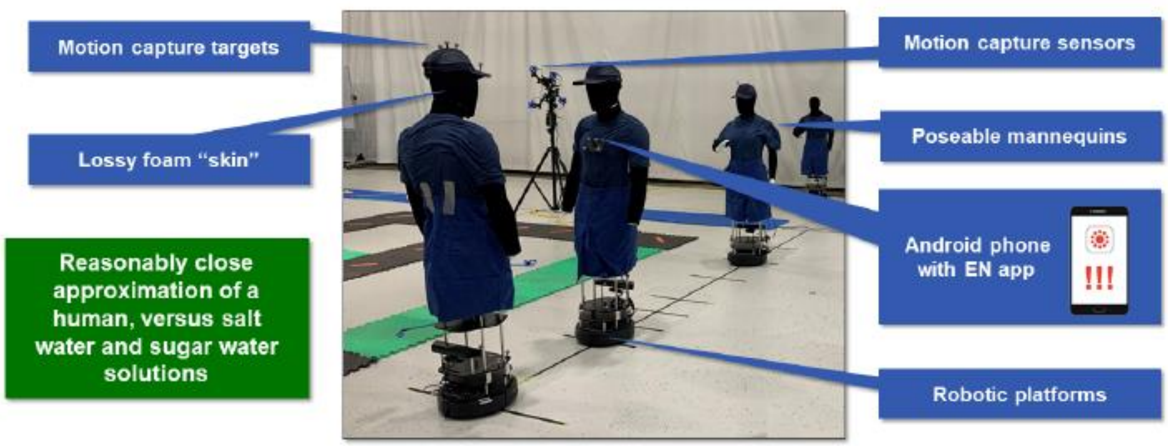

Figure 3. Data collection hardware, software, and infrastructure at MIT Lincoln Laboratory.

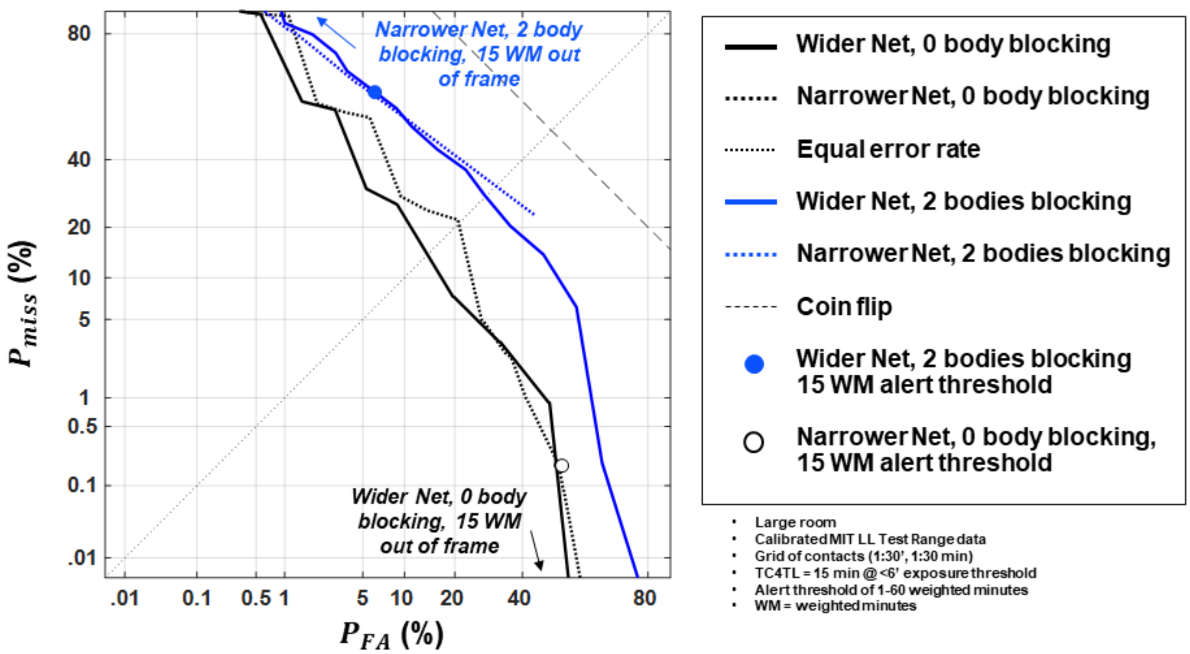

Figure 4. Narrower and wider net settings yield very similar options for operating points.

Estimated RSSI-based attenuation is a very noisy estimator of the actual distance between the smartphones and can be dramatically affected in real-world conditions by where the smartphones are carried, body positions, physical barriers, and multipath environments. To better characterize the effectiveness of range and time estimation using BLE, many research organizations around the world collected BLE as well as other phone sensor data (e.g., accelerometer, gyroscope, proximity) between various types of smartphones with simulated real-world variability. The U.S. National Institute of Standards and Technology (NIST) organized a TC4TL detector evaluation to facilitate this research effort. The evaluation explored promising new ideas in TC4TL detection using BLE, supported the development of advanced technologies incorporating these ideas, and measured performance of the state-of-the-art TC4TL detectors. [13] Although many promising approaches for improving TC4TL estimation were prototyped and tested, none has been incorporated yet into GAEN or any other widely deployed AEN system.

To aid PHAs in the difficult decision of how to tune their AEN deployment to accommodate all of these sources of error and new understanding, a data-driven model (BLEMUR, or Bluetooth Low Energy Model of User Risk) was developed that provides insight into how a set of selected AEN risk and notification settings translates into probability of alert for a given combination of distance and duration. [14] BLEMUR produces a graphical representation (e.g., Figure 5) of the impact of a set of AEN settings upon the contact space of distances and durations from 1 to 30 feet and 1 to 30 minutes. These representations, or "heat maps," gave an estimated probability that a contact of a given distance and duration will be alerted, based on probability distribution functions derived from BLE measurements collected in a lab setting. A perfect system (in this case) would be "white" inside the green box and "black" elsewhere in the heat map. Such heat maps were used by some PHAs in the process of setting and adapting their GAEN configuration parameters.

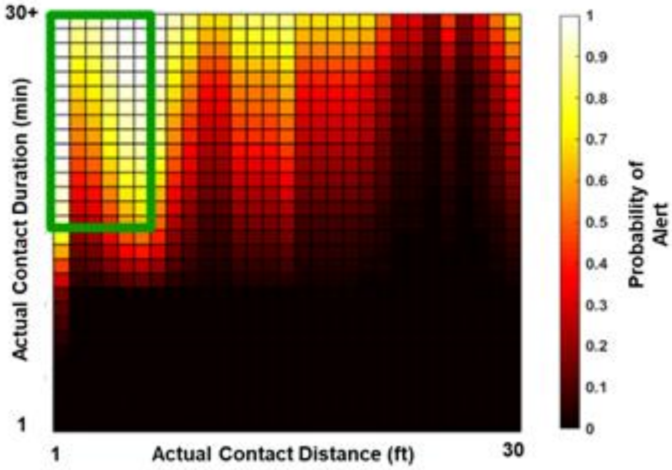

Figure 5. Probability of alert heat map for Wider Net settings, one body blocking.

Agent-based and other types of models were built to estimate the effects of AEN deployment on COVID-19 caseloads and public health workloads in the context of other critical public health measures available during the COVID-19 pandemic. [15] Simulation variables pertinent to AEN deployment options were defined and varied in accord with the pandemic dynamics, and outcomes of key metrics were computed across repeated runs of the stochastic simulations. Parameters were set to ranges of observed values in consultation with public health professionals and the rapidly accumulating literature on COVID-19 transmission, and models were validated against available population-level disease metrics. While estimates from such models could in theory help determine AEN deployment configurations in PHA jurisdictions and in combination with other COVID-19 interventions, use of such models by PHAs was quite limited during the pandemic.

2.4.5 Personal and Environmental Factors

No widely deployed AEN system used personal factors (e.g., vaccination status of the contact, use of PPE by either the contact or the index case) in determining whether to issue an exposure alert. For the first year of the pandemic, vaccines did not exist, and once they were widely available in the second year of the pandemic, PHAs included a contact's vaccination status in their instructions for how to react to receiving an exposure notification instead of conditioning the issuance of a notification on vaccination status. [16] Perhaps because use and effectiveness of PPE was so difficult to characterize (e.g., what type of mask was used by the index case and contact, was it fitted optimally, was it worn during each exposure, etc.), the use of PPE did not figure into either the decision to issue a notification nor in the instructions on how to react to receiving a notification. Neither were environmental factors included in the decision to issue a notification nor in the instructions of how to react to receiving a notification. While sensors on smartphones (GPS or otherwise) could perhaps have been used with difficulty to determine whether a phone was inside or outside a building, no deployed AEN system attempted to use an "inside vs. outside" estimate to influence the decision to issue an alert.

2.5 TECHNICAL GAPS AND FUTURE RESEARCH

The wide availability of BLE signaling iOS and Android-based smartphones together with the low battery power required for transmitting BLE advertisements led development teams to use BLE RSSI measurements for range estimation in AEN systems despite the relatively low accuracy of the resulting estimates. Several sites demonstrated that ultra-wideband (UWB) and ultrasound signaling have the potential for greater ranging accuracy vs. BLE. While UWB and ultrasound signaling systems can provide better ranging accuracy, there are practical problems precluding their use with current smartphones; e.g., UWB is not widely available, and both UWB and ultrasound use more battery power for transmitting vs. BLE, because most current smartphones have special low-power hardware for transmitting BLE without turning on the processor. As smartphones evolve, the selection of one or more AEN signaling systems should be revisited based in part on expected improved accuracy. Furthermore, smartphone manufacturers should be encouraged to consider ways of making transmission of UWB and ultrasound more battery-power efficient. Battery power efficiency is an issue for receiving all three signal types (BLE, UWB, ultrasound), because the smartphone processor must be turned on, and so smartphone manufacturers should also be encouraged to consider ways of making reception of these signals more battery-power efficient.

Estimating range from BLE RSSI is difficult for many reasons. The antenna gains for transmit and receive are not uniformly omnidirectional, and so measured RSSI is heavily dependent on the poses of both the transmitting and receiving phones. The antenna gains also vary among phone models. Metadata available at the transmitting phone, such as pose angle and whether a phone is in a pocket/bag, could be sent to the receiving phone to improve range estimation.

In addition, metadata from other sensor inputs could potentially improve risk estimation separate from range estimation; e.g., estimates of whether each phone is inside or outside a building could be used as part of the risk estimation equation. The common 2-meter and 15-minute thresholds specified by PHAs for COVID-19 are simplifications, and do not take into account either environmental factors (e.g., inside vs. outside, levels of ventilation, volume of interior space) or additional protection factors (e.g., the use of PPE such as masks). AEN was deployed and parameters were set in an attempt to be consistent with these PHA-specified range and duration thresholds. Although this same approach might be followed in future similar events, future AEN systems should minimally be configurable to account for as many factors as possible that are known to be relevant to actual transmission risk.

An important element contributing to AEN effectiveness is the relationship between how the virus is transmitted and how AEN determines whether an exposure took place. For COVID-19, the combination of person-to-person proximity and the duration of that proximity event ended up being reasonably well correlated to COVID-19 transmission. This was largely due to the fact that the primary transmission route for COVID-19 was through the inhalation of virus containing droplets and aerosol particles exhaled from an infected person. Alternatively, fomite-based transmission from surfaces was (and is) not believed to be as important a pathway for infection. If COVID-19 were transmitted mainly by fomites or other mechanisms, AEN might have been much less effective at determining a COVID-19 transmission event. This relationship between the AEN proximity measurements and transmission mechanisms should be studied further to understand AEN's detection performance across the full range of transmission modes. Furthermore, understanding this relationship for other viruses and diseases, beyond COVID-19, will help determine other applications of AEN. Ideally, a mapping of AEN detection capabilities for various transmission pathways, across a wide range of concerning pathogens, would drive the future development of AEN and would help developers tailor the technology for a variety of public health needs.

Accurate modeling, simulation, and prediction of the impact of AEN on overall mitigation of the spread of a disease requires detailed knowledge of how people interact with each other. Without knowing how proximate people tend to be with each other and how they move about each other as a function of location (e.g., public, private, inside, outside, store, school, airport, theater, etc.), time of day, day of week, pandemic-related public health mandates (e.g., no advisory, maintain distance, lockdown, PPE usage, etc.), and culture, we really can not estimate the expected impact of AEN. For example, in a peak pandemic complete lockdown, we expect AEN to have less impact than during pandemic non-peaks when people are allowed to congregate and move about indoors. Some proxemic and local mobility data was collected, but the openly available data seems to have been collected via questionnaires as opposed to instrumentation and sensors. Measuring objectively how people in different countries, in different venues, at different days/times, and at different stages of a pandemic move and dwell around each other would permit more accurate modeling, simulation, and prediction.

The most fundamental question left unanswered in the discussion above is, "Was BLE ranging and signaling as implemented in AEN for COVID-19, with all its weaknesses, effective in notifying contacts of possible exposure events, and if the ranging method were more accurate, how much more effective would AEN have been?" The first question will be addressed in Section 6. The second question can be modeled, but it is really a subject for future research.

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3. PRIVACY AND SECURITY

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3.1 MOTIVATING QUESTIONS

This section considers the following questions related to the privacy and security of AEN systems:

- What are the overarching privacy/security principles for the design and implementation of AEN?
- What tradeoffs between privacy/security and other system goals should be considered in the design and implementation of AEN?

3.2 EXECUTIVE SUMMARY

Privacy and security are key considerations in the design and implementation of an AEN system. For privacy, an AEN system should ensure that no information is revealed beyond the exposure notifications provided to affected users. In particular, a privacy-preserving AEN system should minimize an adversary's ability to learn information about users' locations and movements, social interactions, and infection status. For security, an AEN system should ensure that an adversary cannot introduce false exposure notifications or prevent true exposure notifications.

We focus on the GAEN system and similar decentralized designs. GAEN addresses privacy and security using cryptographic protocols for generating chirps and authorizing uploads, as well as system-level protections. Cryptographic protocols are also used to enable privacy-preserving metrics collection to help public health authorities (PHAs) assess the effectiveness of AEN.

There are many tradeoffs between privacy/security and other system goals in the design and implementation of AEN systems. For example, GPS location or other sensors could improve exposure detection but would introduce privacy concerns. Other design choices and parameters present tradeoffs between privacy/security and system efficacy, scalability, or usability. Despite these tradeoffs, to our knowledge there have not been any successful large-scale attacks on the privacy or security of GAEN deployments.

3.3 PRIVACY AND SECURITY GOALS

We distinguish the more limited functionality of exposure notification from that of traditional contact tracing. Exposure notification focuses on notifying contacts of an index case of their potential exposure, while traditional contact tracing and associated processes may also collect data, monitor contacts, or perform disease surveillance.

For privacy, an AEN system should hide all information except the actual exposure notifications provided to users. In particular, a privacy-preserving AEN system should avoid using location and should minimize an adversary's ability to learn information about users' locations and movements, social interactions, and infection status. Also, no data should leave a user's phone without the user's consent.

For security, an AEN system should ensure that an adversary cannot introduce false exposure notifications or prevent true exposure notifications. For the former, only users who have tested positive should be authorized to upload information used to determine exposure notifications. Furthermore, exposure notifications should only be issued to users who were actually in proximity to a user who uploaded information. For the latter, among other considerations, integrity and availability of the server must be maintained so that users can download complete, correct, and up-to-date information.

These privacy and security goals must be achieved in spite of malicious users, malicious app implementations, and potentially compromised PHAs and back-end infrastructure. They must also be balanced with other system goals such as efficacy, scalability, and usability.

3.4 CENTRALIZED AND DECENTRALIZED DESIGNS

For any system involving sensitive user data, where the data resides and who has access to the data are major design considerations. While most architectures involve a central server for the routing of information, for AEN the terms “centralized” and “decentralized” refer to the following distinction:

- Centralized: Systems in which a central server is responsible for determining exposures and notifying affected users.
- Decentralized: Systems in which each user’s device is responsible for determining the user’s exposures and notifying the user.

In centralized systems (e.g., BlueTrace [1], ROBERT [2]), the central server issues each phone the random chirps that the phone broadcasts. COVID-19-positive users’ phones upload the chirps they have received. The server checks for matches between the uploaded chirps and the chirps that other phones have broadcast, and sends exposure notifications to those users who may be affected.

In centralized systems, the server is privileged and trusted with substantial information about user identities and interactions. In particular, the server learns information about the social graph, including the identities of users who have been in proximity to COVID-19-positive users. While access to such data could enable closer integration between AEN and manual contact tracing, it introduces privacy concerns and the potential for misuse of the data. The server also constitutes a single point of compromise that could be exploited by an external adversary.

We focus on GAEN [3, 4] and similar decentralized designs (e.g., DP-3T [5], PACT [6], PACT [7], TCN [8]). These designs work as illustrated in Section 1, Figure 1. Each phone generates the random chirps (rolling proximity identifiers (RPIs), in the case of GAEN) that it broadcasts from random cryptographic keys. COVID-19-positive users’ phones upload the keys used to generate the chirps they have broadcast. Each user’s phone downloads those keys, checks locally for matches between the chirps generated by those keys and the chirps the phone has received, and displays an exposure notification if the user is potentially affected.

In decentralized systems, the server has essentially the same view as any user in the system and is not trusted with sensitive data. Identities of users who receive exposure notifications are only revealed to the PHA if and when the user takes informed action (e.g., calling the PHA to request information). For users who do not test positive, no information is shared with the server. The server also cannot link observed chirps to identities.

3.5 TRADEOFFS BETWEEN PRIVACY, SECURITY, AND OTHER GOALS

The design and implementation of an AEN system must balance privacy and security with other goals, such as efficacy, scalability, and usability. We show several examples of such tradeoffs to consider. Further discussion of such tradeoffs in the context of GAEN can be found in [9].

3.5.1 Non-use of Location and Other Sensors

While BLE is the primary sensor used in AEN systems, additional sensors such as GPS location, camera, or microphone could be considered in order to improve functionality. However, even limited use of these additional sensors could introduce real and/or perceived privacy risks. Given the likely importance of trust and perception of privacy for adoption, GAEN explicitly excludes GPS location and other sensors besides BLE. Nonetheless, it is worth considering the enhancements that location and other sensors might enable, particularly for improving the detection of COVID-19-relevant exposures.

As discussed in Section 2, incorporating environmental and personal factors (e.g., indoors vs. outdoors, mask wearing) could improve the estimation of exposure risk. GPS location might help detect whether the phone is indoors or outdoors. However, this might introduce general privacy concerns about the use of location, as well as new concerns about potential monitoring of quarantine compliance.

Similarly, the phone camera might be used to detect whether the user is wearing a mask. Mask detection could be incorporated into the existing facial recognition systems on many phones. However, this might introduce general privacy concerns about the use of the camera, as well as new concerns about potential monitoring of mask compliance.

Some proposals (e.g., NOVID [10], SonicPACT [11]) use ultrasonic ranging to improve distance estimation and thus improve exposure detection and risk scoring. These proposals use BLE to establish general proximity and ultrasound to improve accuracy. However, ultrasonic ranging requires devices to use the microphone to intermittently record audio. Again, the use of an additional sensor could introduce privacy concerns that might easily outweigh the potential benefit.

3.5.2 Chirp Unlinkability

For the strongest privacy, an AEN system should ensure chirp unlinkability. That is, different chirps broadcast by the same user should not be linkable, even for a COVID-19-positive user who has uploaded information. However, this privacy goal must be balanced with scalability requirements. A decentralized system requires client devices to download and process data in proportion to the number of positive users who upload information. The system should work over a range of low-end devices in regions with expensive network connectivity.

Most decentralized designs trade off chirp unlinkability and scalability in the following manner. Each phone uses a daily key to generate the chirps broadcast that day, and only the daily keys (not the individual chirps) from COVID-19-positive users are uploaded and downloaded. However, given a downloaded daily key, different chirps that were generated from that key and observed throughout the day can be linked as having come from the same user. This may enable some degree of inference about the interaction patterns of COVID-19-positive users who upload keys.

This tradeoff seems reasonable given the alternatives. Uploading individual chirps would avoid linkability but would lead to very large download sizes. Reducing the one-day key duration would reduce linkability but would still lead to large download sizes. Some academic proposals (e.g., CleverParrot [12], variants of DP-3T [5]) improve privacy by reducing linkability and hiding exposure times but also require larger download sizes.

Selecting scaling factors based on conservative estimates allows worst-case planning in terms of how much bandwidth, storage, and computation are required to use the system. GAEN selected the one-day key duration to support regions having up to 1 million cases at any given time. Future work might consider a more flexible approach that optimizes the privacy/scalability tradeoff by dynamically adjusting the key duration based on the number of cases in a region.

3.5.3 Replay and Relay Mitigation

A secure AEN system should ensure that an uploaded key can only trigger exposure notifications for users who were actually in proximity to the owner of that key. An adversary might try to violate this property by performing a replay or relay attack. A replay attack observes chirps broadcast by other phones and rebroadcasts them at a later time. A relay attack rebroadcasts observed chirps in real time to a different location (using a radio link to transmit the received chirps to this new location). Both attacks aim to trigger spurious exposure notifications if and when the original broadcaster uploads keys. One way to mitigate these attacks is to use a source of data that is shared between devices in close proximity but is outside the control of an adversary.

Replay attacks (rebroadcasts at a later time) are mitigated by incorporating time into the protocol. In the GAEN protocol, from a known key, one can derive both the generated chirps and the times when those chirps should have been broadcast. The exposure checking algorithm compares received chirps, and the times they were recorded as received, to chirps generated by uploaded keys, and the times they should have been broadcast. In this way, the protocol protects against replay attacks up to the granularity of time used for chirp generation and exposure checking.

In practice, AEN implementations must balance replay protection with other system considerations. For example, user devices exhibit a wide range of clock drift. To accommodate most devices, GAEN allows a tolerance window of +/- 2 hours (or 1 hour or 30 minutes in some regions) between the supposed times a chirp was sent vs. received. This tolerance window increases the chance that affected users receive exposure notifications but also increases the window during which replay attacks are possible. Future work might consider ways to improve this tradeoff.

For relay attacks (rebroadcasts in real time), the time shared by devices in close proximity does not have enough precision to detect rebroadcasts. Instead, relay attacks could be mitigated by incorporating coarse-grained location into chirps (e.g., via a one-way hash). This would allow receiving devices to distinguish between chirps originating from a nearby sender and chirps relayed from a different location.

The GAEN design prioritizes the exclusion of location over the potential benefits of location-based relay mitigation, for several reasons. For an adversary, the practical challenges of performing a relay attack, in terms of equipment, complexity, power, cost, and odds of detection, would likely dwarf any benefits he might obtain from the attack. Also, a sophisticated adversary with the resources to perform a relay attack might also have the resources to spoof location and defeat a location-based mitigation strategy. If relay attacks are deemed a significant threat, future systems could consider defining permissions for the limited use of location (e.g., coarse-grained and hashed) specifically for relay mitigation.

3.6 TEST VERIFICATION

A secure AEN system should ensure that only COVID-19-positive users upload keys. Therefore, AEN systems should include a verification mechanism to ensure that all uploads are tied to confirmed positive tests. At the same time, at-home tests, which are not required to be reported to the PHA, are now prevalent and should be handled as well.

Verification requires interaction among the positive user, who chooses to upload keys; the PHA, which can attest to the user's positive test result; and the key server, which must verify that the upload is tied to a positive test without being able to link the user's identity to the submitted keys. The range of possible solutions depends on the level of integration, if any, between the AEN app and the PHA's test reporting system, as described in Section 4.

In the U.S., where such integration does not exist, the GAEN verification mechanism uses verification codes. The PHA sends a verification code to each user who has tested positive. The user submits the verification code to the AEN app, initiating a protocol that signs the keys to be uploaded and interacts with the verification server and the key server to upload the keys. The privacy design separates the verification server, responsible for ensuring that uploaded keys are tied to a positive test, from the key server, responsible for storing and distributing the uploaded keys. This separation ensures that neither server can link user identities to keys. Further discussion of the operation of these servers can be found in Section 4.

To prevent brute-force guessing, verification codes need to be either long or only valid for a short period. This must be balanced with usability, as users need to be able to submit their verification codes correctly and within the validity period. The GAEN implementation provides two options (a code or a link) with different lengths and validity durations depending on the means of distribution (over the phone or via SMS).

To address challenges with distributing verification codes in a scalable and timely manner, as well as the increasing prevalence of at-home tests, GAEN introduced a self-reporting option. This allows any user to report a positive test and upload keys without additional verification, but with a limit on the frequency with which users can upload keys. Self-reporting has been deployed in 15 regions across the U.S. and 5 regions in other countries and accounts for 30–50% of uploads in some regions. Although self-reporting allows the potential for uploads by users who have not tested positive, there have been no indications of widespread abuse in practice. However, no in-depth studies have been conducted yet. Future work could investigate more secure verification and abuse mitigation mechanisms for self-reporting.

3.7 PRIVACY-PRESERVING METRICS COLLECTION

Due to its privacy-preserving design, the core exposure notification system does not transmit exposure notification data from users' phones to PHAs, Apple or Google, or other entities. However, PHAs seek aggregate metrics to help assess and monitor the public health impact of AEN. One approach, taken in some countries with their own AEN apps, is to collect de-identified or pseudonymous individual data [13]. Another approach, offered in ENX with the Exposure Notification Privacy-preserving Analytics (ENPA) system, is to collect aggregate-only metrics in a privacy-preserving manner [14, 15].

ENPA's privacy-preserving design limits the information each entity learns. Only the PHA (not Apple or Google) learns the aggregate statistics, and no entity (not even the PHA) learns the contributions from individual users to those aggregate statistics. ENPA is opt-in at each level: each PHA decides whether to enable privacy-preserving metrics for its region, and each user decides whether to contribute data to be aggregated and shared with the PHA.

ENPA's aggregation protocol combines a cryptographically secure computation protocol called Prio [16] and differential privacy techniques [17]. Cryptographically secure computation allows two or more entities to jointly compute a function of some data without actually seeing the data, by operating on random "shares" that individually reveal no information. Differential privacy limits how much aggregate metrics reveal about any individual user by adding random noise and producing approximate rather than exact results. The ENPA system also includes device attestation and input validity checks to protect against certain malicious behaviors.

The privacy of the metrics collection system relies on non-collusion among the entities involved in its execution. In the U.S., the ENPA system involves servers operated by Apple and Google for device attestation, the Internet Security Research Group (ISRG) and the National Institutes of Health (NIH) for secure computation of differentially private statistics, and MITRE for the interface that provides the metrics to the PHAs.

ENPA supports a small set of defined metrics relevant to public health impact. These are limited to data known to the phone's AEN app; they do not capture user behaviors such as quarantine or isolation. ENPA metrics currently include estimates of the number of exposure notifications issued, the number of users who received an exposure notification and subsequently reported a positive test result and uploaded keys, the number of days between an exposure event and the corresponding notification, and the distribution of risk scores. Future work could consider privacy-preserving collection of additional aggregate metrics based on PHA needs.

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4. PUBLIC HEALTH SYSTEMS INTEGRATION

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4.1 MOTIVATING QUESTIONS

- How were AEN technologies successfully integrated into public health systems? What challenges were faced?
- How could future technology supporting AEN be better integrated into public health systems in both developed and developing nations?
- What parts of the public health infrastructure would need to be streamlined in order to make the most of AEN? What missing resources would be helpful?

4.2 EXECUTIVE SUMMARY

No review of a pandemic-related technology or system integration during the COVID-19 crisis would be complete without considering the digital, legal, and procedural aspects of system integration with public health. Here, we define "public health systems integration" to be the creation of interfaces and procedures that connect contact tracing and disease surveillance procedures, tools, and infrastructure to AEN functions and metrics, ideally to the mutual benefit of both. This definition includes coordination of procedures across institutions and tiers of responsibility, and necessitates interoperability of systems, but is not meant to imply the consolidation of tools or resources.

In order to integrate COVID-19 contact tracing technologies into existing public health systems, PHAs worked with elected officials, tech companies, information technology vendors, local universities and research centers, and the open source community. At times, they also found themselves in both cooperation and tension with the general public and with parts of the public health community itself. This section describes each of these collaborations, as well as conflicting needs, and highlights key components and processes that enabled integration and interoperability.

Governance structures, pre-defined roles, and pre-existing partnerships—and their absence—influenced all levels of AEN integration. Where key infrastructure did not yet exist, PHAs had to choose between devoting internal resources to developing an infrastructure, or partnering with Apple, Google, third-party developers, and infrastructure providers both to develop new tools and to provision them (e.g., for data storage and connectivity). Public-private partnerships fostered innovation from both sectors, with key practical solutions devised by some PHAs and incorporated into the broadly available GAEN service for integration into other regions' public health practice.

Ultimately, the wide availability and international adoption of GAEN made it easier for PHAs to digitally integrate AEN into their contact-tracing workflows because they could learn from each other's experiences and combine their voices to request implementation changes and new features. Wider adoption of a single approach to AEN also smoothed the way for cross-border contact tracing as lockdowns eased and travel resumed.

To better integrate AEN contact-tracing tools into public health systems next time, we recommend continuing national- and international-level efforts to define open data standards for contact tracing data; investing in low-cost and modularized sensing technology for epidemiologically relevant data; architectural rework to provide more useful metrics to PHAs without sacrificing personal privacy; cross-domain education between technology and public health; and bottom-up planning and provisioning of digital, financial, and human resources to PHAs before the next crisis begins.

4.3 INTRODUCTION

When a virulent infectious disease has the potential to spread rapidly within a community, public health teams use the practices of case investigation (CI) and contact tracing (CT) to provide support and care to infected individuals and to reach their close contacts swiftly enough to quarantine them before they spread the disease to others. AEN was designed to enhance the CI/CT workflow by shortening the time to send the first notification. [1] The CI/CT workflow, illustrated in Figure 6, is generally the same regardless of the tools used by public health teams to carry out their CI/CT activities (paper, telephone, fax, or digitally networked software systems). This section focuses on the integration of AEN into public health workflows and systems, leaving aside the topic of other digital contact tracing tools.

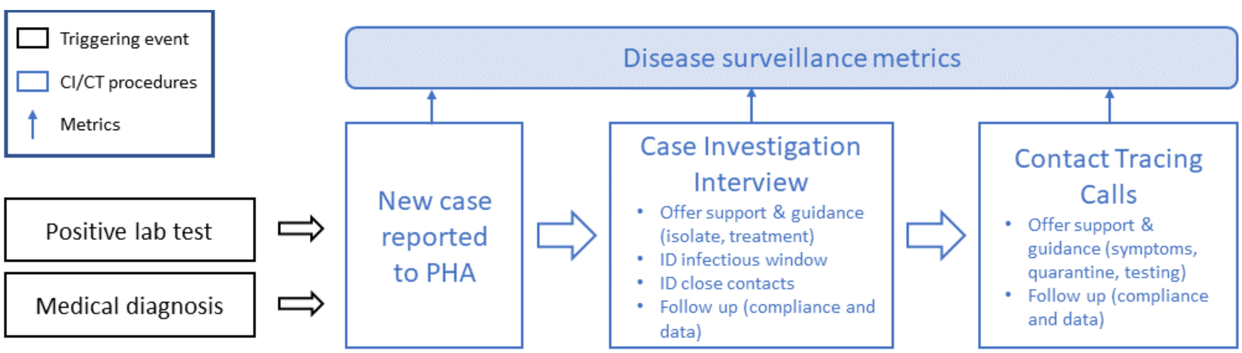

Figure 6. CI and CT procedures at start of COVID-19 pandemic.

The public health mission of swift, effective contract tracing led many PHAs to consider AEN as an extension or augmentation of existing CI and CT efforts. To use AEN within their jurisdictions, regional leaders had to decide whether and how to perform four types of integration efforts:

- **Policy and legal integration:** contact tracing activities must fit within existing laws and public policies, or law and policy must be created or adapted to permit and constrain them
- **CI/CT workflow integration:** contact tracing activities must be performable within existing public health workflows and procedures, or the workflows and procedures must be adapted to implement them
- **Digital integration:** modern epidemiology and health care provision depends on the use of digital tools, which accelerate the delivery of care and public health services, and inform public health decision makers

- **Integration among PHAs:** when many people travel between two jurisdictions, the public health benefits of contact tracing activities are intrinsically shared by both jurisdictions; some level of coordination and interoperability improves the delivery of services in both regions

4.4 POLICY AND LEGAL INTEGRATION

Successful public-health technology integrations must pay attention to existing policy and legal frameworks and may require the creation of new policies or laws to both permit and bound their use. Decision makers at all levels and across all borders struggled to balance conflicting goals: contain disease spread, minimize the economic impact of quarantine and isolation orders, reduce perceived threat to the community's customs, increase or decrease conformity with other political leaders, and avoid public criticism. Every decision around the implementation of AEN touched on these thorny challenges.

With regard to navigating these policy questions, it helped greatly to already have a clearly established ministry or agency to determine whether and how to integrate new public health technologies. Implementation, integration, and course correction actions were delayed wherever decision-making power was shared between multiple ministries at a national level, or across more than one tier of government.

For instance, in the U.S., the CDC showed early interest in and support of AEN pilot programs, but ultimately decided to leave AEN-centered decisions up to individual states. The precedent of conflict between state and federal authorities over other non-pharmaceutical interventions [2] greatly reduced the risk appetite of many state-level authorities, which limited and/or delayed GAEN deployment within the U.S. This state vs. federal tension continued even into the second year of the pandemic [3], regardless of new information about COVID-19 transmission dynamics; as many AEN-using states remained bound (if only by perception, rather than mandate) to the CDC's starkly defined 15-minute detection threshold. Without a nationally coordinated response, states showed tremendous resourcefulness and shared material, data, and innovative solutions with each other, but in an ad hoc fashion with much duplication of effort.[2] [4, 5]

This tension between national and regional decision-making powers affected AEN deployments outside the U.S. as well. In Spain, the national agency Sabah Economic Development and Investment Authority (SEDIA) and regional health services launched different contact tracing apps before gradually converging on a GAEN-based solution. [6]

Integration of AEN systems also required up-front "legal integration;" that is, PHAs and legal authorities needed to come to a shared agreement about how AEN fit into existing legal protections for citizens' personal health information, and whether new legal arrangements should be created both to enable and protect citizens' control of the collection, transmission, and deletion of their health data. Complex governance structures affected this type of integration just as much as the technical and data integrations. In the U.S., state-by-state deployment required duplication of effort. The length of time taken to establish multiparty agreements between state counsel, software providers, and server infrastructure hosts far outweighed the time needed to technically integrate the system components and make sure data was flowing appropriately. This was complicated by a lack of clear legal precedent, which drove the introduction of new legislation in the U.S., such as the Exposure Notification Privacy Act [7], COVID-19 Consumer Data

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[2] Participants (2020–2022). CDC-MIT Learning Lab, virtual meetings, United States.

Protection Act [8], and Public Health Emergency Privacy Act [9] in the U.S. Congress (none of them were signed into law). In the European Union, member states likewise indicated a range of approaches to legal integration of AEN solutions (from "special legislation is needed" to "already based on consent of individuals fulfilling GDPR requirements").

In regions where strong legal precedent for protected sharing of health data existed at the start of the pandemic and few political objections existed, the legal and technical integration of an AEN system went quickly. For example, in Singapore, enabling legislative and technical infrastructure supporting the sharing of data relevant to combating disease outbreaks was extended to the use of the TraceTogether system, which was operationally overseen by the agency with overall responsibility for pandemic response. This facilitated deep integration of the AEN system with systems and groups responsible for contact tracing, quarantine operations, testing operations, and overall epidemiological case management and tracking. Similarly, the UK's National Health Service Act 2006 legislation for healthcare data required no extension or modification for handling AEN data.

Finally, at the largest scope, people's travel patterns demanded some degree of technical and legal integration across borders. Data and critical infrastructure sovereignty had to be examined with regard to data sharing, and with sensitivity to political desires for a "home grown" solution. Although developing a solution completely from scratch would require extra effort, it did not necessarily hinder nations such as India and Singapore from rapidly deploying apps and seeing them adopted by their citizens at very high levels. Interoperability across European nations' apps was accomplished with a federated system of key servers; jurisdictions were given the ability to interoperate, but the decision to do so was left up to each nation. [10, 11] In the U.S., a national public health nonprofit provided the infrastructure for interoperability and each state reviewed their legal policies in order to participate. [12] This infrastructure is discussed further in Section 4.6.

4.5 CI/CT WORKFLOW INTEGRATION

For AEN to effectively supplement traditional CI/CT processes, it was necessary to integrate it as early as possible into the CI/CT workflow, and alert close contacts as quickly as possible. It was not necessary for a PH field practitioner to know exactly how a specific AEN service works on phones and servers, but to use it effectively, it was necessary to understand how it "touches" the pre-existing case investigation and contact tracing procedures. AEN was intended to complement—not complicate—existing procedures, so the number of touchpoints was minimal by design.

Figure 7 illustrates how GAEN contact tracing procedures (solid green boxes) were integrated into preexisting public health procedures (white/blue boxes). The green arrows illustrate new data streams, which enabled GAEN functionality and informed PHAs of population-level metrics from GAEN.

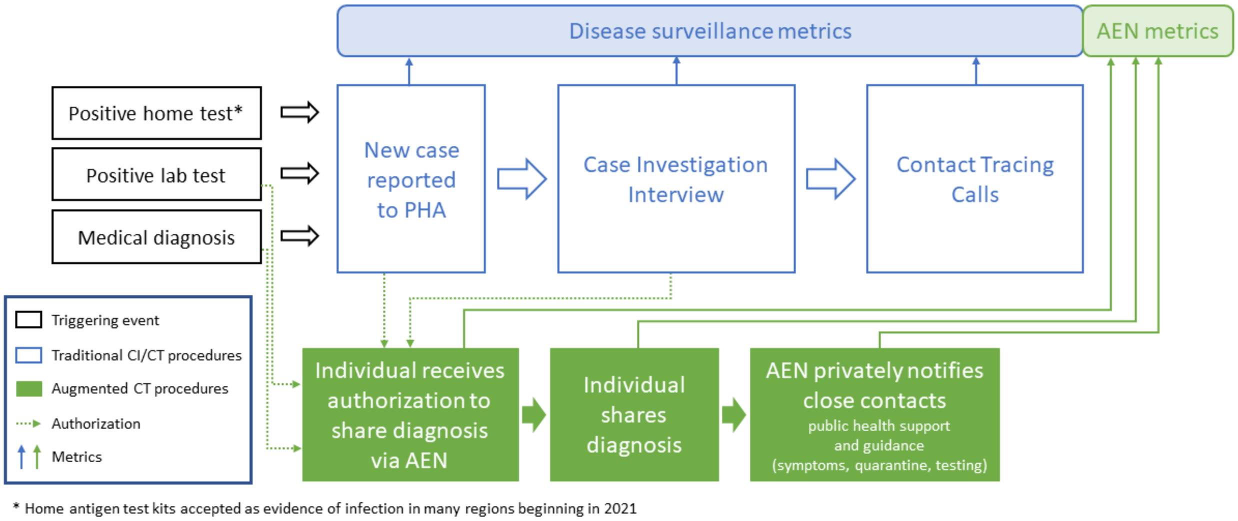


Figure 7. Public health procedures with GAEN integration points.

The three steps of AEN differed somewhat from conventional contact tracing steps:

- **Individual receives authorization to share diagnosis via AEN.** In some places, PHA staff issued authorization codes/links themselves, either during case investigation or by sending an automated message to newly infected individuals, using the contact information provided at the test site. However, in other regions, PHAs gave healthcare workers the credentials needed to authorize diagnosis sharing for patients, reducing delay. Some PHAs shared this ability with the labs or healthcare facilities themselves, who directly authorized individuals in parallel with result reporting procedures. [13, 14] Finally, some regions allowed AEN users to request authorization, by entering their polymerase chain reaction (PCR) test's unique identifier [13] or by self-reporting a positive rapid antigen test or a PCR test taken outside the jurisdiction.

- **Individual opts to share diagnosis.** In conventional contact tracing, the individual provided information about their activities and close contacts to PHA staff. In GAEN-based systems, the individual provided consent to distribute their exposure keys through the service, without requiring PHA staff time beyond the initial GAEN setup. Instead of providing one-on-one consultation, PHAs integrated guidance messages into the GAEN user interface. This eased the workload on PHAs and protected the privacy of AEN users, although it provided impersonal and less nuanced information. To compromise, a few regions chose to integrate AEN close contact alerting directly into conventional contact tracing, such as Australia, with limited benefit. [15]

- **AEN privately notifies close contacts.** In conventional contact tracing, PHA staff attempted to contact those who may have been infected by the index case, according to direct identification and "matching" (e.g., students enrolled in the same classes or residents of the same building). In distributed AEN systems such as GAEN, this was delegated to the close contacts' own smartphone; and in centralized AEN systems, it was delegated to "matching" software on a central server that issued automated notifications.

Finally, a fourth function of AEN also merited integration into PH workflows (light green rounded rectangle):

- **PHA systems receive deidentified data from AEN.** The PHA needed information about the number of cases and close contacts alerted through AEN, and if possible, demographics and other contextual information, in order to make informed decisions about configuration tuning, messaging to the public, and the effectiveness or impact of AEN. Section 6 of this report, "Public Health Impact," explores the sources of AEN metrics and the practice implications of their collection more deeply.

These touchpoints to traditional CI/CT activities were limited by design, in systems that prioritized the privacy of the individual with respect to the PHA. A notable exception to this approach was Singapore's TraceTogether system, which prioritized both speed and thoroughness of tracing chains of infection, and did not hide the identity of potential close contact matches from the PHA's contact tracing staff. Rather, the PHA was notified of all potential close contacts, and conducted full contact tracing procedures. The implications of this centralized approach to digital contact tracing (DCT), in contrast to distributed AEN, are discussed in further detail in Section 5.

The shift from relying on polymerase chain reaction (PCR) and nucleic acid amplification (NAA) tests to the widespread use of rapid antigen tests in homes, schools, and workplaces began at the end of 2021. Test results performed in laboratories were required to be sent to the PHAs, while the at-home tests are only reported if the patient chooses to do so, and only in states that have set up workflows for citizens to report their test results. This required PHAs to consider whether and how to authorize AEN users to share their diagnosis on the basis of a rapid antigen test alone. The introduction of the self-report or self-request authorization workflow allowed AEN users to begin the notification chain of events immediately after testing, reducing the time-to-notification for their close contacts by hours or days. The same self-report workflow allows users with positive lab tests to also self-request authorization to upload as soon as they received test results, rather than waiting for the authorization to arrive via a phone call or automated Short Messaging Service (SMS) after it made its way through the electronic laboratory reporting (ELR) system.

These system changes have both sped up notifications and reduced the number of calls to help desks seeking authorization codes. U.S. PHAs that deployed the self-request feature through ENX described the effect as a "sea change" in the behavior of GAEN users who chose to upload keys, with self-request triggering 40–50% of the number of authorizations issued per week after a few months of availability.[3] While there was much concern over the potential for system abuse with self-reporting when these systems were being developed (also see Section 3 "Privacy and Security"), so far the data indicate that this has not been an issue.

4.6 DIGITAL INTEGRATION

AEN systems have the functions typical of most distributed sensor networks: sensing, logging, data sharing, and node-to-node communication (both peer-to-peer, for the private proximity sensing exchanges, and client-server, for the sharing of infection status and associated metadata). Deploying AEN within a

[3] Participants (2022). CDC-MIT Learning Lab, virtual meetings, United States.

jurisdiction required digital integration across several architectural levels and with a broad range of technologies, their vendors, and existing information technology (IT) systems used by PHAs.

Pre-existing partnerships between government technology centers and health departments lowered the hurdles to integrating AEN systems with other streams of contact tracing and disease surveillance data. Some countries, e.g., New Zealand and Singapore, had centers of excellence which could (and did) tackle the architecture, creation, and maintenance of AEN tools, including open source solutions such as Herald and TraceTogether. There were also jurisdictions, such as Ireland and Finland, where the health authority had sufficient technical expertise and resources to find an appropriate vendor to build and launch an AEN solution based on the GAEN solution, and to integrate with national health information systems as needed.

In other regions, PHAs had the desire to implement AEN but lacked the information technology expertise and resources to launch a large-scale app on a short timeline. PHAs' resources were overwhelmed by the onslaught of new activities and workflows related to the COVID-19 response, and the availability of a turnkey solution such as Exposure Notification Express (ENX) or an open source custom app already developed for another jurisdiction provided welcome relief.

4.6.1 Big Tech

While some regions were already equipped with digital tools to support traditional CT for other diseases [16], and swiftly adapted them for COVID-19 tracing [17], the AEN proposition was digitally transformative [18] by creating a distributed sensing network to supplement existing clinical and public health data streams. The decentralized and privacy-preserving architectures of most AEN protocols required the implementation of new software and prediction of where it would have the most impact. In order to quickly launch any kind of rapidly deployable AEN tool for the public, it was critical to rely on hardware that was already broadly deployed and equipped with suitable sensors, namely, mass-market smartphones. PHAs would need to work within the predominant smartphone ecosystems in their jurisdictions, and therefore, work within the interfaces set by the dominant operating system and hardware vendors (Apple and Google[4]), or else develop a complete sensing and communication solution from the ground up. Several private companies launched wearable Bluetooth- and ultra-wideband-based contact tracing solutions, based on existing centralized architectures (e.g., for industrial safety systems); however, PHAs opted to work with smartphones first and only later did a small number branch into wearable AEN tech. [19]

Apple and Google recognized the critical role they would play in enabling a new public health technology. They sought input from public health and other experts to design and improve a system that would support the needs of PHAs as well as individual smartphone users, and made some necessary changes to their pre-pandemic policies and application programming interfaces (APIs). However, the PHAs and the private tech companies were unlikely bedfellows at the start of 2020, and it took time to build relationships across subject matter domains. In retrospect, it was not clear to PHAs who in the public health community was providing input to Apple and Google, or how that input was being taken into account. Some

[4] The 2019 U.S. Huawei ban effectively blocked GAEN from being available in China, as it included the Google Mobile Services package in which GAEN is implemented. China's digital contact tracing system, while widely used on smartphones within China, is not technologically similar to the GAEN or other Bluetooth-based AEN systems, and this report does not include it for consideration.

jurisdictions felt they lost design decision-making power over the risk estimation algorithm and did not have adequate say in what information would be available to the user regarding exposure risk.[5]

Apple and Google decided to require a governmental sign-off from each jurisdiction and provide users access to only a single implementation per region. This had mixed effects in practice. On one hand, it improved interoperability for PHAs by allowing them to select a single integration approach for their CI/CT systems and workflows and it conveyed to users that there was a vetted, trusted app from their PHA. On the other hand, there could be no "open market" of trusted apps within a region, in which apps with richer features would attract more users. Users were restricted to the feature set implemented by the PHA (or their vendor) and over time, the ease of deployment of the feature-light ENX attracted more and more PHAs. The small feature set may have somewhat suppressed user adoption and retention (in contrast, German public health officials saw a dramatic increase in adoption of their AEN app once they integrated the vaccine credential feature).

"Big Tech" also helped to simplify the integration of AEN apps with the PHA's workflow for case investigation by providing solutions for authorizing users who tested positive to share their status. Google provided an open-source reference implementation of a verification server to help PHAs who wished to run their own service. In the U.S., the Association of Public Health Laboratories (APHL) undertook the operation of a single verification server with technical support from Microsoft, a decision that was motivated by the desire to have the service run by parties independent from Apple and Google. This smoothed the path for state-level PHAs to integrate their ELRs with the verification server API.

The tech companies and the PHAs have largely continued in partnership, in spite of having to figure out how to share interjurisdictional design and integration decisions without benefit of a formal cooperative decision-making structure. Some PHAs were not content with the speed at which the tech companies incorporated feedback. At times, it appeared that the tech companies were more interested in messaging control as public facing companies than in providing messaging to the public that supported the needs of the PHAs (for instance, reluctance to respond publicly to claims of security problems).[5] At other times, public vitriol rooted in a misunderstanding of how AEN works was inappropriately directed at Apple and Google, and their leadership nevertheless continued to provide technical, logistical, and financial support of the system and of the PHAs who have it deployed. As the conversation moves toward the future of GAEN apps, PHAs and the tech companies continue to work together.

4.6.2 IT Subsystem Partners and Vendors

In order for an AEN system to slow the spread of disease, there are a few ways in which it has to communicate with other systems beyond the smartphone ecosystem, such as electronic health records (EHR), electronic lab reporting (ELR), digital case management systems for contact tracing, and often, communications subsystems such as Simple Messaging Service (SMS) texts, peripheral public health technology (websites, metrics collection), and/or other components that operate across jurisdictions, such as data-sharing services for ELR. We give examples below of different implementation approaches to each link in the chain of communication. Many jurisdictions eventually implemented a combination of these options as staffing capacity was unable to keep pace with subsequent waves of infections, and as new

[5] Workshop participants (2021, Oct. 26–27). Public health integration [working group]. ImPACT '21, Cambridge, MA, United States.

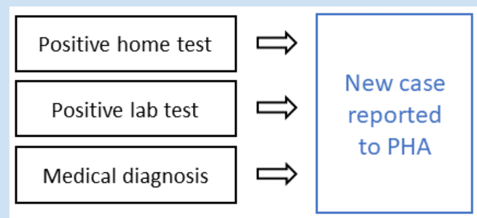
technologies were integrated to meet demand for code distribution (e.g., automated SMS delivery of verification links, self-report of positive test).

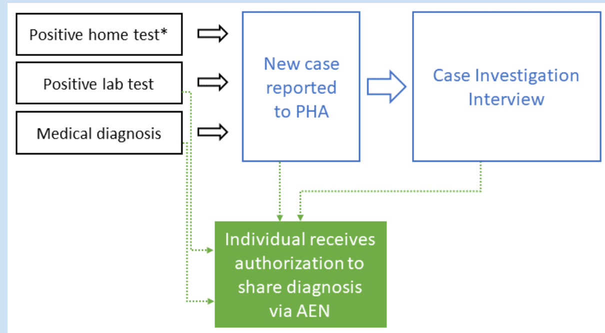
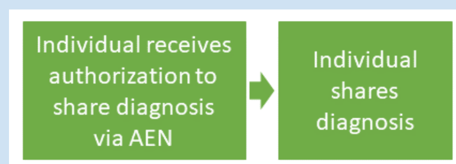
In order to save time and cut off the chain of infection, close contact alerting was implemented as a notification on the close contact's smartphone. The options available for integration varied widely based on the underlying protocol used and what features were available in the app that the jurisdiction deployed. No matter the approach, all involved some amount of integration with messaging infrastructure (SMS, verification and key servers, other public health server infrastructure whether owned by PHA or contracted out), and some reliance on the Android/iOS APIs for generating alerts.

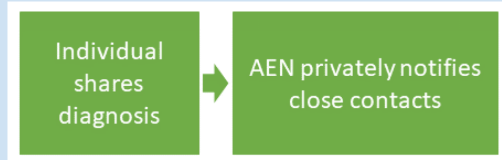
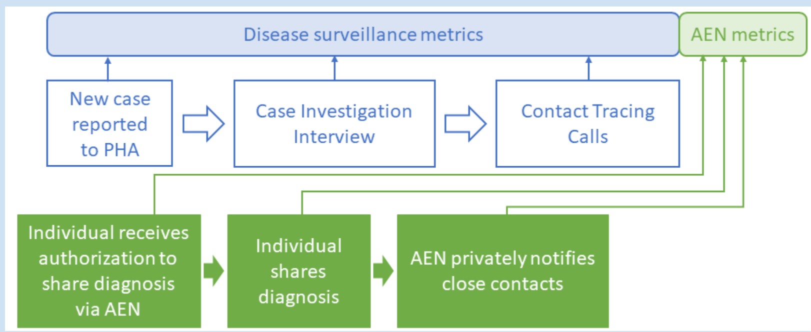
Table 2 describes the most common subsystem integrations and protocols for each of the procedural integration points. To help orient the reader to the existing and augmented workflows from Figure 7, the relevant portions of Figure 7 are shown in each section of the table.

Table 2

IT Subsystem and Component Integrations for AEN

Source	Data	Delivery System	Recipient
1. Competent authority is made aware of new positive case			
Test processing laboratory	Molecular test result, patient identity, contact information	Electronic Laboratory Reporting system	PHA case management system
Point of care (POC) site	Molecular or antigen test result, patient identity, contact information	Electronic Health Records system	PHA case management system
Infected individual	Home antigen test result or out-of-jurisdiction molecular or antigen test result, contact information	AEN interface on individual's phone or web form hosted by PHA or phone call to PHA	Depends on jurisdiction, but usually implemented as an HTTPS service that logs the information and triggers next step

Source	Data	Delivery System	Recipient
2. Competent authority authorizes individual to “share” or “unlock” status			
PHA’s code verification server	One-time code or “deep link” with embedded one-time code	SMS text	Infected individual
PHA’s code verification server	One-time code	Phone call from case investigator	Infected individual
Lab or POC test result portal (with help from AEN verification server)	One-time code	Test results delivery website, SMS text, phone call from health care worker	Infected individual
3. Infected individual makes anonymous infection report available to other users of the AEN system by reporting in a cryptographic key			
Individual’s cell phone	Cryptographic keys that allow phones to uniquely and privately determine whether they have been in proximity to an infected individual	HTTPS upload to key server	Centralized or federated AEN key server

4. Information about exposure reaches the close contacts of infected individuals			
Centralized or federated exposure key server	Recently shared cryptographic keys of infected individuals	HTTPS download to phones for comparison to logged encounters; if it meets the definition of a close contact, system alert on phone screen with guidance on next steps	Close contacts of infected individuals
5. Information about the numbers of cases and close contacts alerted through AEN, and if possible, demographics and other contextual information, reaches the PHA			
AEN system	Number of codes generated and used	Code verification server(s) dashboard/ CSV download	PHA
AEN system	Number of keys shared, number of phones accessing keys	Key server(s) dashboard/CSV download	PHA
AEN users opting in to metrics sharing from phones	Number of alerts received, risk estimate level, frequency of encounters, number of keys shared after receiving exposure alert	Analytics server(s) dashboard/CSV download[6]	PHA
Newly infected individuals, or individuals presenting for testing	Demographic data, whether using AEN, whether/when received an alert	Case investigation phone call, anonymous survey, test administration intake form	PHA

[6] In GAEN's ENX, this was implemented as a secure multiparty computation and aggregation service, "ENPA."

During the course of the pandemic, many integrations followed a similar trajectory: start with simple, semi-manual, and regional systems simply to get something working and judge its usefulness; then automate, scale up, innovate, and look to neighbors for ideas; finally, converge on interoperable systems that meet the needs of multiple jurisdictions. Rapid caseload increases during winter seasons and variant waves motivated PHAs to rely less on manual code distribution and more on automated code delivery through SMS. However, even these resources were strained during the Omicron surge in the winter of 2021–22, emphasizing the need to plan ahead for appropriate IT capacity, such as with telecom companies, messaging service providers, and server hosting providers. The SARS-CoV-2 virus also mutated in such a way that the latent period was reduced, making the speed of identifying close contacts even more critical, and outstripping the ability of even well-resourced contact tracing teams to keep up. Jurisdictions that had moved code distribution as close as possible to test result generation, and automated the delivery of codes, were better equipped to handle this development (affirming the conclusions of [20]). In the GAEN system, this brought the time-to-notify for close contacts down to 4–5 hours (when triggered by a rapid antigen test), compared to 2–3 days at best (when triggered by a PCR test and routed through ELR for authorization). In alternative systems, such as those in which an infected individual could share the contact information or location of their likely close encounters, an alert could be issued quickly via SMS as well as more slowly through conventional contact tracing methods.

EN deployments offered a limited view of anonymous statistical data to PHAs by design (see Section 3.7. for an overview). Analysis and use of GAEN data was difficult for many PHAs in the U.S. due to the changing nature of the data schemas in the key sharing and private analytics platforms, regional variations in data collection methods, and statistical limitations. Many PHAs struggled to interpret or use the data from the Exposure Notification Privacy-preserving Analytics (ENPA) platform due to the implementation of local differential privacy (DP): not only was this dataset difficult to analyze without a strong statistical background, but many important measurements—such as codes sent by individuals who had recently been exposed, or "pseudo-SAR"—were below the DP noise floor and unusable (particularly in smaller states). Additionally, the ENPA and Exposure Notification Code Verification (ENCV) data sources presented data in aggregate format (as opposed to record-level format), making many public health objectives, including health equity and intervention retention, impossible to measure. The Omicron surge of Jan–Feb 2022 drove cases to levels where the DP noise had reduced impact on statistical analysis. After new features were added to the ENPA and ENCV data exports in early 2022, it became possible to estimate the SAR and "excess SAR" by combining data exports; this is an area of ongoing development at the time of this report. [21]

4.7 INTEGRATION AMONG JURISDICTIONS

During the initial lockdown phase of the pandemic, citizens tended not to travel between jurisdictions, and PHAs were spared much cross-border contact tracing effort. However, within a few months, testing became more widely available, and travel restrictions began to ease. This required PHAs to plan how to share data more efficiently on positive cases who had crossed jurisdictional borders.

In the U.S., where GAEN-based systems were deployed state-by-state, this took the form of a national key server hosted by the Association of Public Health Laboratories (APHL); all keys were available to all participants regardless of which states were relevant. [12]

In the European Union/European Economic Area (EU/EEA), member states established the European Federation Gateway Service to enable the exchange of GAEN diagnosis keys amongst national key servers. [22] Under this architecture, individuals could indicate "countries of interest" to check for exposures in places to which they traveled, or exposures at home to individuals using other EU nations' implementations. Cross-border integrations such as these required interoperability at the data format (syntactic) level, and also implied interoperability at the semantic level, i.e., the alignment of epidemiological criteria for "positive" status and for meeting "close contact" criteria (distance, duration, and expiration). So far, there has not been a feasible worldwide integration of GAEN key servers due to both technical and policy constraints. The amount of data to be pooled, without a location-based partitioning scheme (implicitly implemented under the current national-server system), would be impractical, and the EU's General Data Protection Regulation (GDPR) and similar schemes have yet to be integrated with adequate data protection regulations in, for instance, the United States. [23]

Under the GAEN system, a limited amount of epidemiological metadata was made available on the key server (test date, symptom onset date if provided, and "report type" of confirmed test, clinical diagnosis, or self-report). PHAs decided independently which report types their users would be allowed to upload, and decided (for their users) how to weight or mask exposures based on these criteria. Therefore, an individual's risk exposure level could be affected by the combined epidemiological risk postures of two PHAs: that of the infected individual, and that of the exposed individual. Generally this was considered to be mutually beneficial, rather than a source of conflict. PHAs that implemented GAEN systems established both formal[7] and informal[8] mechanisms to share epidemiological heuristics, regional AEN metrics, and integration solutions. For instance, the PHAs that first piloted tiered risk estimates, automated SMS-based code distribution, and self-report freely shared their approaches, key performance indicators, and configuration details with other PHAs. PHAs also shared ideas and feedback on efforts to increase user adoption, to mutual benefit. APHL, Apple, and Google also served as conduits of technical information requests between PHAs, and where pilot programs showed promise, implemented new features and data exports to better support all participating PHAs.

4.8 SUGGESTIONS FOR FUTURE AEN-TYPE INTEGRATIONS

Reviewing the course of the pandemic and the range of PHAs' successes and frustrations suggested several ways to translate hard-won experience into better preparation. We attempted to categorize "tool-oriented" and "relationship-oriented" suggestions separately, but they are inherently linked: existing tools enable and constrain the formation of information-sharing relationships, and existing relationships (or their absence) strengthen (or weaken) the market share of existing tools, as well as fostering/suppressing the development of new ones.

Start with the systems we have: the tools and procedures developed for contact tracing (both conventional and AEN-based) should be inspected, sharpened, and used to create templates for interoperable standards and procedures. Structured data definitions and protocols for exchanging data should be standardized and not tied to proprietary eHealth tools and APIs (e.g., through an international, independent, standards body such as [27]). PHAs should identify their specific system integration "pain

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[7] E.g., through the European Commission's Health Security Committee. [24]

[8] E.g., the U.S. CDC-MIT Learning Labs community of practice meetings, ad hoc regional alliances [25], the two Risk Scoring Symposia hosted by LFPH [26], and ongoing technical exchanges among the original PACT and DP-3T research teams.

points," whether digital, procedural, or political, and identify alternative decisions and "wish list" resources that would have led to better outcomes.

Begin now to build the systems we wish we had: local and regional policy makers should receive these after-action evaluations, and coordinate process and resource development across their agencies and ministries. National and transnational organizations (CDC, eCDC, WHO, etc.) should work with the architects of existing systems and subject matter experts (SMEs) to converge on a system architecture that can be kept warm for rapid response capability, and that has modular components for sensing, risk estimation, and value-added capabilities, such as vaccination information. We should not dismiss these efforts as "preparing for the last war;" we learned the limits of our collective tolerance for lockdowns and should be humbled by the profound epidemiological interconnectedness of our communities. Without an open, modular, and pre-distributed sensing network and rapid response capability, we will fare no better than we have so far.

Plan for the unknowable: competent authorities should be clearly identified, funded, and tasked with pre-planning processes for PHAs to adopt new solutions, in all regions. Bottom-up approaches to information gathering are crucial to informed decision-making in times of rapid change or high uncertainty, such as when a new pathogen is in circulation (as in the first months of the pandemic) or a pathogen evolves new abilities to evade the immune response (as with Omicron and vaccine-based immunity). Competent authorities should pre-plan what bottom-up information they would find useful, and how it will be gathered, as well as how information sharing will be coordinated across borders. The public-private partnerships that enabled rapid and durable responses to the COVID-19 crises should be maintained in "peacetime" preparations, with both public and private stakeholders participating in modeling, gaming, integration, and analysis activities in order to develop well informed and mutually responsible crisis plans. This could be coordinated by a national agency, a non-governmental professional organization, or an industry consortium, as long as the incentive structure is established that will nurture partnerships and a spirit of mutual aid even when we are between emergencies.

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5. ADOPTION, EQUITY, AND PUBLIC ACCESS

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5.1 MOTIVATING QUESTIONS

This section discusses the adoption of AEN within a sample of U.S. states, Europe, and Asia. In particular, we are interested in highlighting the impact of barriers, adoption, and engagement with/usage of these technologies:

- What were the barriers for PHAs to adopt and users to opt-in to exposure notification (EN) technologies?
- What are notification processes, perceptions, risks, and willingness in the event of COVID-19 infection?
- What are users' expectations, behaviors, and attitudes upon receipt of notification of possible exposure?

5.2 EXECUTIVE SUMMARY

When the COVID-19 pandemic began, a handful of digital tools for public health teams existed, but they were not universally available to public health teams and did not empower the individual citizen to share infection status broadly and privately. Automatic exposure notification systems sought to close these capability and availability gaps, but in order for that to happen, both the public health authorities and the citizenry would need to become aware of the systems, gain an adequate understanding of how they worked, and decide to use them. The design decisions made by system implementers, the messaging and deployment decisions made by public health authorities, and the personal trust and altruistic tendencies of individual citizens jointly affected the overall adoption and use of AEN systems. Case studies of specific deployments illuminate the ways in which specific decisions improved or hampered the utility of the deployment and/or the experiences of public health staff and citizens using the AEN app. The lessons learned from studying AEN features and human factors are of immediate benefit to those developing and deploying public health and personal health technology solutions, as well as to pandemic-oriented technology responses.

5.3 INTRODUCTION

AEN technology solutions have been deployed around the world. Each solution requires PHAs or other controlling entities to opt in to provide the service to their populations; individuals within those populations need to subsequently opt in to use the service. The network effects implicit in the peer-to-peer nature of the exchange indicate that pervasive adoption is key to the utility of the system as a whole—for both public health objectives as well as individual users [1, 2]. Though a modeling effort showed that 56% adoption by the population could potentially stop the spread of the virus [3], a subsequent modeling effort indicated that the service can help to mitigate SARS-CoV-2 spread at a 15% adoption rate [4]. AEN benefits generally from high adoption by both users and PHAs, with the efficacy of the system closely dependent both on the degree to which users participate in and use the service, as well as deployment decisions made by PHAs.

In this section, we discuss perception and adoption concerns regarding different types of exposure notification technologies that use existing mobile OS proximity detection functionalities:

- **GAEN-based apps**: API framework requiring jurisdictions to build a custom app and integrate with smartphone users need to download the app to be notified of a potential exposure.
- **ENX**: A turnkey exposure notification solution deployed by Apple and Google, which eliminates the need for PHAs to build a custom app. Comes with the option to push "availability alerts" out to eligible devices.
- **Custom Contact Tracing apps**: Apps that use one or more existing OS features to track possible contacts (e.g., GPS tracking, scanning quick response (QR) code, manually entering a business name or location).

We also discuss the impacts and use of AEN within four U.S. jurisdictions, and compare experiences with Italy, the United Kingdom, and Singapore. The solutions deployed in these jurisdictions are summarized in Appendix A.

Barriers to Adoption. As shown in Figure 8 and Table 3, there are multiple events that require an opt-in for the service to notify others, and a number of potential barriers affecting each required opt-in event. First is PHA adoption of the technology, which follows many of the same barriers as user opt-in events. A jurisdiction or user needs to be aware that the technology or step exists. Other barriers include functional understanding of how to opt in to a given aspect of deployment or use, access/ability to take the required actions, and trust in the technology as well as perception of related risks and the risk/benefit trade-off. Finally, whether people opt in to a given event is affected by the priority/willingness/attention they give to the service or step, which is influenced by their state of mind at the time they become aware of the event.[9]

The following sections discuss each opt-in event and barriers to adoption in detail. Though each barrier is discussed separately, there are many interconnections between the barriers that complicate adoption. This discussion is informed by circumstances and events from May 2020–October 2021, except where otherwise noted.

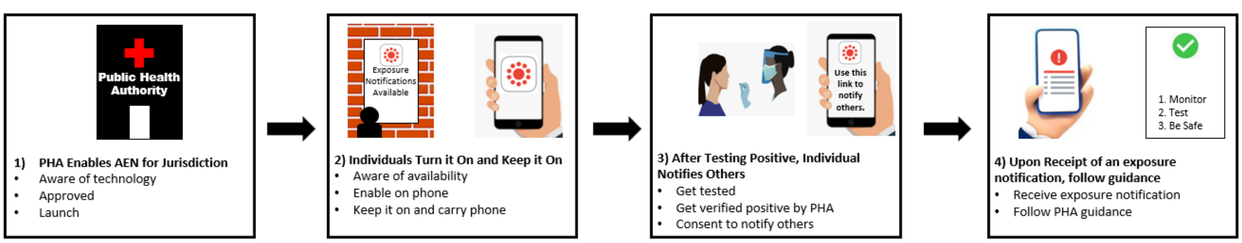

Figure 8. Events required to share a positive diagnosis and alert other users of close contact.

[9] We show the workflow of adoption within the United States for the Google Apple Exposure Notification (GAEN) protocol, as it arguably requires the most opt-in steps.

Table 3

Events Required to Share a Positive Diagnosis and Alert Other Users of Close Contact

	Opt-In/Adoption Event	Barriers to Opt-In/Adopt
1	Providing the Service for a Jurisdiction (PHA)	• **Awareness** of AEN availability • **Functional Understanding** of how AEN works and what is required to make it available • **Access** to necessary technology • **Trust and Perception** of AEN risks and benefits • **Priority/Willingness**—e.g., prioritizing funding to implement and maintain the service
2	Turning it On and Keeping it On (Individual Users)	• All from #1 • **Awareness** of AEN availability • **Functional Understanding** of how AEN works • **Access** to necessary technology • **Trust and Perception** of AEN risks & benefits • **Priority/Willingness**—e.g., attention paid to keeping AEN, Bluetooth on
3	Notifying Others (Individual Users)	• All from #1–2 • **Awareness** of verification code process • **Functional Understanding** of how to notify others • **Access** to verification code • **Trust and Perception** of notifying risks & benefits • **Priority/Willingness**—e.g., attention paid to code and required notification steps due to being busy, dealing with COVID-19 symptoms, etc.
4	Changing Behavior Upon Receipt of Notification (Individual Users)	• All from #1–3 • **Awareness** of notification process, recommended behavior Changes • **Functional Understanding** of notification process, recommended behavior changes • **Access** to receipt of notification, ability to implement recommended behavior changes • **Trust and Perception** of exposure risks, behavior change risks and benefits • **Priority/Willingness**—e.g., attention paid to recommendations, willingness to isolate

5.4 EVENT 1: ENABLING THE SERVICE FOR A JURISDICTION

Awareness. Though technology developers and other technology proponents took significant steps to ensure awareness of AEN technology and available support services, each jurisdiction required at least one tech-savvy proponent to fill in information gaps and champion the technology.

- ***Case Study: Italy.*** *AEN was introduced nationally with good technical support from the government, though most regional PHAs have not integrated it fully into their disease surveillance and intervention systems.*

- ***Case Study: USA.*** *There was no national push for app deployment or initiatives to recommend or support state or regional deployments, so state governments needed to pursue the technology on their own with support from technology companies and technology researchers. As of 12/31/2021, there were 26 states, territories, and the District of Columbia that launched services integrated with exposure notification, reporting varying levels of public engagement and integration with existing systems.*

Functional Understanding. Jurisdictions needed to make decisions about exposure notification with, at best, incomplete data, both with regard to whether to implement the service in the first place, as well as how to implement and integrate various aspects. For example, allowing users to self-report a positive test without PHA validation allowed for the risk of false reports, but requiring a code or a call from PHAs could result in underreporting of cases. Both situations could result in the perceived or actual inaccurate count of cases and contacts in their system, though services implemented features to minimize the risk of false reports. Many jurisdictional decision-makers felt that they did not have enough data or specific knowledge of AEN function to make informed decisions.

- ***Case Study: Singapore.*** *In Singapore, the proposed system was a true digital contact tracing system (DCT) as it intrinsically enabled and supported PHA's contact tracing activities. There was initial reluctance to adopt DCT because it was unclear what effects enabling the service would have on existing infrastructure. PHAs requested data from trials to bolster confidence in the technology prior to committing to deploying it. At the same time, contact tracing teams were concerned that the volume of contacts generated through DCT would include significant false positives and further tax already burdened public health systems, as isolation protocols in Singapore from 2020 to 2021 were PHA-supervised/mandated.*

- ***Case Study: Massachusetts, USA.*** *The Department of Public Health in Massachusetts created a cross-functional team including public health professionals and IT professionals to evaluate AEN in spring 2020, and were cautious about moving forward too quickly without proof of AEN's safety and efficacy. The release of the Lancet study on the UK experience in December 2020 [5] provided concrete evidence of efficacy that helped decision-makers move forward with implementation. The team also modeled various scenarios and settings for key configuration parameters, before finalizing configuration decisions.*

Access. AEN prompted discussions about equity in several contexts. In the case of GAEN, the underlying service and the ENX interface was made available to PHAs at no cost. However, even with free technology, jurisdictions incurred ancillary costs associated with implementing AEN, including staff time, outreach, education, and marketing initiatives. Balancing numerous high priorities with extremely limited bandwidth can make the process for standing up new technologies challenging.

- ***Case study: Italy.*** *AEN was introduced nationally with good technical support from the government. However, configuration and optimization of the app and the messaging was delegated to regional PHAs, who were in charge of the management of COVID-19 testing and were charged with the task of issuing codes. Most regional PHAs did not prioritize the app and did not fully integrate it into their disease surveillance and intervention systems. As a result, codes were rarely issued, even to users who explicitly requested them, and users who tested positive were rarely reminded to share their code with the app. The delegation of implementation logistics from the national to the regional level issues resulted in a greatly reduced impact of the app.*

- ***Case Study: Massachusetts, USA.*** *In Massachusetts, ENX accelerated the process of adopting AEN by lowering the cost to implement and maintain the service as compared to a custom application. Massachusetts could adopt the technology at no cost, eliminating the need to engage with an app vendor. Operational oversight, help desk, and public communications were expected to be a minimal cost compared to maintaining a custom app. In addition, the integration of ENX into the iOS operating system was reported to substantially improve adoption rates in some states [6] to the level that justified the Commonwealth's modest investment in AEN.*

Trust and Perception. A number of trust issues center around integration of an unknown technology. One early consideration was whether exposure notification's association with "big tech" and related privacy concerns would erode public trust in manual contact tracing, where the known distrust of tech companies would affect the relatively positive public opinion of health care providers (comparative trust discussed in [7, 8, 9]). This concern was reduced as the terms "contact tracing" and "exposure notification" became more widely discussed in general discourse, and as research reported on the general trust of PHA and contact tracing information requests, such as reported in [10].

There were also concerns with how integration of AEN would affect PHA access to required data, with perceived and actual AEN function and information visibility driving decisions. For instance, with manual contact tracing methods, a public health agent who is aware of the current and ever evolving guidance can correctly determine whether a person is a true contact or not, while AEN may not be able to make such a distinction. Automated integration could make it difficult to distinguish between true and false contacts, potentially introducing noise into reporting metrics.

- ***Case Study: Singapore.*** *Singapore held discussions on whether to transition from TraceTogether's published BlueTrace protocol to GAEN. However, the PHA had concerns that using GAEN would not provide information germane to shaping public health mitigation efforts, such as the number of close contacts, reconstructions of transmission chains, the number of people being notified to isolate who were subsequently diagnosed with COVID-19 (or otherwise)—in order to evaluate and improve the accuracy of the AEN system, or the identification of super-spreading events/individuals. These concerns over the lack of identifying information available through the use of GAEN led to the retention of BlueTrace, which allowed for more real-time tracking and calibration of public health response, while retaining the precision and recall of AEN/DCT relative to manual contact tracing.*

- ***Case study: Italy.*** *Several regional PHAs did not actively utilize the AEN app. The main initial concern was the lack of integration of the app with existing manual contact tracing and its inability to support the work of contact tracers and provide them with information. Local governors and public experts have repeatedly expressed their preference for more integrated apps like TraceTogether.*

- ***Case Study: Massachusetts, USA.*** *In Massachusetts, a distinction was made between exposure notification and manual contact tracing processes in order to mitigate concerns related to the integration of AEN into the public health surveillance system. Potential contacts notified via exposure notification methods were counted separately from contacts notified by manual contact tracing methods. Individuals identified through exposure notification as a potential contact of a COVID-19 case were only counted as a contact if that individual called into the ENX help center line. A contact record was then created for the individual in the help center system and subsequently imported into the Massachusetts infectious disease surveillance system, but in a manner so that they could be counted separately from contacts identified through manual contact tracing efforts. Due to the anonymous nature of exposure notification, follow-up interventions were only offered to contacts identified through exposure notification who called in to the help center.*

As mentioned earlier, trusted entities such as PHAs may wait for the technology to be proven helpful before being willing to risk their social capital advocating for it, while the technology is unable to prove its effectiveness without broad adoption by the population. This is where technology advocates need to step in; as our case studies highlight, proving the effectiveness and relative safety of the technology has made it easier for states and jurisdictions to buy into the service and offer it for their populations.

Priority/Willingness/Attention. In the United States as of 12/31/2021, there were 26 states, territories, and the District of Columbia that launched exposure notification beginning in August 2020. Since that first launch, there were a number of technology advances that jurisdictions adopted to varying degrees, as shown in Appendix B. Initially, states had to secure an app developer and fund the development themselves prior to ENX. Once ENX was launched, they were able to opt into a service that Apple/Google spent their expertise and resources to build. In some states, such as Massachusetts, this resulted in the decision to field the technology. Other states reported noticeable adoption rate increases after fielding ENX[10] [6].

While a jurisdiction's decision to turn on exposure notification was extremely important, those who prioritized integrating system improvements could realize much larger benefits. System improvements helped jurisdictions integrate exposure notification technology into systems managing CI/CT workflows and were correlated with higher adoption numbers, more rapid and extensive issuing of verification codes, and more notifications sent.

- ***Case Study: Singapore.*** *TraceTogether began as a parallel CI/CT system that public health officials could use to complement information from manual CI/CT. Over several months, system enhancements to existing infectious disease surveillance and outbreak management systems were undertaken, so as to integrate TraceTogether as a key data source. This meant taking an end-to-*

[10] Participants (2020–2022). CDC-MIT Learning Lab, virtual meetings, United States.

end approach to systems integration, beginning with diagnostic test results, integration into a contact tracing interface used by human contact tracers, and eventually into an automated process with human-over-the-loop supervision. Ultimately, the PHA's willingness to adopt and customize an AEN/DCT tool and integrate it closely with contact tracing processes enabled TraceTogether to achieve the PHA's desired outcomes.

- ***Case Study: Massachusetts.*** *Due to concern over the number of codes that would need to be generated manually, the Massachusetts Department of Public Health used the verification server APIs to generate and deliver codes via text to the phone number of all individuals statewide who tested positive, along with instructions for anonymously sharing that result via AEN. Those who contacted the help desk after testing, seeking an authorization code, could obtain one from support staff. Massachusetts also incorporated the GAEN self-report feature, which allows users to request a verification code from within MassNotify. Each choice was intended to improve ease of access to codes, and in turn, increase notifications to potentially positive individuals.*

There is a high level of connection between PHA actions and individual user action, where a jurisdiction needs to make the service available to its population before individual users can opt-in. Once the service is available, there are a number of steps a user must take to fully contribute. The first of these is to decide to turn the service on, and to leave it on.

5.5 EVENT 2: TURNING IT ON AND KEEPING IT ON (INDIVIDUAL USERS)

Awareness. For a user to turn a service on, the service needs to exist, and potential users need to be made aware of its existence. Though many jurisdictions engaged in notification efforts, we should note that there is a difference between being familiar with the terms "contact tracing" and "exposure notification" and knowing that there is an app or service available in a given jurisdiction. Where there is one country-wide deployment, this may be an easier concern to overcome. However, in many U.S. states, there can be multiple college-issued apps competing with the state deployment. There are also known issues with trying to track deployment numbers in areas with high visitation rates from other areas, such as Washington DC and Hawaii [6]. It is unclear from the reporting of these numbers whether users are functionally aware of which state app they are using if they live close to the border between states, or regularly cross over.

Stress levels throughout the general population were much higher during the pandemic [11], while chronic stress has been shown to reduce people's attentional resources [12]. As a result, we can expect that communications need to be more immediate and salient than what would be required during a less stressful time. This perhaps helps to explain the State of California's reported experience of direct messaging to people's phone being the most effective communication strategy [13]. Sufficient marketing efforts for non-pandemic times will likely not be enough to ensure awareness within the demographics they target. In addition, marketing by some entities such as smartphone providers and non-health-related government officials may actually be detrimental to awareness efforts in countries such as the U.S., where there is reported higher distrust in the government [9] as well as smartphone providers [7]. For similar reasons, communications by trusted entities such as health officials including federal public health, and social influences both within someone's local circle or online, may improve willingness to engage.

Functional Understanding. User understanding of app function was shown to affect willingness to engage. In a UK study on app perceptions, many participants expressed lack of knowledge or incorrect knowledge about app function [14].

As discussed in Barriers to Adoption as well as [15], there are a number of required steps built into the app function. People need to enable the service, keep their phone on them and not (for instance) buried in a backpack, and be close enough to other people who also have the service on and phone in a position where its Bluetooth signals are not blocked. Many apps require their users to be 18 or older, which bars most school-age people and children from using the service. Even those who enable the service may turn it off, or turn off Bluetooth to conserve battery, and may forget or not know to turn either back on when they are around others.

Access. Users unable (due to not owning or not being able to own a phone) to or unwilling (due to lack of perceived benefit or safety concerns) to upgrade devices to AEN-capable models were unable to opt into the service. The proportion of Bluetooth-capable devices in general circulation is limited by smartphone penetration rates. There were also concerns about whether introduction of AEN technologies would exacerbate already problematic inequities in health care access by excluding those who do not own smartphones.

- ***Case Study: Singapore.*** *Efforts to subsequently field a wearable device allowed for more comprehensive AEN/DCT coverage over the population. However, retrieval and extraction of data from patients proved operationally and logistically fraught, with the app-based AEN/DCT continuing to achieve superior responsiveness (less than half the upload latency) and cost-effectiveness (by two orders of magnitude). Nevertheless, a wearable device ensures equity of access to AEN/DCT technology for digitally excluded segments of the population, and also goes some way to addressing the concerns of privacy-sensitive users who are assured that the device lacks networking capabilities and cannot independently/automatically upload data that is perceived to be private. In Singapore, about 15% of the population used a wearable device to participate in the national AEN/DCT system, with the remaining 85% using the AEN/DCT app exclusively, or a combination of both app and wearable device. The manufacturing cost of the device was about US $7, excluding distribution, replacement, and collection logistics costs.*

- ***Case Study: Massachusetts, USA.*** *Though the Commonwealth was and is concerned about inequities, exposure notification was deployed as an additional COVID-19 intervention because of its ability to reach populations other public health interventions may not. Massachusetts focused on ways to improve adoption of MassNotify among underrepresented and at-risk communities by conducting focus groups and through targeted public communications and outreach. Targeted communications, outreach, and research were leveraged to engage underrepresented and at-risk communities. Alternative Bluetooth devices (key fobs, etc.) were discussed as potential technologies for future use, to expand the impact of AEN to a broader population.*

Trust and Perception. Privacy and trust are both subjective and context sensitive, and societies and cultures differ in their attitudes toward each, just as cultures differ in their attitudes toward governmental structures. Privacy and perception of suitable trade-offs being made on privacy can increase or decrease trust in technology implementation.

A person's peers can affect awareness of deployments as well as their perception of the service in general. Lack of critical mass of adoption was also shown to be a concern, as the general sense that people were using it [8, 16, 17] and gaining positive benefits from use [18] was cited as a concern in a number of research efforts. The general tone of communications from one's peers can also affect willingness; for instance, if a potential user is first made aware of AEN through social media allegations about a new technology covertly installed on their phone to “track” them [19], jurisdictions will have an uphill battle to counteract these first impressions.

Information privacy was consistently cited and shown to be a concern [8–9, 16–21], with some studies distinguishing which entities the information was shared with. Both [8] and [20, 21] showed that people have concerns with information flows to certain authorities; [8] additionally showed, in alignment with [14], that people are concerned with information flows to people around them, while [20, 21] showed that people were less concerned with information shared with their personal doctor. As discussed in [9], people in the U.S. and Germany are comparatively less trusting in the government, which correlates to them being comparatively less trusting of exposure notification apps. There is some limited evidence in [21] that U.S. populations do not consider PHAs to be “the government,” with PHAs being generally more trusted when compared directly.

The most frequent motivation was wanting to use the service to be alerted of a possible contact, or for using the apps for “the greater good” (UK [14], Germany [22]), which seemed to be fairly consistent across countries. In a U.S. survey, people were most willing to notify others when compared to other exposure notification actions [20, 21]. Personal health providers were consistently shown to be more trusted than others in the U.S. [20, 21, 23, 24], so much so that requests from personal providers moved some sub-demographics from being overall unlikely to use an app [21]. In Fiji, a strong sense of community was shown to correlate with a higher likelihood for using the apps [17].

It should be noted that surveys are not the same as revealed preferences/attitudes; in order to understand what people do as opposed to what they state they would do, more research needs to be conducted on whether people actually used the technology and responded to the notifications.

Priority/Willingness. Many items discussed above are moderated by the priority people put on using the service, as well as their willingness to do so. A strong predictor of this willingness appears to be the extent to which individuals had already adjusted their lifestyle because of the pandemic, even ahead of situational factors such as the contemporaneous severity of the pandemic [25]. Ultimately, if people see the service as safe, effective, easy to access and use, and in broad use in their community, and have already taken actions to manage personal risk, the more likely they are to be willing to engage.

5.6 EVENT 3: NOTIFYING OTHERS (INDIVIDUAL USERS)

Individuals who test positive for COVID-19 and receive a verification code can choose whether or not to notify others through AEN. The number of individuals who choose to do so is an important adoption metric. People who opt into the system prior to a positive diagnosis have the largest opportunity to prevent virus spread. Someone who enables exposure notification at least 14 days prior to telling the service to notify others will have the opportunity to trigger more notifications than a user who enables exposure notification after receiving a positive COVID-19 test result. According to Association of Public Health Laboratories (APHL) data, approximately 25% of all publish requests in October 2021 were from users who enabled AEN on the same day as publishing, essentially enabling the service when being told of a positive test result. While encouraging these individuals to enable the service will not send notifications to their close contacts from the past 14 days, it could help provide the positive word of mouth and perception of many people using the service needed to encourage others to opt in, and may help ensure use should they test positive again in the future.

People also need to be aware that they need to take action to notify others. Usability and user experience researchers know that the more people are asked to do, and go out of their way to do, the less likely they are to take the steps. For instance, apps that require download ask users to take the most steps before using the technology; some U.S. states that required an app download, then subsequently empowered them to enable the service through settings, saw their opt-in numbers increase [6]. Likewise, some jurisdictions required a call from PHA staff to authorize users to upload their keys (so that only people with valid test results would notify others). Functionally, this further limited key uploads to those who answered the phone when a case investigator called. It also required the user to prioritize typing a code in their phone and to ensure they follow the steps required, at a time when they just learned of a positive COVID-19 diagnosis and may be juggling symptoms, loss of work, etc.

Factors influencing whether or not an individual notifies others of their positive COVID-19 status via AEN include:

- Receipt of a verification code
- Interest/ability to turn on AEN if they have not previously (Event 2)
- Interest/ability to complete the process to publish TEKs

5.6.1 Receipt of a Verification Code

In the beginning of AEN in the U.S., codes were provided manually and typically only to those individuals that reported having AEN and indicated a willingness to use it for notifying others. Beginning in December 2020, some jurisdictions began providing verification codes in bulk to a large number of individuals who tested positive for COVID-19, regardless of their use of AEN. Issuing codes in bulk resulted in many more codes being sent and a significantly higher percentage being received (note that not all codes sent are received as a result of various SMS errors, the most common of which occurs when attempting to send a code to a landline).

- ***Case Study: Singapore.*** *TraceTogether began with uploads that were prompted by human contact tracers reaching out to patients with a verification code. This introduced significant human process latency. To reduce the time between exposure and notification, test laboratories' systems nationwide were integrated with a central test registry by August 2020. Positive PCR test results were linked to TraceTogether enrollment through the use of a national ID number, so that SMS messages could be sent to all diagnosed patients, to prompt COVID-19-positive users to upload data with a provided verification code. Coupled with pervasive adoption in public spaces, by the middle of 2021, close to 7 in 10 persons diagnosed with COVID-19 were receiving and choosing to consent to uploading information to facilitate onward notification (also through SMS) of downstream close contacts. During this same time period, it was found that about 1 in 2 individuals, who would have been alerted by manual contact tracing processes, were also being notified by automated SMS. The median latency between the report of a positive diagnosis to notification of these close contacts was well under an hour, instead of hours or days.*

- ***Case Study: European country.*** *An interesting natural experiment occurred in an European country with comparatively high levels of uptake and key sharing. Verification codes were usually shared together with positive test results via SMS. An unrelated change in the structure* *of the SMS resulted in a reduced emphasis and visibility of the verification code itself. This change caused a sudden large drop in the fraction of positive tests recorded by the app and of keys shared: the majority of users who would normally share their keys did not enter their verification code into the app, because they were not made sufficiently aware of the app and the code while receiving their test results. This example illustrates the huge importance of (i) ensuring that codes can be retrieved in a straightforward way by users, (ii) including both the code and a reminder about the app in the positive test confirmation to increase awareness at a crucial time, (iii) careful content design and messaging.*

- ***Case Study: Massachusetts, USA.*** *The process for distributing verification codes to AEN users was designed to minimize delays with users receiving and subsequently entering codes, as well as mitigate user frustration with any technical difficulties encountered during the code receipt or redemption processes. First, before at-home testing was readily available, verification codes were obtained through laboratory testing. As described above, the Massachusetts Department of Public Health (DPH) distributed verification codes embedded in HTTPS links via automated, bulk text messages. All individuals in the state who had a positive test reported to DPH received a text message, sent to the phone number associated with the laboratory test, with a verification link. Second, in order to account for cases where incorrect phone numbers or land lines were associated with laboratory tests, Massachusetts established an email help desk that AEN users could contact to request a verification code in the event that they did not receive one, or if the link they did receive expired (after going unredeemed for 24 hours). Third, as at-home testing became readily available and began to replace laboratory tests, Massachusetts implemented the self-report feature that allows users to request a verification code from within the AEN tool.*

5.6.2 Interest/Ability to Complete the Process to Publish TEKs

AEN is an “opt-in” system both in terms of turning it on and in consenting to share positive COVID-19 status. Upon receiving a verification code, AEN users must still decide to share and complete the necessary steps to consent to publish their TEKs.

The average number of daily publish requests to the U.S. National Key Server [26], for the period May–December 2021, represented approximately 2% of the average daily COVID-19 cases [27] reported by 25 jurisdictions that used the National Key Server. A publish request represents an individual that received a verification code and successfully notified others through GAEN by publishing their keys, see Figure 9.

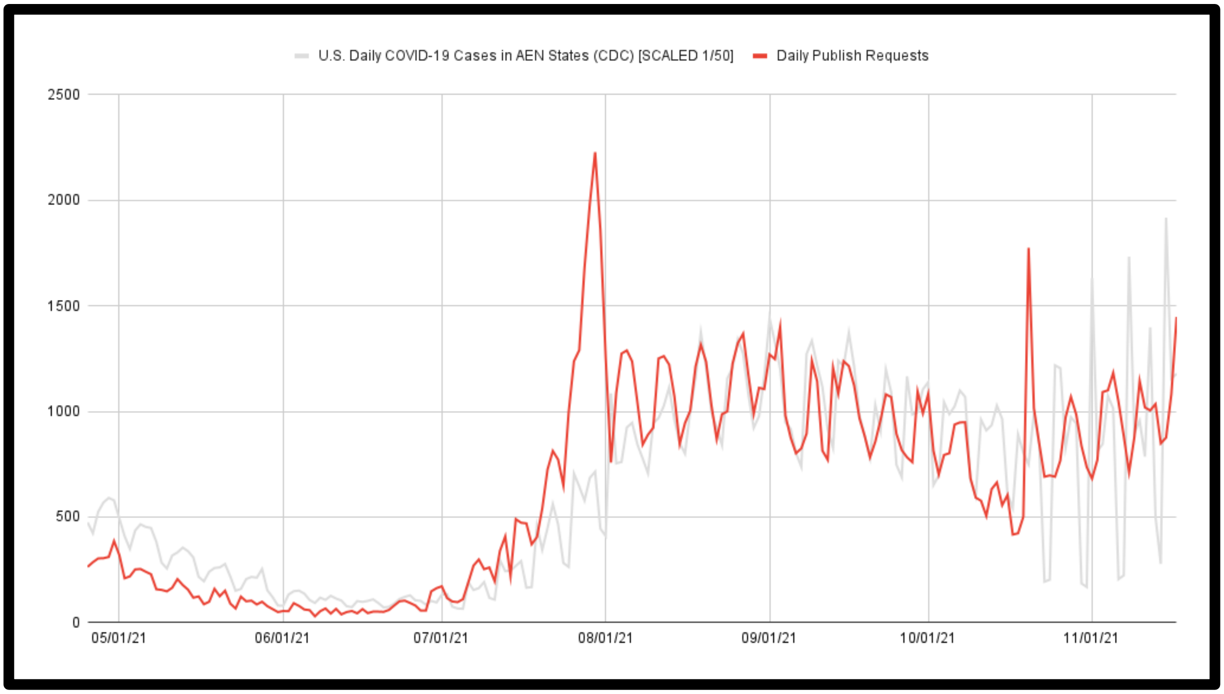

Figure 9. Daily publish requests to U.S. National Key Server.

The information in Table 4 was collected by the Association of Public Health Laboratories (APHL) through their work as operators of the National Key Server for exposure notifications. This represents cumulative publish requests from the 25 participating jurisdictions.

Table 4

Daily Publish Rate to U.S. National Key Server

Month	Average Daily Publish Requests to U.S. National Key Server (25 Jurisdictions)	Average Daily COVID-19 Cases per CDC (25 Jurisdictions)	Average Daily Publish Rate
May 2021	149	14281	1.0%
Jun 2021	69	5284	1.3%
Jul 2021	646	15608	4.1%
Aug 2021	1102	49196	2.2%
Sep 2021	1002	52771	1.9%
Oct 2021	783	40532	1.9%

This data indicates that in all U.S. jurisdictions there is a low percentage of COVID-19 positive cases that result in a publish request, and there is a clear opportunity to improve the publish rate across AEN users. This is a critical adoption step and one that was not as successful in the U.S. compared to other countries.

One advance that made a quantifiable improvement on this adoption step is the use of bulk or automated code distribution, where PHAs send verification codes to all known cases. Due to the anonymous nature of AEN, this approach typically results in all positive cases in a jurisdiction who recently tested positive for COVID-19 receiving a text message from the PHA that includes a verification link; by following the link in the text, individuals are connected into the AEN workflow and can quickly and anonymously share their test result with other users. Recipients who do not use the jurisdiction's AEN tool can be routed to the AEN onboarding workflow and may be encouraged to enable the tool for future use.

Because text messages are sent to all positive cases reported to the jurisdiction's PHA, and there is no way for the PHA to target the subset of AEN users, this approach results in a lower percentage of codes being claimed. That said, it also results in a statistically significant increase in the percentage of cases that result in a publish request as compared with manual code distribution, which requires individuals to procure a verification code manually and independent of the AEN workflow, Table 5.

Table 5

Daily Publish Rate of Four U.S. Jurisdictions in October 2021

Code Distribution Method	**Manual**		**Bulk or Automated**	
Jurisdiction	**Juris. 1**	**Juris. 2**	**Juris. 3**	**Juris. 4**
Average Daily COVID-19 Cases	2831	2106	2532	1480
Average Daily Verification Codes Issued	8	54	2631	1135
Average Daily Publish Requests	4	16	155	40
Average Daily % of Codes Issued that Result in Publish Request	50%	30%	5.9%	3.5%
Average Daily % of Cases that Result in Publish Request	0.1%	0.8%	6.1%	2.7%

The content and data in this subsection is limited to the period from May 2021–October 2021, and does not reflect the positive impact that self-report had on adoption numbers. The impact of self-report on adoption is a topic of active research at the time of the report, and warrants further analysis.

5.7 EVENT 4: CHANGING BEHAVIOR UPON RECEIPT OF NOTIFICATION (INDIVIDUAL USERS)

Once users receive a notification, they need to agree to test and/or quarantine according to the guidelines issued by their jurisdiction. Willingness to do so is very much tied to many of the points brought up prior: visibility of the instruction, with users needing to see and attend the notification; trust in the entity perceived as giving the instruction and the veracity of the information; and finally, belief that it is a necessary action to prevent further virus spread.

As detailed in Appendix B, PHAs learned lessons throughout their deployments, which were used by developers to improve the technology. First, items such as SMS Intercept and Self-Reports resulted in more people choosing to notify others. Second, items such as Risk Score Adjustments and Multiple Notification Classifications resulted in notifications being sent in more appropriate circumstances, and users receiving more accurate guidance for their situations. Jurisdictions that implemented these improvements saw an increase in user confidence in the service and recommendations, which is expected to increase user adherence to behavior change recommendations.

5.8 CONCLUSIONS AND RECOMMENDATIONS

EN provided a means to reduce user adoption barriers and push AEN technology to the masses. However, by itself, and without support of PHA and trust in the PHA by society, adoption will not be adequate. The ultimate goal of AEN is to impact user behavior upon receipt of an exposure notification. While it is challenging to measure the precise impact of AEN on behavior during the COVID-19 pandemic due to the anonymous nature of the technology, different approaches to implementation and roll-out in different jurisdictions, and the changing role of AEN technology depending on the various stages of the pandemic, the authors suggest several areas for further investigation and considerations regarding future efficacy and value of AEN technology.

Technology accessibility. First, consider AEN-enabled hardware devices to cater to populations that are less digitally savvy and to promote equity. Singapore implemented hardware devices, and Fiji also considered this approach. However, operational logistics for retrieval of tokens that do not have network access are significant, and affect the freshness of data uploaded and timely notification of downstream contacts. Second, extend standards to allow for true interoperability between systems, and integrate technology into existing public health workflows [28].

Trust and perception. There is much discussion regarding the extent to which the public's trust in government, and in public health in particular, is required to drive adoption of AEN technology. Different cultural perceptions of government's role and different levels of trust in government resulted in dramatically different approaches to the implementation of AEN technology, as described in this report. The role for the PHA in encouraging adoption is complex and must straddle the line between sharing information and addressing questions and concerns raised by prospective users. Ideally, PHAs will educate users such that they arrive at an informed and positive opinion of AEN technology.

Additional research is warranted to determine the value of marketing, outreach, and education campaigns conducted by PHAs. Even though there were extensive marketing campaigns implemented in some jurisdictions in the United States, for example, AEN adoption was still relatively low and driven in large part by the automated push notifications that accompanied ENX implementations. Perhaps lessons can be taken from Fiji [17], where a strong sense of community was linked to a higher willingness to use the app. Targeting communities that are more prone to adoption, or where trusted individuals can encourage adoption may lead to wider app use in those communities. Trust could then be reinforced by the involvement of the whole community, providing value for both the community and the user.

Privacy. The anonymous nature of AEN technology was perceived by technology companies as critical to the adoption of the technology by PHAs and by individuals. That said, a majority of users surveyed were not explicitly concerned about data privacy and security regarding AEN. However, it is unclear if the seeming lack of sensitivity to how data was treated was due to confidence with the anonymous nature of the AEN architecture or, more likely, a lack of focus on the details of data use in a user-friendly, succinct way. There is value in creating a standardized "treatment paradigm" for data collected via AEN technology to help establish a standardized set of expectations in users (for example, data is always aggregated, users must always opt in to AEN technology, etc.) that is consistent across PHAs. There may be value in collecting additional data through surveys after the pandemic to provide a baseline, though it is unclear how broadly we can ask without responses being anchored to press coverage of AEN systems. Consistent, easy to understand communication regarding data privacy and security will undoubtedly be important for future applications of AEN technology.

User Compliance. There are other potential opportunities to ease user burden, such as providing a quick response (QR) scan at the entrance to the supermarket, or other ways to alert users and potential users to enable the service when it is most needed.

Similar workflow considerations should be made throughout use. In order to maximize compliance with public health guidance, it is important that AEN provides resources that facilitate the dissemination of information to users in a way that is informational, easy to understand, and easy to integrate into their daily lives. For example, PHAs must be able to communicate clearly and concisely to AEN users within the tool regarding:

- Next steps for accessing social services (access to food, health care services, worker's comp, childcare services, etc.) if you need to quarantine
- Clear and local-relevant guidelines on when one can *leave* quarantine
- Clear and local-relevant guidelines on *how* one can take next steps, such as getting tested

PHAs should also consider establishing a live help desk (via email and/or telephone) for users to access appropriate technical, clinical and/or social support to further improve compliance.

PHA Trust in AEN. The role of AEN in future public health emergencies will be determined, at least in part, by the degree to which PHAs trust that AEN is efficacious. To that end, more data regarding AEN should be collected and shared; create forums and expectations for regular release of data, and centralized bodies like CDC and WHO should create anonymized rollups to allow PHAs to share this data in a way that reduces the political risk. Researchers and practitioners should strive to publish evaluations of AEN's efficacy, regardless of whether the results are "positive" or not, to help establish this technology as something that can be used, measured, and improved with rigor.

Ideally, a shared framework for measuring efficacy across PHAs will be developed. Defining a common set of objectives for AEN, and driving shared awareness of that framework and the ability to measure performance relative to those objectives such that a system can be easily legible as "good" or "needs improvement" by most PHAs, will provide the conditions for more widespread use of AEN in the future.

AEN Deployment. Future considerations for AEN deployment should include moving toward more open standards with customizable parameters, for both app-based and OS-settings-based AEN models.

- Risk score structure should be standardized and support different sets of parameters
- Increased ability to customize parameters to handle distance, duration, and infectiousness
- Additional, optional parameters such as mask wearing, vaccination status, indoor versus outdoor setting, etc., should also be evaluated for incorporation in the infectiousness parameter

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6. PUBLIC HEALTH IMPACT

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6.1 MOTIVATING QUESTIONS

- How well did AEN solutions perform in the countries in which they were deployed and what has been their actual public health impact to date?
- What insights and lessons can inform future deployments and can further improve such AEN performance and impact?

6.2 EXECUTIVE SUMMARY

There is clear evidence that deployed AEN systems had a positive public health impact in multiple countries during the COVID-19 pandemic. A number of published papers provide compelling empirical evidence and systematic analysis of the success and public health impact of AEN in certain countries and jurisdictions, as well as anecdotal indications from others.

However, in general, the number of such systematic evidence-based impact studies that are publicly available is surprisingly small. For multiple reasons, in most countries and jurisdictions very little information was shared publicly about the impact of their AEN deployments, beyond basic general parameters such as levels of adoption.

Clearly, more unified, more complete, and more widespread sharing and analysis of AEN performance and impact information in different jurisdictions will lead to important insights, valuable optimizations, and improved benefits, without sacrificing privacy or autonomy.

In this section we highlight some empirical evidence from selected countries on AEN actual performance and impact, as well as offer certain insights and directions for further improvements.

6.3 REAL-WORLD EVIDENCE OF AEN PERFORMANCE AND PUBLIC-HEALTH IMPACT

In Section 1, we outlined the following expected value proposition categories for AEN solutions:

- **Speed**: AEN can lead to faster exposure notification than traditional conventional contact tracing alone.
- **Scope**: AEN can reach persons who are not personally known to an index case.
- **Scale**: AEN can still work when caseloads exceed the capacity of conventional contact tracing.
- **Privacy**: AEN alerts contacts privately and automatically about potential exposure, enabling them to choose how they wish to engage with PHAs. (This is true of GAEN and some of the related other AEN protocols).

- **Adaptability**: PHAs can configure an AEN operating point at different points during a pandemic, so that benefits from AEN detection of true exposures outweigh potential costs from AEN false positives.

There is compelling anecdotal evidence from a number of countries that deployed AEN solutions indeed provided significant benefits in each of these categories, and consequently had important positive overall public health impact.

However, for multiple reasons, very little AEN performance and impact data is available from most countries, limiting the ability to perform systematic analysis, to fine-tune deployment parameters for optimal impact, and to meaningfully compare AEN performance and impact levels across multiple countries with different AEN solutions and deployment approaches.

We provide anecdotal evidence from particular countries as a general AEN "proof-of-value," indication of the levels of public-health benefits and impact due to AEN, and a guide for future AEN deployments with enhanced performance and impact.

In general, anecdotal evidence of actual benefits in each one of the above value proposition categories include:

- **Speed**: An analysis of the Swiss deployment concluded that infected individuals who received AEN notifications entered quarantine on average 24 hours earlier than other infected individuals [1].

- **Scope**: An analysis of the England and Wales deployment concluded that for each infected index case, there were on average at least 2.6 more AEN notifications than Manual Contact Tracing (MCT) notifications, at comparable post-notification positivity rates [2].

- **Scale**: In general, AEN deployments adjusted smoothly to increased caseloads at different phases of the pandemic, including in circumstances in which MCT resources were overwhelmed.

- **Privacy**: In general, there were no reports of any significant AEN-related privacy violation incidents. Overall, the privacy guarantees provided by AEN were significantly higher than those of MCT.

- **Adaptability**: Multiple countries adjusted their AEN risk scores at different phases of the pandemic, in response to prevalence of new variants, varying caseloads, or evolving levels of public health resources. In Germany, AEN was deployed with two risk scores simultaneously, enabling AEN notifications associated with two different risk levels, each with corresponding policy guidelines for notification recipients [3].

Even though a variety of AEN solutions have been deployed in tens of countries during the COVID-19 pandemic, surprising little evidence is publicly available on how well most of these solutions actually performed and what their actual public health impact was. Also, crucial data on manual contact tracing (as a comparator for effectiveness analyses) or on post-AEN-notification COVID-19 test results were often not publicly available due to data protection and privacy concerns. Therefore, AEN data published by most countries and jurisdictions focused mostly on levels of adoption.

However, some countries were able to collect, analyze, and share evidence on AEN performance and impact and these represent compelling specific “proofs-of-value” of AEN solutions, which can be generalized, amplified, and optimized.

Table 6 summarizes selected influential empirically analyzed cases and their corresponding performance and impact data.

In general, these “proof of value” cases establish that AEN solutions were able to identify significant number of new cases (not identified by other measures such as manual contact tracing, or identified earlier than other measures) at a significantly higher positivity rate than prevalence rate (random selection) at the corresponding time intervals.

The attributes in the different rows of the table correspond to different pandemic timeframes and were derived at different countries in different ways, often with different underlying data semantics and context.

Therefore, the objective here is not to compare the impact of AEN solutions across different countries but rather to systematically accumulate key AEN impact parameters for the few countries from which these are available.

The “Exposure Notification Adoption” column in the table represents the percentage of the total population in a country that had AEN activated on their smartphones during a target period. Obviously, a higher AEN adoption rate generally corresponds to higher positive public health impact.

AEN level of adoption was one of the only parameters that were commonly tracked and publicized by most countries during the pandemic. However, adoption rates had multiple data semantics across different countries, including percentage of AEN downloads, installations, or activations relative to total population, relative to population of smartphone owners, or relative to adult-only population.

The “Post Notification Positivity Rate” column in the table represents, for a given country and time interval, the percentage of AEN notification recipients that were COVID-19 positive within a short period after receiving the notification. The higher that rate is (above the general prevalence infection rate at that population at that time interval) the more effective the AEN solution is at identifying true new infected individuals and minimizing false positives.

Such AEN positivity rate is a key performance parameter that in most countries was not readily available. The few countries that did assess it used different measurement methods that led to multiple semantic interpretations. In particular, in some countries the COVID-19 testing registration processes included capturing whether a tested individual has recently received an AEN notification or not (say within the 14 days prior to the test). In such cases, it is possible to derive the AEN positivity rate simply from the test results of all individuals that received AEN notifications (while also considering biases such as the fact that AEN notification recipients who are symptomatic are more likely to register for a test than asymptomatic recipients, and consequently the measured AEN positivity rate can be higher than the true overall AEN positivity rate).

In certain other countries in which it was impossible to capture AEN notification information at test registration time, the AEN positivity rate was derived indirectly by computing the ratio between the number of individuals who agreed to share their positive test results via the app and the total number of AEN notifications sent overall. Obviously, such a derivation method does not consider the percentage of AEN users who choose not to share their positive test results via app, and consequently the AEN positivity rate derived in that manner represents a lower bound of the actual rate.

The “Number of Notifications Per Index Case” column represents the average number of AEN user notifications triggered by each AEN user who shares a COVID-19 positive status, in a given country and period. That value is dependent on the “risk score” parameters that specify the notification threshold conditions (as a function of timing and attenuation).

In general, a higher number of AEN notifications per index case implies a higher detection of new infected individuals and so enhances public health impact. However, in a given target environment, a higher average number of AEN notifications per index case is expected to generally correspond to a lower post-notification positivity score.

The “risk score” parameters thus need to be set in a manner that maximizes public health positive impact at an acceptable public health cost—that is, setting risk score parameters that maximize the average number of AEN notifications per index case, beyond a certain low threshold level of post-notification positivity rate. Lower post-notification positivity rates are associated with increasing costs due to an increased number of false positive notifications (increased loads on public health resources such as testing and increased social and economic costs due to increased number of quarantines of non-infected individuals).

The “Comparison with Manual Contact Tracing (MCT)” column aims to capture relationships between AEN and MCT corresponding performance attributes, in the given country and period. AEN is a public health intervention that is complementary to MCT and AEN incremental public health impact needs to be assessed relative to the value of MCT.

In particular, for the number of AEN notifications per index case, it is important to compare the number of MCT notifications per index case, and the percent of AEN notification recipients that did not also receive an MCT notification. In general, the higher the number of AEN-only notification recipients, the higher the relative positive public health impact of AEN (assuming an AEN post-notification positivity rate above a certain threshold).

It is also important to compare the average relative receipt times of AEN and MCT notifications. In general, earlier AEN notifications relative to MCT notifications correspond to higher AEN relative positive impact.

To establish the relative public health costs and benefits of AEN and MCT, and their optimal joint operation, it is useful to compare the relative positivity rates, operational efficiency, and scalability of each system. Very few countries had such AEN and MCT data available for analysis and comparison.

The columns “Assessed Number of Cases Averted Due to Exposure Notification” and “Assessed Number of Lives Saved Due to Exposure Notification” aim to estimate these AEN public health impact values based on actual data from specific countries during specific time periods.

Such estimations were performed systematically for very few countries and utilizing different analysis methods.

For example, the highly influential paper [2] assessed these values in England and Wales for a time interval of four months using two analysis approaches. The first approach relied on modeling based on the number of AEN notifications and the AEN Secondary Attack Rate (the post-notification positivity rate discussed above). The second approach relied on statistical analysis of neighboring geographical regions with varying AEN adoption rates.

The modeling-based approach resulted in a more conservative AEN assessed impact outcome and concluded that in these four months period in England and Wales, AEN averted 284,000 cases and saved 4200 lives. This is for a total population of 58.9M with AEN adoption rate of 28% and estimated AEN adherence rate of 50–60% (adherence rate represents attributes such as the likelihood that users will test or quarantine following receipt of an exposure notification or will consent to upload their code following a positive test result).

Such benefits can possibly be extrapolated (with appropriate assumptions) to gain some insights about potential AEN benefits for periods longer than four months, and in environments with populations larger than 58.9M.

For any period length and target population, such benefits can be amplified by maximizing the AEN level of adoption (up from 28%) as well as maximizing the rate of AEN adherence (up from 60%).

In Germany, there are two risk level AEN notifications: high risk level (on average five per index case with 21% post notification positivity rate) and lower risk level (11 per index case and 10–14% post-notification positivity rate) [3]. Which of these two levels is more cost-beneficial from a public health impact? Should other levels be considered that may further optimize the public health impact and cost?

In all countries, such measurements, analysis, and optimizations can potentially lead to increasingly significant, cost-effective, and provable exposure notification public-health benefits in the future.

Table 6 presents AEN performance and impact data from a few selected countries from which such data is available. The data in the table should be considered as an anecdotal “proof-of-value” of the general impact of AEN solutions to date, and their potential for the future.

Because of the different time frame involved and the multiple data semantics, the table is not intended to provide any systematic comparison on the AEN deployment effectiveness between countries.

Table 6

AEN Performance and Impact Data

	Exposure Notification Adoption[a]	**Post Notification Positivity Rate (EN-SAR)**	**Number of Notifications Per Index Case**	**Comparison to Manual Contact Tracing (MCT)**	**Assessed Number of Cases Averted Due to Exposure Notification**[a]	**Assessed Number of Lives Saved Due to Exposure Notification**[a]
England & Wales *Assessed Period:* *Sept '20–Dec '20* [2]	28% Pop. 58.9M	6%	4.4	1.8 MCT notifications per index case 6.9% MCT-SAR	Approach A: 284,000 Approach B: 594,000	Approach A: 4,200 Approach B: 8,700
Switzerland *Assessed Period:* *Jan '21–Mar '22* [1] [3] [4]	36% Pop. 8.6M	19–41% depending on time period (prevalent variant)[b]	1.5–6[b]	ENs received on average one day earlier than MCT notifications	Not Assessed	Not Assessed
Netherlands *Assessed Period:* *Oct '20–May '21* [5]	17% Pop. 17.4M	10.4% (3% for recipients with no symptoms, relative to 1% prevalence rate)	Not Available	77% of ENs received before MCT notifications[c]	15,228 (218 hospitalizations averted)	Not Available
Germany *Assessed Period:* *Mar '21–Oct '21* [6]	27% Pop. 84.3M	A (High Risk): 21% B (Med): 10–14% (2 EN risk levels)	A: 5 B: 11 (2 EN risk levels)	Not Assessed	Not Assessed	Not Assessed
Washington State *Assessed Period:* *Dec '20–Mar '21* [7]	27% Pop. 7.5M	5.1%	3.4	2.7 MCT notifications per index case 6.7–13.7% MCT SAR	2636	35

[a] During assessed period.   [b] Based on survey data.   [c] 50% of exposure notification recipients had no MCT notification.

6.4 PUBLIC HEALTH IMPACT OF AEN—GENERAL INSIGHTS

We outline some general insights from various countries regarding the performance and public health impact of current and future AEN solutions.

Post-AEN notification policies should be evaluated systematically. Requiring every recipient of an AEN notification to quarantine may be a counter-productive burden as it may lead to a significant economic cost, reduce adoption, and discourage users from submitting codes as these may trigger quarantine requirements for their contacts. Multiple countries eventually relaxed their AEN post-notification policy from a quarantine requirement to a test requirement.

Certain human factor aspects in AEN app design can make a big difference. In some countries AEN apps required multiple steps to complete certain actions such as approving the sharing of test results and submitting relevant codes. Such design deficiencies significantly decreased levels of participation and adherence and so reduced the overall benefits. In some cases, a significant AEN impact difference between two countries was attributed to single particular app usability weakness.

The benefits of AEN relative to manual contact tracing vary at different pandemic stages. In general AEN is a highly beneficial intervention complementary to manual contract tracing (MCT) and other measures. In countries that were able to compare the performance of AEN and MCT it was established that in most stages of the pandemic multiple AEN notifications were received by users who did not receive MCT notifications. However in some pandemic stages dominated by lockdowns and limited mobility, the number of users who only received AEN notifications was significantly lower.

Different AEN metrics are important for evaluating the success of AEN systems from multiple perspectives. These include metrics for establishing AEN performance, outcome, adoption, adherence, comparison among geographical locations and time intervals, as well as AEN metrics that can provide epidemiological insights such as level of infectiousness of new variants.

The level of integration with PHAs significantly affects the impact of AEN. Countries varied in their level of integration between AEN and PHA coordination and provisioning of other services, from no integration, to partial integration, and ultimately to full integration. The benefits of increased integration vary at different pandemic stages and scenarios.

Improved AEN data collection can lead to better AEN performance analysis and optimization without compromising privacy guarantees. Some countries were able to associate more meaningful context information with individual test results, such as whether the tested person received an AEN notification prior to the test, among others. In such countries, it was possible to measure AEN post-notification positivity rate more directly and accurately than in countries that relied only on indirect measures, such as Google and Apple's Exposure Notification Privacy-preserving Analytics (ENPA), which derive only lower-bound estimates of the actual post-notification positivity rate.

Reducing AEN user constraints increases benefits and impact. Multiple countries expanded their AEN deployments to support home testing with a more relaxed verification of the validity of the test results. It turned out that the amount of cheating and erroneous test results submissions was very small. On the other hand, the added flexibility and accessibility increased the usage and resulted in significantly earlier AEN notifications, and thus consequently amplified the overall AEN impact and benefits.

AEN performance and impact information should be communicated to the public to increase adoption and adherence. For example, indication of the infection risk level following the receipt of an AEN notification (the post-notification positivity rate) relative to the corresponding prevalence rate may encourage users to adhere and counter misperceptions and ping-demic fatigue.

AEN risk scores should be systematically analyzed and optimized. In each deployment environment and pandemic stage circumstances it is possible to measure the average number of contacts within each risk score boundary (attenuation and interval). By associating risk score parameters of contacts with test results it is possible to assess the average AEN post-notification positivity rate associated with each risk score. To date, almost no country was able to perform that level of AEN analysis and optimization, and risk scores were mostly pre-set in a relatively ad hoc manner.

AEN cost benefit models and assessments should be developed to optimize and justify exposure notification deployment decisions. Cost should include direct costs related to AEN deployment and operations as well as costs associated with additional testing, but also indirect costs to individuals and to the economy such as those due to additional burdens related to false-positive AEN notifications. Systematic cost benefit analysis is critical not only to justify the deployment and significant positive impact of AEN solutions, but also to determine the best risk score that represents the optimal balance between the number of true positive notifications and their corresponding value on one hand, and the number of false positive notifications and their corresponding cost on the other hand.

AEN performance and impact data should be made more transparent, more globally standardized, and shared more freely. Valuable AEN aggregated information can be accumulated and shared without any violation of privacy, leading to significant overall public health benefits worldwide.

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7. GOVERNANCE

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7.1 MOTIVATING QUESTIONS

The preceding sections of this report outlined observations and recommendations in the domains of privacy and security, public health, user adoption, and technical implementation. During the pandemic, collaboration and coordination among experts from each domain were critical to successful deployments of AEN technology. The function of governance for AEN efforts was, and still is, to integrate and align the priorities and needs of each of these domains, in order to serve their common purpose. Key questions include:

- How were AEN governance questions—those that rise above single domains of expertise—identified, developed, and resolved during the COVID-19 pandemic?
- Which governance challenges were surmountable? What factors brought about those successes?
- Which governance challenges were not addressed, whether by accident or deliberate avoidance? Why?
- What governance principles and procedures would we desire to have in place, in preparation for another global public health emergency?

7.2 DISCUSSION

The design, development, deployment, and operation of AEN functionality through the COVID-19 epidemic were remarkable for many reasons. Many PHAs were quick to enable AEN within their jurisdictions, even without fully understanding its effectiveness and attendant costs. In parts of western Europe and in more than half of U.S. states, PHAs came together quickly to ensure basic levels of exposure notification (EN) interoperability across jurisdictional boundaries. In some countries and U.S. states, more than 40–50% of adults owning smartphones enabled exposure notification. As summarized in Section 6, the public health impact of exposure notification in terms of cases averted and deaths averted was substantial. Finally, for GAEN specifically, Apple and Google, who are normally fierce competitors, collaborated with an unprecedented level of cooperation to provide exposure notification capability quickly, with little fanfare and with no expected related revenue stream.

Even in light of these successes, the ways in which AEN was defined and governed during the pandemic had some shortcomings that were almost inevitable given the need for speed and the absence of a framework and norms for how such unprecedented systems should be developed and used. [1] There was not sufficient time to work out a fully formed and optimal system for governing AEN that completely balanced the roles and interests of all stakeholders. Points of friction developed between three broad classes of stakeholders, each of which had roles to play and interests to advance and protect with respect to the operation of AEN:

- ***Users.*** The potential users of AEN are members of the general public, who are both customers of the mobile device industry as well as citizens of their respective states. We believe (and Section 5 shows in part) that users want AEN to be effective, private, and have little or no impact on other functions provided by the devices through which AEN is delivered.

- ***PHAs.*** Each PHA is part of an executive branch of government with responsibility for ensuring the health of the public within its jurisdiction. It must follow the laws and executive orders of its jurisdiction. In many nations, PHA is a shared responsibility among several different levels of government (e.g., municipal, state, federal), which can lead to complicated decision-making. Many PHAs have very limited human, financial, and technical resources, and most are tasked with tracking and responding to multiple concurrent public health concerns. Each PHA wants to make an informed and independent decision regarding whether to use AEN, how to provide the capability to its public within its jurisdiction, and how to configure it as a function of time according to its laws, orders, current and projected state of health within its jurisdiction, and overall best judgment. Because members of the public move freely in and out of PH jurisdictions, some PHAs seek to make AEN interoperable across public health borders. Because some PHAs are so resource limited, they tend to seek direction and/or advice from national and international health authorities. Some PHAs are tightly integrated with health care systems, disease testing centers, and health-related Information Technology (IT) services; and these PHAs are well-positioned to take leadership roles with respect to the use and configuration of AEN within their jurisdictions. Other PHAs have almost no resources to allocate to AEN, and so without help from national-level agencies (e.g., U.S. Centers for Disease Control and Prevention [CDC]), multilateral PHAs (e.g., World Health Organization, European Centre for Disease Prevention and Control, E-Health Network) or tech companies, they can not possibly decide to use, configure, and deploy AEN effectively.

- ***Technology companies.*** Tech companies design, develop, license/sell, and operate the platforms (hardware and software) on which AEN runs. They want to ensure that implementations of AEN running on their platforms interoperate with all the other functionality that the platform provides with modest cost in terms of compute, storage, communication, energy, and maintenance. A tech company wants to ensure that providing AEN functionality does not threaten its brand, quality, or internal policies enabling it to deliver on its commitments to its shareholders, customers, and employees.

Some notable AEN governance challenges between these three classes of stakeholders during the COVID-19 pandemic included:

- ***Engineering the right level(s) of PHA control over AEN functionality.*** Developers and research sites thought at first that AEN functionality could be provided by applications that would run on top of the smartphone operating systems; however, the highly integrated design of smartphone platforms means that most AEN functionality had to be integrated into the operating system itself to be most efficient. This integration was achieved through the tech companies defining and exposing a limited API to those PHAs who developed their own AEN apps and an even more limited API to those PHAs who enabled GAEN ENX. These constraints strongly limited the design choices of app developers and PHAs in making tradeoffs between privacy, security, and epidemiological utility of the systems. [2] While some PHAs chafed under these limitations and had a difficult time configuring AEN to achieve their desired outcomes in a manner that was consistent with relevant laws and epidemiological doctrine, other PHAs were overwhelmed by all the choices they were being asked to evaluate and make.

- ***Coordinating how users receive information from AEN.*** When users decide to enable AEN on their smartphones, they may reasonably expect that the capability will communicate with them from time to time. This is no different than when a user installs an airline app on a phone and then expects to get notifications from the airline regarding upcoming flights, delays, etc. Confusion can arise when more than one entity communicates information regarding the capability to the user through the app (or underlying OS). In the case of GAEN, there were times when both PHAs and tech companies were communicating information to the users that could be confusing, and it was not possible to resolve this problem quickly.[11] In addition to coordinating and deconflicting these types of "tactical" messages, unity of strategic messaging (e.g., advocating adoption, conveying trustworthiness, etc.) was a challenge.

- ***Constraining usage of AEN on a per-jurisdiction basis.*** At first, when tests were expensive, vaccinations were scarce or non-existent, and the consequences of an exposure were severe, the decision by tech companies to entitle only national or state PHAs to enable AEN within their jurisdictions seemed reasonable to most. As time went on, users in jurisdictions where the PHA had not yet enabled AEN could get some AEN functionality anyway (they could receive notifications of exposure), but they could not upload their own test results. But it is not obvious from first principles that AEN enablement should require PHA approval, with its attendant process, delays, and cost. There may be situations where altruistic members of a population who seek to warn each other of possible exposure in a privacy-preserving way should be encouraged and enabled to do so even without any government action. There might even be cases where users would seek to participate simultaneously in PHA-administered geographically-constrained and "grassroots" AEN networks.

[11] One example occurred in Switzerland, where exposure notification warned some users that they had N exposure contacts in the past M days as an operating system pop-up message, which was not part of the messaging that the national PHA wanted to send.

A well-defined governance structure for future implementation and operation of AEN might help ensure that decision-making among the actors is consistent with fundamental principles of public health and compatible with the interests of all the actors/domains. While it may not be practical to anticipate and resolve all potential conflicts that could arise, we recommend that a standing international experts group (IEG) be established: to provide a forum for world-wide coordination and consensus-building around AEN policy-making and engineering; to support the development of equitable design and governance decisions through a transparent, well structured, and legally supported deliberative process; to serve as a receptacle for accumulated explicit and tacit lessons learnt from COVID-19; and to provide a baseline of knowledge to guide and inform future efforts. A non-exhaustive list of issues that such an IEG might consider includes:

- Developing standards and protocols to support interoperability of AEN systems across jurisdictional boundaries.

- Maintaining a database of PHA-led AEN implementations, coordinated at the appropriate levels of government (municipal, state or national).

- Harmonizing standards for the APIs between functionality produced by the tech companies and functionality provided by the PHA.

- Convening forums for PHAs and other government organizations to discuss approaches to legislation and executive orders that permit emergency, temporary, and narrow and lawful compromises in privacy for the purpose of enhancing public health—and to promulgate one or several sets of principles with which such legislation should align.

- Articulating principles to inform current and future privacy law as it relates to highly pseudonymized health-related data, such as ephemeral tokens. The legal status of pseudonymous data that doesn’t contain private information (such as TEKs in the GAEN system) needs to be addressed, clarified, and acknowledged.

- Establishing standards for providing PHAs with situational awareness and a means of appraising how AEN is being used and is performing within their jurisdictions, without compromising privacy of individual users.

- Performing the system analysis, modeling, and simulations needed to recommend AEN parameter settings as a function of the pandemic status within a jurisdiction, the cost of testing/tracing/isolation, etc.

- Recommending effective communication templates between a PHA and the public it serves.

- Convening forums for discussions between PHAs and tech companies providing AEN capability—which should either report a set of consensus principles or a set of core consensus principles complemented by a minimum set of alternate principles. Some such networks already exist and include the E-Health Network (a part of the EU) and APHL and ASTHO in the US.

- Providing a receptacle for retention and transmission of lessons learned by PHAs who deploy AEN.
- Sponsoring periodic scientific workshops focusing on new developments in AEN and similar technology.
- Supporting the collection of data sets to assist in the development and assessment of new AEN technologies.
- Encouraging outreach to other forums for non-AEN, technology-enabled user-focused public health functionality.
- Sponsoring tabletop exercises testing AEN technologies and structures for a simulated pandemic.

An IEG should have broad and inclusive representation from the various domains identified (privacy, security, public health, user adoption, and technical implementation). Besides ensuring adequate consideration of all relevant factors, representation is also important to ensure legitimacy of principles and positions put forth by the IEG, and to recognize the inherent need to be able to adapt AEN implementations to the diverse circumstances of different geographies and communities, different cultures, legal/health policy traditions and governance systems, and different severity and phases of disease outbreak response.

One model that could be considered as a reference for the IEG and for future work in AEN might be the multi-stakeholder model that evolved to support decision-making on Internet governance. The IEG might also consider interfacing with existing international governmental and non-governmental organizations in relevant domains. A non-exhaustive list of such organizations might include: UN, WHO, IEEE, ACM, Bluetooth SIG. The proposed IEG will need to prioritize agility, however, as considerations in a future pandemic may evolve rapidly.

Ultimately, in recommending the creation of an IEG, we believe that advance preparation and consideration of governance issues that arose (during COVID-19) and will inevitably arise in a future global public health emergency is necessary to ensure more optimal outcomes for all interested stakeholders—especially the global public and citizenry.

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8. DISCUSSION AND CONCLUSIONS

Automatic Exposure Notification (AEN), as described and evaluated in this report, was in many respects a notable success:

- Although this was a new approach, AEN systems were quickly designed and built, through the collaboration of PHAs, “big tech” (the major smartphone vendors), and academia.
- AEN systems were widely adopted and used in many states and countries. This rollout happened with the leadership of PHAs and the efforts of tech companies to provide the operational support.
- The privacy assurances built-in to the design were not violated in practice.
- AEN systems were sufficiently flexible that one could make modifications “on the fly,” such as modifying the formula for risk estimation, modifying how tests were administered, or simplifying the implementation from a custom app to a generic operating system functionality.
- Many lives were saved by the use of AEN.

Nonetheless, AEN systems have had many limitations:

- They act only indirectly, by influencing the behavior of exposed parties. They do not directly stop the infection of others, as masking, vaccination, or isolation do.
- COVID-19 infection is often asymptomatic either initially or altogether, reducing the number of infected parties who seek to be tested in the first place.
- It is difficult to accurately estimate risk of COVID-19 infection based only on Bluetooth transmission levels. Much potentially useful information is unavailable, and Bluetooth is very “noisy.”
- Automatic exposure technology is complex and may be difficult for many to understand. Furthermore, such complexity makes it hard to audit implementations of exposure notification systems to ensure that they actually live up to the assurances provided by their design.
- The ability to assess the efficacy of AEN is hampered by the fact that a user’s smartphone may not know what a user does in response to an exposure notification, and by the privacy guarantees built into the AEN system.
- “No battle plan survives contact with the enemy.” (von Moltke) The initial design for AEN systems were built on assumptions that turned out to be false:

- COVID-19 transmission was not by large droplets (six foot range) and fomites, but by aerosols (more like smoke).
- Testing was not only by PHAs, but also by individuals testing at-home with rapid antigen tests.

Note: The AEN systems could be adjusted to cope moderately well with such changes in assumptions.

AEN may be a useful tool in fighting future pandemics. Of course, the qualitative characteristics of future diseases may be quite different from those of COVID-19, so the AEN systems described here for fighting COVID-19 may not be usable, or may need substantial modification to be useful.

We hope that this report will nonetheless be useful to those fighting such future pandemics in deciding whether and how one might best use widespread existing technology (such as smartphones) in such a fight.

Finally, we wish to thank all of those who gave selflessly of their time and effort to design, implement, deploy, and evaluate AEN systems. It helped save lives, and the lessons learned may be helpful in saving lives in the future.

APPENDIX A. AEN DEPLOYMENTS INCLUDED IN THIS REPORT

Jurisdiction	Type	When Available	Summary of AEN Solution
U.S., Massachusetts	GAEN-based ENX	Pilot: April–May 2021 State-wide: June 2021	**Managed by:** State public health authority (PHA) **How Enabled:** User opt-in, phone settings **Authorization to Upload:** Verification codes sent via text to all known positive
U.S., Jurisdiction 1	GAEN-based App	Winter 2020/2021	**Managed by:** State PHA **How Enabled:** User opt-in, app download and/or phone setting **Authorization to Upload:** Verification codes distributed manually, via phone call or text, as part of case investigation process
U.S., Jurisdiction 2	GAEN-based App	Summer 2020	**Managed by:** State PHA **How Enabled:** User opt-in, app download and/or phone setting **Authorization to Upload:** Verification codes distributed manually as part of case investigation process
U.S., Jurisdiction 3	GAEN-based ENX	Fall 2020	**Managed by:** State PHA **How Enabled:** User opt-in, app download and/or phone setting **Authorization to Upload:** Verification codes sent via text to all known positives

Jurisdiction	Type	When Available	Summary of AEN Solution
U.S., Jurisdiction 4	GAEN-based ENX	Spring 2021	**Managed by:** State PPHA **How Enabled:** User opt-in, phone settings **Authorization to Upload:** Verification codes sent via text to all known positives
Singapore	Custom Contact Tracing apps	March 2020	**Managed by**: Ministry of Health/Government Technology Agency, Singapore **How Enabled**: User opt-in, app download **Authorization to Upload**: Six-digit code sent to each positive TraceTogether user via SMS together with notification of positive test result
Italy	GAEN-based App	June 2020	**Managed by:** Ministry of Health and regional PHAs **How Enabled:** User opt-in, app download **Authorization to Upload:** regional PHAs in charge of issuing and distributing verification codes at the time of confirmation of test positivity
England and Wales	GAEN-based App	September 2020	**Managed by:** Department for Health and Social Care of the UK government **How Enabled:** User opt-in, app download **Authorization to Upload:** Verification codes issued via SMS together with positive test results

APPENDIX B. SIGNIFICANT AEN ADVANCES AVAILABLE IN U.S. AND IMPACT ON ADOPTION

Advance	Available	Impact on Public Adoption	Known Participating Jurisdictions [a]
Exposure Notifications Express (ENX)	Sept 2020	**Improves: Turning it On and Keeping it On** **PHA:** ENX generates greater awareness by allowing jurisdictions to send an availability alert directly to all devices at the time of launch. (Note that Android does allow Custom Apps to send availability alerts as well.) **Users:** ENX simplifies the process to "Turn On Exposure Notifications" by allowing iPhone users to enable it in their phone settings rather than downloading an app. PHAs may opt to present their ENX solution through Android settings, as well. This results in more people being aware of exposure notification and choosing to turn it on.	17
Automated or Bulk Verification Code Distribution	Nov 2020	**Improves: Notifying Others** **PHA:** Automated or bulk code distribution enables the PHA to send a verification code to all new COVID-19-positive cases without relying on case workers and the manual case investigation process. **Users:** Far more people are able to receive verification codes much faster (in contrast to manual distribution). This results in more people having the ability to notify others, and to do so more quickly.	16

[a] Out of 25 possible as of 12/31/2021.

Advance	Available	Impact on Public Adoption	Known Participating Jurisdictions [a]
SMS Intercept (ENX Only)	iOS = May 2021 Android = Nov 2021	**Improves: Notifying Others** **Users:** By allowing the OS to "intercept" the verification code text message, it provides a more legitimate-looking system notification and begins the "sharing" step with a single tap on the notification (reduces steps required to share). This results in more people choosing to notify others.	7
Additional Availability Alerts (ENX Only for iOS)	Sept 2021	**Improves: Turning it On and Keeping it On** **PHA:** Exposure Notification Availability Alerts can be sent directly to devices at times other than initial launch, to promote adoption. (Note that availability alerts for iOS are only available to jurisdictions using ENX) **Users:** Exposure Notification Availability Alerts can inform and simplify the process for additional users to "Turn On Exposure Notifications". This results in more people being aware of exposure notification and choosing to turn it on.	12
Self-Report	Sept 2021	**Improves: Notifying Others** **PHA:** Self-report provides an option for people who do not receive a verification code to request one from within exposure notification. This reduces exposure notification help desk inquiries, improves satisfaction, and results in more notifications occurring faster. **Users:** This enables people who have not received a verification code from their PHA, people who have not received a code fast enough due to code distribution delays, and people who test positive on at-home tests to notify others rapidly. This results in more people being able to notify others, closer to symptom onset or test date.	6

Advance	Available	Impact on Public Adoption	Known Participating Jurisdictions [a]
Multiple Notification Classifications	Ongoing	**Improves: Changing Behavior Upon Receipt of a Notification** **PHA:** Multiple notification classifications can provide individuals with varying risk level notifications (e.g., low risk to high risk) and associated varying behavior change recommendations (e.g., monitor for symptoms or isolate), allowing PHAs to provide more nuanced guidance. **Users:** This results in an increased confidence that exposure notification is working and more specific behavior modifications based on the level of risk. This results in more appropriate behavior change recommendations.	2
Risk Score Adjustments	Ongoing	**Improves: Notifying Others** **PHA:** Adjusting the modifiable risk score parameters allows jurisdictions to adjust the sensitivity and specificity of the Bluetooth detector, based on evolving variants and recommendations. **Users:** This results in more appropriate notifications to users.	Unknown

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GLOSSARY

AEN	automated exposure notification	Generalized name for smartphone exposure notification services developed and deployed during the COVID-19 pandemic.
CI	case investigation	Interview a new infected person; support, and obtain a list of contacts and activities.
CT	contact tracing	Calling (texting, emailing) the contacts of an index case to determine whether they are a true close contact, and instructing on next steps (e.g., quarantine, isolate)
DCT	digital contact tracing	Not always synonymous with AEN/EN, because it can include other digital tools for performing contact tracing activities (c.f. https://doi.org/10.1002/14651858.CD013699). Many recent papers use it to refer to AEN-like systems.
ENX	Exposure Notification Express	A turnkey solution for GAEN user interfaces. PHAs provide their desired configuration values and user-facing messaging to Apple and Google, who create a basic user interface as an app (Android) or in the Settings (iOS, Android). Also supports sending push notifications to potential users within the jurisdiction, when the system becomes available.
GAEN	Google Apple Exposure Notification	An operating system service and API framework published by Apple and Google, which allows apps to access mobile device features that perform exposure notification functions.
PHA	public health authority	Refers to organizations responsible for the public health of a given jurisdiction, e.g., Massachusetts Dept. of Public Health or the National Health Service.
TEK	Temporary Exposure Key	Name of the code required by GAEN deployments to enable a user's device to flag its Bluetooth chirps and enable notifications of a close contact to other system users.

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LIST OF ACRONYMS

AEN	Automated Exposure Notification
APHL	Association of Public Health Laboratories
API	Application programming interface
ASTHO	Association of State and Territorial Health Officials
BLE	Bluetooth Low Energy
BLEMUR	Bluetooth Low Energy Model of User Risk
CDC	Centers for Disease Control and Prevention
CI	Case investigation
COVID-19	Coronavirus Disease 2019
CSAIL	Computer Science and Artificial Intelligence Laboratory
CT	Contact tracing
CSV	Comma-separated values, a text file format
DARPA	Defense Advanced Research Projects Agency
DCT	Digital contact tracing
DP	Differential privacy
DP-3T	Decentralized Privacy-Preserving Proximity Tracing
DPH	Department of Public Health
EEA	European Economic Area
EFGS	European Federated Gateway System
EHR	Electronic health records

ELR	Electronic laboratory reporting
ENCV	Exposure Notification Code Verification
ENPA	Exposure Notification Privacy-preserving (or Private) Analytics
ENX	Exposure Notification Express
EU	European Union
EUA	European Economic Area
GAEN	Google Apple Exposure Notification
GDPR	General Data Protection Regulation
GPS	Global Positioning System
IT	Information technology
LFPH	Linux Foundation Public Health
MIT	Massachusetts Institute of Technology
MIT LL	MIT Lincoln Laboratory
NAA	Nucleic acid amplification
NGO	Non-governmental organization
NIST	National Institute of Standards and Technology
NPI	Non-pharmaceutical intervention
OS	Operating system
PACT	Private Automated Contact Tracing
PCR	Polymerase chain reaction
PHA	Public health authority
POC	Point of care

PPE	Personal protective equipment
QR code	Quick response code
RF	Radio frequency
RPI	Rolling proximity identifier
RSSI	Received signal strength indicator
SAR	Secondary attack rate
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
SMS	Short Messaging Service
TEK	Temporary Exposure Key
TC4TL	Too close for too long
UWB	Ultra-wideband
WHO	World Health Organization

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
14 February 2023	Technical Report	

4. TITLE AND SUBTITLE

Automated Exposure Notification for COVID-19

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

10383-1

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

TR-1288

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Centers for Disease Control and Prevention

10. SPONSOR/MONITOR'S ACRONYM(S)

CDC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.

13. SUPPLEMENTARY NOTES

13. ABSTRACT

Private Automated Contact Tracing (PACT) was a collaborative team and effort formed during the beginning of the Coronavirus Disease 2019 (COVID-19) pandemic. PACT's mission was to enhance contact tracing in pandemic response by designing exposure-detection functions in personal digital communication devices that have maximal public health utility while preserving privacy. This report explains and discusses the use of automated exposure notification during the COVID-19 pandemic and to provide some recommendations for those who may try to design and deploy similar technologies in future pandemics.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	None	116	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18