Project Report
ACTA-4

Modeling Probability of Alert of Bluetooth Low Energy-Based Automatic Exposure Notifications

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27 April 2022

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LEXINGTON, MASSACHUSETTS

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Massachusetts Institute of Technology
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Group 45

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1. INTRODUCTION

BLEMUR, or Bluetooth Low Energy Model of User Risk, is a model of the probability of alert at a given duration and distance of an index case for a specific configuration of settings for an Exposure Notification (EN) system.

The Google-Apple EN framework operates in the duration and Bluetooth Low Energy (BLE) signal attenuation domains. However, many public health definitions of "exposure" to a disease are based upon the distance between an index case and another person. To bridge the conceptual gap for public health authorities (PHAs) from the familiar distance-and-duration space to the signal attenuation-and-duration space, BLEMUR uses BLE signal attenuation as a proxy for distance between people, albeit an imprecise one.

The relationship between BLE signal attenuation and distance that BLEMUR uses is derived from data collected in a laboratory setting as described in 4.2. The process by which the data is used to inform the distance-attenuation relationship model is presented in 4.3.

When a population of contacts and a definition of an "exposed contact" are also provided by the user, BLEMUR additionally outputs probabilities of detection, miss, or false alarm. BLEMUR also outputs a false discovery rate within that population. An "exposed contact" is someone who PHAs would like to notify of their exposure and desired follow-up public health actions such as testing and quarantine. The definition of an "exposed contact" used in this paper is a contact that has been within 6 feet of the index case for 15 minutes or more.

This paper will discuss the EN settings that can be manipulated, the BLE data collected, how data support a model of the relationship between measured attenuation and distance between phones, and how BLEMUR calculates the probability of alert for a distance and duration based on the settings and data.

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2. BACKGROUND

2.1 AUTOMATED EXPOSURE NOTIFICATION

In response to the COVID-19 pandemic, the Google-Apple Exposure Notification (EN) capability was developed and released, providing nations, states, and other jurisdictions globally with a mechanism for issuing exposure notifications to iOS- and Android-running cellphone users when they were close enough to a COVID-19 index case to generate an alert. This automatic exposure notification supplements manual contact tracing services to find and alert exposed contacts whom the index case might have forgotten or whom the index case does not know, such as fellow passengers on a bus.

The EN capability [1] is based on BLE "chirps" emitted by phones with an EN app installed. These chirps are heard by other phones using the EN app and the metadata encoded in the chirp is saved, along with the time and date. If a person tests positive (referred to as an "index case"), the cryptographic keys for chirps their phone has emitted are uploaded to an anonymized database. Other phones compare the chirps that they have heard against the cryptographically regenerated list of chirps associated with any index cases during their contagious period, and if there is a match, they display to the user an exposure notification with instructions from PHAs on how to proceed with testing, quarantine, or other personal and public safety measures.

The PHAs of jurisdictions planning on releasing an app based on the EN framework are provided with a number of parameters that they can adjust to tune their system to the current understanding of COVID-19's contagiousness and spread, as well as to raise or lower the threshold for an exposure notification to be generated. PHAs can adjust risk thresholds and parameters, including infectiousness weights on days since the onset of index case symptoms, and risk-distance weights and thresholds placed on the attenuation level of BLE signal strength during the contact. They can also adjust the notification threshold, which is the cumulative risk-weighted duration of the contact at which an exposure notification is generated.

2.2 MOTIVATION

The decision of which settings PHAs should use for their EN deployment is a challenging one, complicated by the fact that the mapping of BLE signal attenuation to distance is a fuzzy one, impacted significantly by phone orientation, location on the user's body, the number of bodies between the phones, and multipath effects with the environment. As a result of this imprecision, there is no exact way to define settings such that they alert 100% of the exposed users and 0% of non-exposed users—there will always be some error, either in the form of false alarms, missed exposures, or both. PHAs must carefully consider the impact of false positives and negatives on the contact tracing infrastructure—too many false positives could overwhelm the contact tracers and result in erosion of trust in the system, while too many false negatives (missed exposures) undermine the effectiveness of the system at preventing further infections.

Additionally, as understanding of the disease evolves and new variants emerge—be it COVID-19 or any other disease for which EN might be deployed in the future—the infectiousness profile of an index case will likely change to reflect new data. The definition of an "exposed contact" may also change, which impacts any estimate of probability of detection or false alarm. As a result, the tuning and evaluation of any EN system are likely continuous tasks over the lifetime of the system.

To aid PHAs in the difficult decision of how to tune their EN 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 EN risk and notification settings translates into probability of alert for a given combination of distance and duration.

3. AUTOMATED EXPOSURE NOTIFICATION SETTINGS

3.1 ATTENUATION BUCKETS

There are four BLE attenuation buckets in the EN implementation: the Immediate, Near, Medium, and Other buckets. These buckets are defined by attenuation thresholds: the Immediate, Near, and Medium thresholds. Signals with attenuations below the Immediate threshold would be categorized as within the Immediate bucket, for instance.

As a mechanism to indicate buckets that carry more exposure risk, each bucket is assigned a weight between 0 and 2.5. Multiplying these weights by the number of minutes that a contact spends at an attenuation that falls within each bucket, a value of "weighted minutes-at-attenuation" (WMs) can be summed up across the buckets. WMs are the metric of exposure risk—the more WMs an individual accumulates, the more likely they have been exposed.

The actual implementation of EN allows cumulative WMs to be summed from contacts with multiple index cases to trigger an alert for an individual. Because BLEMUR is focused on modeling the contacts of a single index case, the calculation of WMs described in this paper only considers the contributions of a single index case to each individual contact.

3.1.1 Infectiousness and Report Type

The EN system factors in infectiousness of the index case and report type by multiplying WMs by weights for both parameters to get a value of "exposure minutes" (EMs). These infectiousness weights vary based on the time since symptom onset and a profile can be designed by PHAs.

BLEMUR can model a single infectiousness weight at a time. This paper assumes an infectiousness weight of 100%.

3.1.2 Alert Threshold

Public health authorities decide where to set the threshold of EMs for alert. A low threshold has a higher probability of detected exposed individuals, but comes at the cost of a higher false alarm rate. A high threshold will reduce false alarms but may miss exposed individuals that they would otherwise wish to alert.

3.1.3 Proposed Baseline EN Settings

As a starting reference point for PHAs, two sets of parameters were proposed by the Risk Score Symposium Invitational ("RSSI"): a "Narrower Net," which prioritizes a lower false alarm rate but at a higher miss rate, and a "Wider Net," which prioritizes a lower miss rate at the expense of a higher false alarm rate.[1] The settings are included in Table 1 [2].

TABLE 1

RSSI Workshop EN Setting, November 2020

		Immediate	Near	Medium	Other
Narrower Net	Threshold	55 dB	63 dB	70 dB	-
	Weight	150%	100%	40%	0%
Wider Net	Threshold	55 dB	70 dB	80 dB	-
	Weight	200%	100%	25%	0%

3.1.4 Contact Duration

Sampling intervals in EN, or the cadence at which the phone "listens" for BLE chirps from neighbouring devices, are implementation-dependent. In practice, sampling intervals are usually between two and five minutes. The time elapsed since last sample is multiplied by the weight of the attenuation bucket it is binned into to add additional WMs to the cumulative total.

BLEMUR assumes that each sample equals five minutes of contact with the index case, which is consistent with a constant five-minute sampling interval. However, depending on when the contact actually begins relative to the last sample, the contact duration can be underestimated as a result (e.g. a contact lasting nine minutes may only be sampled once, leading to a contact duration estimate by EN of five minutes) or overestimated (the same nine minute contact being sampled twice, leading to a contact duration estimate of ten minutes).

BLEMUR addresses this by determining the probabilities that a contact of an X minute duration is recorded as either N = ceiling(X/5) or N-1 samples and folding these probabilities into the probability that a contact of a given actual proximity and duration accumulates enough WMs to cross the alert threshold as described later, in 4.4.2.

---

[1] The RSSI Workshop was reconvened in August 2021 to review the original proposed settings in light of the Delta variant's higher infectiousness, and in the context of newly available data from the Exposure Notification Private Analytics (ENPA) system. The "narrow" and "wide" net settings were adjusted by the community, but we present here the original settings as used with BLEMUR in order to document the analysis delivered to CDC and to state partners in the 12 months prior to RSSI-2.

4. BLEMUR DESCRIPTION

4.1 BLEMUR INPUTS AND OUTPUTS

Input: Attenuation bucket thresholds and weights, alert threshold

The weights and thresholds separating attenuation buckets and dictating when an alert is issued by EN are described in the previous section. BLEMUR allows users to easily change these weights and thresholds to see how the outputs are affected.

Input: Contact distribution (optional)

BLEMUR accepts a list of *N* contacts, given in pairs of distance and duration. For the purposes of the model, the contacts are assumed to stay a fixed distance from the index case for the duration of the contact period.

For calculations that require a list of contacts, namely the probability of detection, false detection rate, false alarm rate, and expected counts, this paper uses the *contact grid*: a list of 900 contacts, one at each point in a grid of 1-30' in distance and 1-30 minutes in duration. This 30 x 30 grid is also what is always used to visualize in heatmap format the probability of alerting contacts at given distances and durations.

The contact grid is not a realistic contact distribution for the average index case, but it provides good visualization of which regions within the distance-domain are most likely to be alerted, either falsely or correctly. This can help public health authorities visually understand what types of contacts are likely to be missed or falsely alerted.

Output: Probability of alert heatmap

BLEMUR always outputs heatmaps showing the probability of alert at integer values of distance and duration between 1 and 30 (feet and minutes).

Output: Probability of detection, false discovery rate, false alarm rate, and expected counts (optional)

If a contact list is provided, BLEMUR outputs probability of detection, probability of false alarm, and false discovery rate, as well as the counts of contacts for each of the rates out of the total. These rates are highly dependent on the contact list provided, so it is important that any discussion of detection and false alarm rates be accompanied by a description of the contact distribution used. P(D) and FDR are inputs to SimAEN [3], a population-level model of the effects of EN in conjunction with other interventions for COVID-19.

4.2 BLUETOOTH LOW ENERGY DATA COLLECTION

BLEMUR draws from BLE data taken in MIT Lincoln Laboratory's Autonomous Systems Development Facility (ASDF) at a range of distances between Android phones carried by mannequins that simulate the RF properties of the human body [4].

In particular, BLEMUR uses the BLE signal strength attenuation (dBm), which is defined as the transmit power ($Tx_{\_power}$) of the emitting phone minus the received power (RSSI) [5]:

$$Attenuation = Tx_{power} - (RSSI_{measured} + RSSI_{correction})$$

The attenuation data is used by BLEMUR along with the distance between transmitting phone and receiving phone, the number of bodies between the phones ("body-blocking"), and the location of the phones on the body.

BLE signal strength and attenuation data (in dBm) was collected with and without "body-blocking" between the phones to capture how having bodies between the phones impacted the attenuation of the signal. Data was also collected with the phone in various locations on the mannequin, including front shirt pocket, front pants pocket, and a nylon bag worn in front of the body.

4.3 DISTANCE-ATTENUATION DISTRIBUTION MODEL

Histograms were formed of the attenuation data at each of the distances where data was collected (2, 3, 6, 9, 12, 15, 20, 25, and 30 feet) for each of the three body-blocking profiles (0 bodies, 1 body, and 2 bodies). The data for each distance and body blocking histogram includes all the tested phone locations together, which is a potential source of error compared to a real life scenario given that there is likely an uneven distribution of phone locations in reality. This section will use data collected at 6 feet with 0 body blocking to illustrate the process of mapping a given distance to an attenuation probability distribution through an example, the histogram of which is shown in Figure 1.

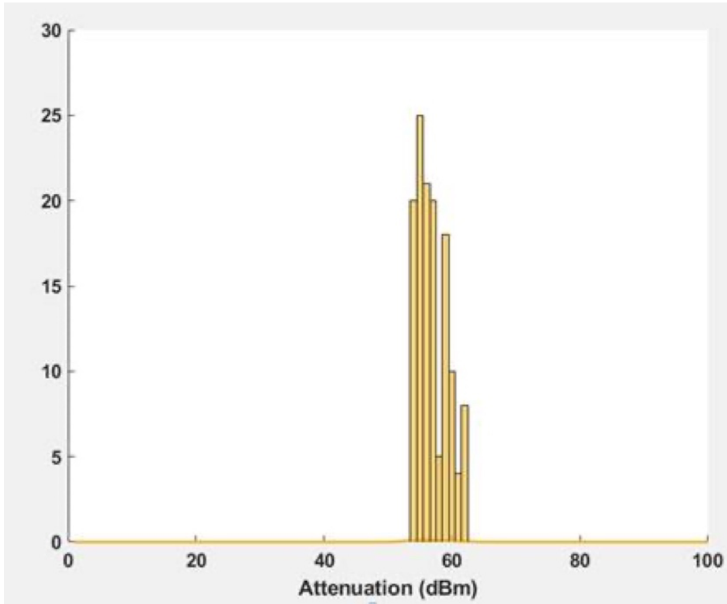

Figure 1. Example histogram of attenuation (dBm) of ASDF recorded signals at 6' distance and no bodies between phones.

Kernel distributions were fit to the histograms and normalized in order to estimate the probability density function (PDF) of attenuation at each collected distance, shown for our example in Figure 2.

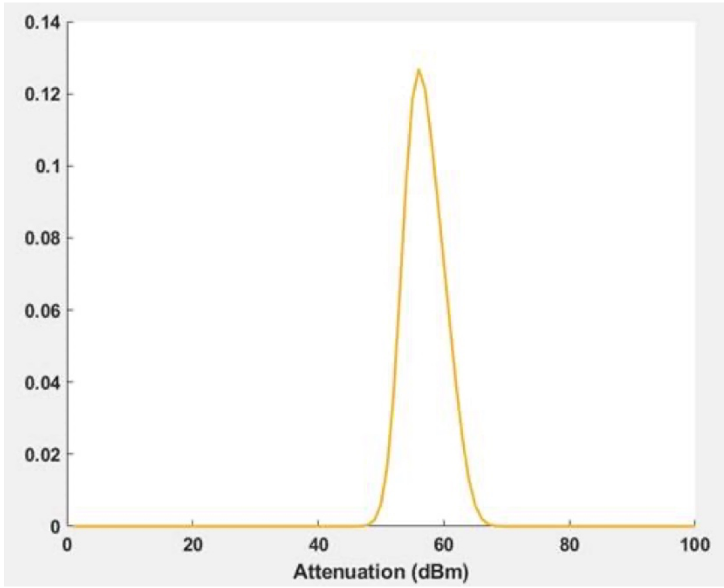

Figure 2. Example probability distribution function for 6' and 0 body blocking between phones.

For distances that weren't collected, one of the PDFs was used as a template for the PDFs at uncollected distances, shifted so that the median of the new distribution aligned with the interpolated median at that distance.

4.4 PROBABILITY OF ALERT

4.4.1 Probability of a Sample at a Given Distance Being Recorded in Each EN Bin

The PDFs generated from the BLE data were used within BLEMUR to calculate the probabilities that a contact at a given distance would be recorded as each attenuation value. These probabilities combine to determine the probability that a contact at a given distance would be recorded in each of the four BLE attenuation bins, as defined by the input EN setting selections. The probabilities shown for the 6' distance example below in Figure 3 are calculated using the "Wider Net" settings from 3.1.3.

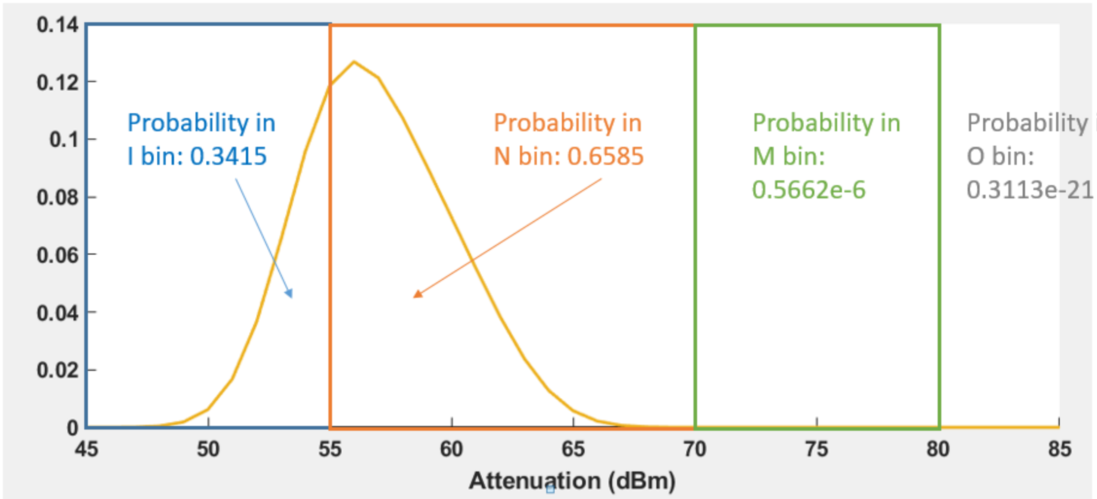

Figure 3. Probability of a signal recorded at 6' and 0 body blocking between phones having an attenuation in each of the four EN bins using Wider Net settings.

4.4.2 Probability of a Given Contact Duration and Distance Crossing Alert Threshold (Probability of Alert)

As described in 3.1.4, a given contact duration is assumed to be recorded as the number of samples collected during the contact times five minutes. Each of those collected samples has a likelihood based on the contact distance and the attenuation PDF associated with it (as described in the previous section) to end up in each of the four bins and therefore add W_{Bin} $\times$ 5 minutes to the cumulative WMs for that contact.

For a duration that might result in more than one sample, such as a contact duration greater than five minutes, there is a combinatorial set of 4^N possible binning outcomes for each possible number of samples *N* for that duration.

For two samples, for example, this set would be II, IN, IM, IO, NI, NN, NM, NO, MI, MN, MM, MO, OI, ON, OM, and OO.

For a given duration, the following process is done for each set of combinatorial outcomes of lengths 4^N and 4^{N-1}:

1. Calculate the number of weighted minutes resulting from each outcome by multiplying five minutes by the total weights for that combination of bins.

- E.g., for sample combo IN, it would be 5 minutes × ($W_I + W_N$), which for the Wider Net would be 5 × (2 + 1) = 15 WMs for the IN combo.

2. Calculate the probability that each of those outcomes occur for a given distance and number of samples N.

- For a distance of 6' and N = 2 samples, we can see from the figure above that the probability of the IN combo outcome occurring for two samples would be × P_N, or 0.3415 × 0.6585 = 22.49%.

3. Multiply the probability of occurrence of each outcome by the probability that that number of samples (N or N-1) would be recorded based on the duration of the contact.

- For a 6 minute contact, there's an 80% chance that a single sample would be recorded, and a 20% chance that two samples would be recorded.

- For a 6 minute contact, therefore, there is a 22.49% × 20% = 4.5% chance that 2 samples are recorded and that it is the IN outcome.

4. Determine which of the combos/outcomes WMs from Step 1 would pass the user-defined WM alert threshold.

- If the alert threshold were set at 15 WMs, for instance, the IN combo in our example would pass.

5. Sum the probabilities from Step 3 for those outcomes that pass the WMs threshold in Step 4.

Then sum together the result of Step 5 for N and N-1 samples. This is BLEMUR's expected value of the probability of alert for a contact at a given distance for a given duration.

4.4.3 Probability of Alert Heatmaps

The probability of alert heatmaps roll up the probabilities of alert for integer values of distance and duration from 1–30' and 1 to 30 minutes. These heatmaps can be combined with a definition of exposed contact to give a visual reference for how well the input EN config would perform with respect to the desired "ideal" outcome of only alerting exposed contacts and no one else. The definition of exposed contact used in this paper (≤6' for 15+ minutes) is shown on a contact distance and duration grid in Figure 4.

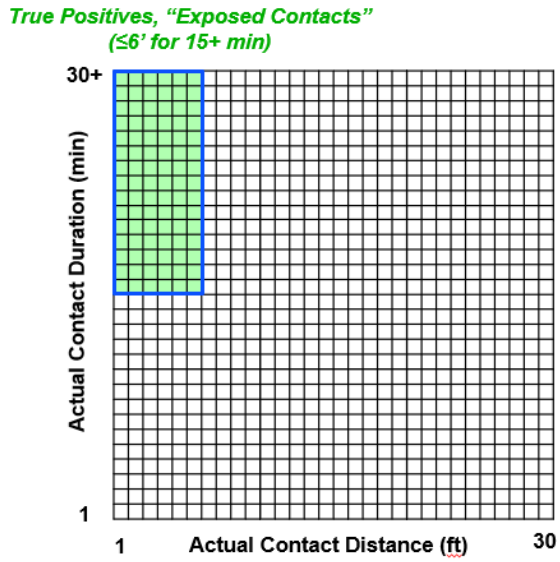

Figure 4. Example definition of exposed contacts as a region on a contact distance and duration grid.

Because of the noisiness of the distance-attenuation relationship; the wide variety of phone locations, orientations, and environments; the limited data points that were collected at each distance; and the need to interpolate at uncollected distances; the heatmaps are approximations of the probability of alert and should be used largely to compare changes in settings rather than as a means to derive exact values for a given duration and distance.

Shown below in Figure 5 through Figure 10 are probability of alert heatmaps for each of the Narrow Net and Wider Net settings, for each of 0, 1, and 2 body blocking. It can be seen that for contacts with 0 body blocking, both the Narrow and Wider Nets notify the exposed contacts, but they also notify a number of other contacts at greater distances as well. For 1 body blocking, there are fewer false positives but also more false negatives. For contacts with 2 bodies blocking, such as the case where two people are looking at their phones while facing away from each other, EN notifies very few if any contacts at any duration or distance for either the Narrow or Wider Net.

These heatmaps highlight the challenges of using a relatively limited set of parameters to attempt to unanimously notify only exposed contacts in a population of people who might be standing in a variety of body blocking situations and environments.

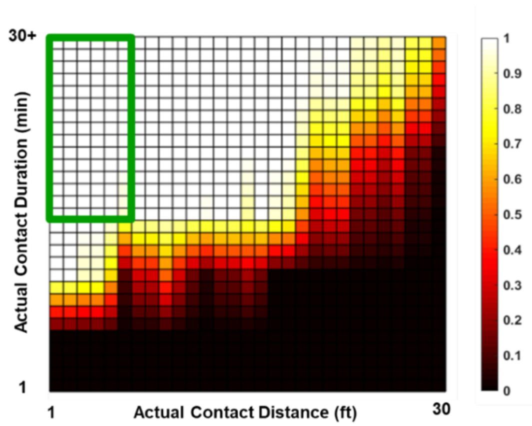

Figure 5. Probability of alert heatmap for Narrow Net settings, 0 body blocking.

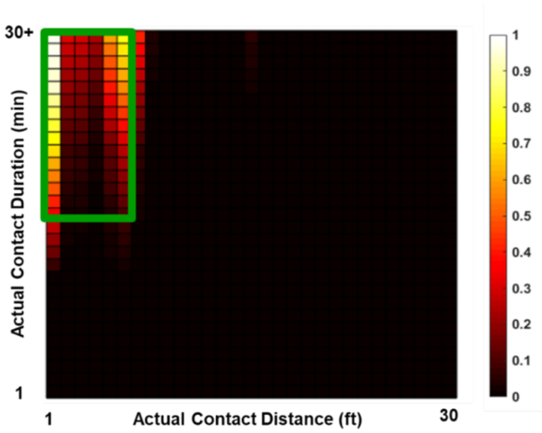

Figure 6. Probability of alert heatmap for Narrow Net settings, 1 body blocking.

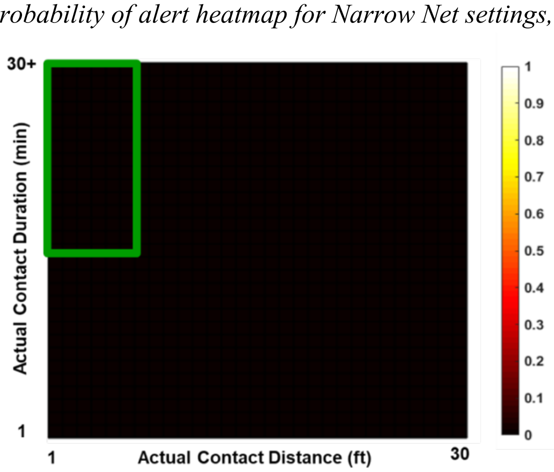

Figure 7. Probability of alert heatmap for Narrow Net settings, 2 body blocking.

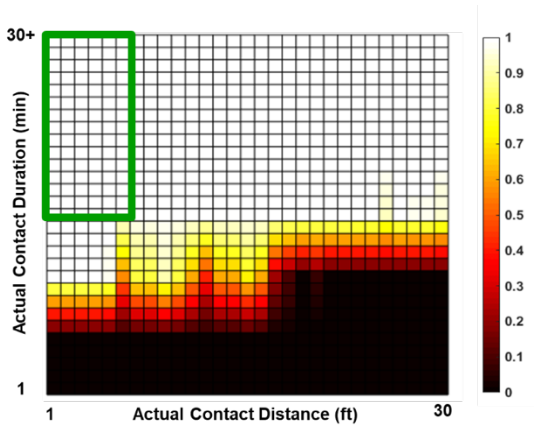

Figure 8. Probability of alert heatmap for Wider Net settings, 0 body blocking.

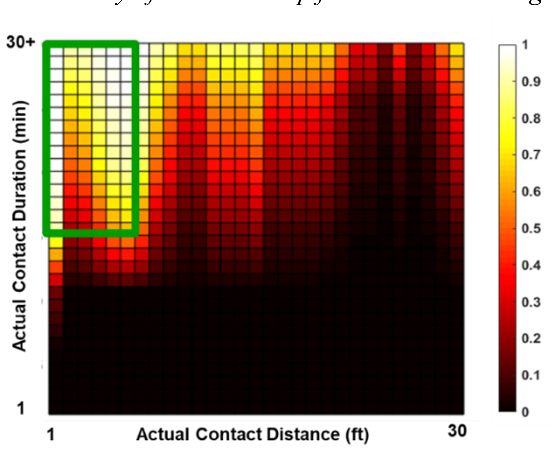

Figure 9. Probability of alert heatmap for Wider Net settings, 1 body blocking.

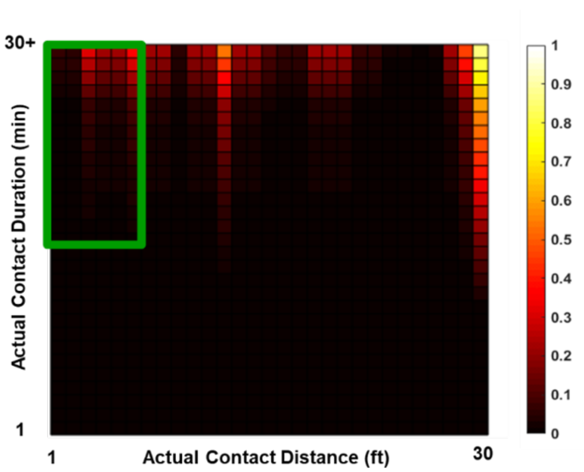

Figure 10. Probability of alert heatmap for Wider Net settings, 2 body blocking.

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5. FUTURE RESEARCH

There are a number of directions that future BLEMUR development could take:

- BLEMUR uses an unrealistic "contact list" for its calculations of true and false positives and negatives—one contact per grid cell on the distance and duration grid shown throughout this paper. Some preliminary work was done on developing a more representative contact list by drawing contacts from distributions defined by index case behavior—such as working from home or going to the grocery store—and U.S. household size statistics. Future work could be done to develop more realistic contact lists for different societies and pandemic conditions to further improve those calculations.
- Continuing to update the model with new data would also improve its fidelity, especially data collected at the intermediate distances that were modeled by interpolation in this work.
- As new sets of setting suggestions are issued in addition to the Narrow and Wider Nets, BLEMUR can be updated to include those as template configurations off of which PHAs can make parameter excursions.
- The ability to include an entire infectiousness profile with multiple infectiousness weights and see how the probability of alert varies over days since symptom onset would be useful.
- Currently BLEMUR assumes a fixed sampling interval of five minutes, when in reality the sampling interval varies on a per sample basis. The model could be updated to allow for other sampling intervals or even a realistic distribution of intervals.
- BLEMUR also assumes a single recorded value of signal per "sample." In reality, the number of recorded data points per sample is implementation dependent but often higher than 1. Some work has been done on a Monte Carlo model that pulls three signal values per sample (the observed expected value of sample count on Android phones in August–September 2020) and takes the mean or max of those values as the "sample" value. Further work needs to be done to examine how the real-world implementations and variance impact the probability of alert.
- The real-world distribution of body blocking should also be factored in in order to combine the 0, 1, and 2 body blocking heatmaps into an overall probability of alert.

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6. CONCLUSIONS

BLEMUR produces a graphical representation of the impact of a set of EN settings upon the contact space of distances and durations from 1 to 30’ and 1 to 30 minutes. These representations, or “heatmaps,” give an estimated probability that a contact of a given distance and duration will be alerted, based on probability distribution functions derived from Bluetooth Low Energy measurements collected in a lab setting. When combined with a definition of an “exposed contact,” a depiction of which true and false positives and negatives will result from a given set of EN settings.

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GLOSSARY

APHL	Association of Public Health Laboratories
ASDF	Autonomous Systems Development Facility
Attenuation	reeduction of signal amplitude
BLE	Bluetooth Low Energy
BLEMUR	Bluetooth Low Energy Model of User Risk
CDC	Centers for Disease Control and Prevention (U.S.)
COVID-19	Coronavirus disease caused by the SARS-CoV-2 virus
dBm	decibel-milliwatts (unit of power level)
EM	exposure minutes
EN	Exposure Notification
FDR	false detection rate
MIT	Massachusetts Institute of Technology
MIT LL	Massachusetts Institute of Technology Lincoln Laboratory
P(D)	probability of detection
PDF	probability density function
PHA	Public health authority
RSSI	Received Signal Strength Indicator
WM	weighted minutes

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
BLEMUR, or Bluetooth Low Energy Model of User Risk, is a model of the probability of alert at a given duration and distance of an index case for a specific configuration of settings for an Exposure Notification (EN) system.The Google-Apple EN framework operates in the duration and Bluetooth Low Energy (BLE) signal attenuation domains. However, many public health definitions of "exposure" to a disease are based upon the distance between an index case and another person. To bridge the conceptual gap for public health authorities (PHAs) from the familiar distance-and-duration space to the signal attenuation-and-duration space, BLEMUR uses BLE signal attenuation as a proxy for distance between people, albeit an imprecise one. This paper will discuss the EN settings that can be manipulated, the BLE data collected, how data support a model of the relationship between measured attenuation and distance between phones, and how BLEMUR calculates the probability of alert for a distance and duration based on the settings and data.

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**		23	**19b. TELEPHONE NUMBER** *(include area code)*

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