# Accuracy of Bluetooth-Ultrasound Contact Tracing: Experimental Results from NOVID iOS Version 2.1 Using Five-Year-Old Phones

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#### Abstract

A common standard for close contact in the context of COVID-19 is 6 feet in the United States (2 meters elsewhere in the world). Many smartphone contact-tracing apps attempt to measure distance using Bluetooth received signal strength, but it remains an open question to reliably translate signal strength into an accurate distance metric. The NOVID app publicly launched for Android download with an approach combining Bluetooth and ultrasound on April 7, 2020, using sound time-of-flight calculations to reduce the number of false positive detections in app-based contact tracing. In this experiment using publicly-accessible features of the app, we systematically test the latest version of NOVID (iOS version 2.1) in a variety of realistic and adversarial at-rest settings. We find that a simple 9-foot classification threshold based on the NOVID distance measurement is very effective. Even though this experiment put the app in challenging circumstances (not an anechoic chamber), 99.6% of the 225 tested 12-foot-or-higher interactions were correctly classified as over-9-feet, while over 50% of the 187 tested under-6-foot interactions (and 94% of a representative subcategory) were correctly classified as 9-feet-or-under. This demonstrates that ultrasound can significantly contribute to app-based contact tracing.

### 1 Introduction

The COVID-19 pandemic has wrought havoc on ordinary life around the world. A distinctive characteristic that makes this novel disease difficult to control is its high level of contagion, coupled with a tendency for pre-symptomatic spread. Indeed, a recent paper by He, Lau, and Wu, *et al.* [2] in *Nature Medicine* estimated from their dataset that 44% of the infectiousness profile occurred presymptomatically. This naturally inspired much work on accelerating contact tracing with current technology.

In Spring 2020, a large number of smartphone contact tracing app projects emerged, spearheaded by the TraceTogether app developed by the national government of Singapore. Perhaps inspired by the TraceTogether app, which used a novel application of Bluetooth for anonymous short-range smartphone-to-smartphone communication, many projects based their core technology on Bluetooth. The core technological problem at the heart of a contact tracing app is the accurate

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detection of distance with the ability to discern at the meter-scale. Much of the world settled on a 2-meter standard (6 feet in the United States<sup>1</sup>).

On April 7, 2020, the NOVID app launched for public download on Android devices [3], introducing the combination of Bluetooth and ultrasound to more effectively prevent false positive classifications of faraway interactions as close-proximity. The principle was to accurately measure the time-of-flight of sound, which is theoretically possible because modern smartphones can reliably quantify time with millisecond-accuracy; when multiplied by the speed of sound, this produces sub-meter distance accuracy. To enable third-party verification of accuracy, NOVID then exposed the estimated distance proximity on its deployed app user interface for public testing, together with a button that triggers a distance scan on demand.

The experiment in this report uses this publicly accessible feature to systematically test the latest iOS version of NOVID (2.1) in a variety of real-world adversarial at-rest settings, to quantify its strengths and limitations in practical situations. The app does have Doppler correction built into its signal processing code, but this initial public report focuses on the at-rest setting because a very significant proportion of sustained human-to-human close-proximity interaction occurs when their smartphones are at rest. In addition to testing the ultrasonic distance measurement system in simple line-of-sight settings, this experiment includes a variety of adversarial settings designed to interfere with the physical limitations of any ultrasound-based approach: ultrasound has difficulty penetrating obstacles, and its reflections off objects create multipath effects that complicate time-of-flight signal processing calculations. However, the theoretical physical characteristics of ultrasound work in favor of reducing false positives, because any time-of-flight measurement of a reflected path is an overestimate of the truth. The objective of this experiment is to understand the degree to which this system can categorize interactions as under-6-feet settings with minimal false-positive rate, while still positively detecting a substantial fraction of true under-6-feet interactions.

## 2 Materials and Methods

The latest iOS build of NOVID was used for this experiment, corresponding to the Version 2.1 branch. The distance measurement interface within the app, depicted in Figure 1(v), can be used by anyone to reproduce the results of this experiment by downloading any Version 2.1.x iOS build from the App Store.

Figure 1 show a typical open-plan office environment, which was selected as the experimental setting, with standard walls, floors, and 8-foot-6-inch drop ceiling. Imperial units are used throughout this report because the USA version of the NOVID app was used for testing, and it displayed Imperial units on its user interface. Office desks, chairs, monitors, computers, cups, etc. were distributed throughout the office without obstructing the direct pathway of the experiment, as in Figure 1(ii) where the clear walkway in Figure 1(i) was used for testing the app at a range of distances. An anechoic chamber was intentionally not used so as to simulate a real-world environment with many sources of multipath interference.

The devices used were an Apple iPhone 6s and an iPhone 6s Plus, so as to test the performance on five-year-old smartphone technology. This is relevant because the app's ultrasonic communication frequency range (18.5–19.5 KHz) approaches the limit of smartphone speaker and microphone

<sup>&</sup>lt;sup>1</sup>As of June 25, 2020, the relevant COVID-19 webpage maintained by the USA Centers for Disease Control [1] https://www.cdc.gov/coronavirus/2019-ncov/php/public-health-recommendations.html defined close contact as "< 6 feet," with a footnote indicating that data to inform the definition of close contact are limited.





(i)





(iii)



(iv)







(vi)

Figure 1: Experimental setup

capability. Throughout the experiment, the phones had at least 30% charge, so that the operating system would not engage power saving features.

The phones were placed flat on bar stools at height 30.5 inches off the ground, with each phone centered on the axis of each bar stool's rotating support pole as confirmed by visual checks from two perpendicular perspectives. The bar stools had circular bases, which facilitated center-to-center measurements through the use of a 25-foot Stanley metal measuring tape that was tangent to the perimeter of each circular base. This setup permitted the positioning of phones such that actual distance measurements were within one inch of accuracy.

The experimental procedure ran through many different setups. In each setup, three numerical measurements were sought. The nature of this version of the NOVID app is such that after each distance measurement, one of three possible results is displayed: an actual distance, or "Heard A Device But Could Not Measure The Distance" (recorded in our data as "Heard"), or "No nearby users" (recorded in our data as "Unheard"). The measurements within each setup stopped as soon as a total of three distances were received, or as soon as three non-distance results were received in a row. However, all non-distance results were recorded, so this effectively only increased the number of samples in some setups.

Throughout, the human experimenter(s) remained at least 3 feet away from the phones while they were measuring distances. In situations when one phone was placed in a mens' shorts pocket, the person stood motionless. Po-Shen Loh was the primary experimenter supervising all data collection, assisted by Vivian Loh for the portion of data collection at distances of 13 feet and higher, and for all settings where he placed one phone in his shorts pocket.

Some settings involved positioning small obstacles 2 inches away from the smartphone speakers, as in Figure 1(vi). The small obstacles used were a Logitech M185 wireless mouse and the charging box of a TOZO T10 Bluetooth earbud set. Both of these were slightly irregular shapes, with approximate dimensions  $4 \times 2 \times 1$  inches. Some settings involved bags, both of which were made of durable nylon luggage-type material and depicted in Figure 1(iii). The large bag was not padded, and measured  $19 \times 14 \times 5$  inches when loosely crumpled with an iPhone inside. The small bag was a padded camera bag which held its form due to the internal 1/4-inch foam-like padding, with dimensions  $8 \times 8 \times 2$  inches. Some settings involved a 59-inch-tall, 20-inch-wide self-standing 1/4-inch foam core board placed at the midpoint between the two phones, obstructing their line-of-sight, as in Figure 1(iv). Some settings involved a pair of mens' shorts, made of a light khaki-type material and worn by an approximately-120-pound man. Therein, the phone was placed in different pockets, where its center was 27 inches above ground when in the front pocket, and 29 inches above ground when in the back pocket.

Background music (1990's pop hits via Spotify high-quality streaming for maximum frequency range) was continuously played through a pair of floorstanding Wharfedale Emerald 97 Mark IV speakers and a 500-watt Infinity Interlude IL120s subwoofer. The equipment was chosen so as to deliver a frequency response that would reproduce the near-ultrasonic frequencies in music intermixed with frequent spikes in the amplitude due to pop-music rhythmic beats, so as to interfere with the app operation. The floorstanding speaker high-frequency tweeters 35 inches off the ground and about 10–12 feet away generally facing toward the phones. The volume was set such that the ambient sound level at the phone position (as measured by the "Sound Meter" Android app [4] on a Samsung Galaxy S8) was in the 60–70 dB range. Conversation between the experimenters required mild shouting to achieve audible clarity.

# 3 Procedure

For each number of feet in  $\{2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 20, 25\}$ , as measured from the center of one phone to the other, perform the distance measurement protocol in the previous section (stop after a total of 3 measurements, or after 3 consecutive non-distance measurements) in each of the following settings.

- Line of sight. Place the phones on the bar stools so that they have clear line of sight, and then test the following four settings:
  - A1. Orient the phones in the same direction, where that direction is perpendicular to the line between the phones. The external speaker is on the bottom edge of the phone, and so this orients the speakers in parallel directions which are perpendicular to the line between the phones.
  - A2. Orient the phones so that their speakers point directly towards each other.
  - A3. Orient the phones so that their speakers point directly away from each other, and there are no other objects within 5 feet directly in front of each phone's speaker.
  - A4. Orient the phones so that their speakers point directly away from each other, but place small obstacles 2 inches in front of each speaker: place the wireless mouse in front of the iPhone 6s and the Bluetooth earbud charging box in front of the iPhone 6s Plus.
- **In bags.** Orient the phones so that their speakers point in the same direction perpendicular to the line between the phones. Place the phones on the bar stools so that they have clear line of sight, except as detailed in the following two settings:
  - **B1.** Leave the iPhone 6s exposed, while enclosing the iPhone 6s Plus in the large non-padded bag.
  - **B2.** Enclose the iPhone 6s Plus in the large non-padded bag, and enclose the iPhone 6s in the small padded bag.
- Blocked by foam core board. Orient the phones so that their speakers point in the same direction perpendicular to the line between the phones. Place the phones on the bar stools so that they have clear line of sight, except for the foam core board blocking at their midpoint and as specifically detailed in the following three settings:
  - C1. Leave both phones exposed.
  - C2. Leave the iPhone 6s exposed, while enclosing the iPhone 6s Plus in the large non-padded bag.
  - C3. Leave the iPhone 6s Plus exposed, while enclosing the iPhone 6s in the small padded bag.
- In shorts pocket. Place the iPhone 6s Plus flat on a bar stool, exposed and oriented such that the speaker is pointing in a direction perpendicular to the line between the phones. Place the iPhone 6s vertically in a mens' shorts pocket, with the speaker pointing upwards. The phones have a clear line of sight apart from the person wearing the shorts. That person stands next to the measuring tape, facing towards the other phone, such that their center of mass is at the specified distance from the other phone. Measure the distance in these two settings:

- **D1.** Place the iPhone 6s in the person's front left pocket.
- **D2.** Place the iPhone 6s in the person's back right pocket.

Note that since there are 16 distances, and 11 settings per distance, this is a total of 176 setups. After performing all measurements, perform a sanity check to confirm that in situations when ultrasound should not be detected, the app correctly reports "Unheard." In our experiment, this was accomplished by going into a bathroom 29 feet away from the iPhone 6s Plus, closing the wooden door, going to the back of the bathroom (6 feet beyond the door), and facing the door with the other phone (iPhone 6s) in a back pocket. The app was then invoked three times.

#### 4 Results and Analysis

The following pages contain all 589 of the raw data points measured over the course of experimental measurements on June 24–25, 2020. All numbers are expressed in units of inches. All cells less than or equal to 72 inches (6 feet) are highlighted in green, and all other cells less than or equal to 108 inches (9 feet) are highlighted in yellow. The reason for this color coding is because *a priori*, a reasonable threshold for separating 6-feet-and-under interactions from 12-feet-and-over interactions would be to classify based on whether the NOVID distance measurement was less than or equal to 9 feet.

In this color-coding scheme, the green and yellow cells collectively cover all interactions at distance less than or equal to 9 feet. Consequently, it is good if most of the cells corresponding to actual distance at most 72 are green or yellow, and most of the cells corresponding to actual distance at least 144 are uncolored. The column "Un/heard in notes" totals the number of non-distance measurements recorded for each setting, if at least one distance measurement was obtained.

Actual distance	Setting	Measure 1	Measure 2	Measure 3	Un/heard in notes	Notes	
24	Al	22	22	22			
24	A2	16	16	15			
24	A3	198	100	198			
24	Δ4	33	32	34			
24	D1	35	32	29			
24	BI	24	30	28			
24	B2	اک	24	96			
24	C1	24	58	27	1	1 Heard between Measure 1 and 2	
24	C2	116	155	243			
24	C3	165	53	46			
24	D1	32	22	20			
24	D2	201	276	102			
36	Δ1	35	35	35			
70	40	35	35	35			
30	AZ	26	26	26			
36	A3	293	238	194			
36	A4	45	45	44			
36	B1	53	49	54			
36	B2	Heard	Heard	Heard			
36	C1	36	36	35			
36	C2	153	164	166			
36	C3	159	245	149	1	1 Heard between Measure Land 2	
70	00	100	243	71			
30		26	32	31			
36	D2	184	.70	14	2	2 Heards between Measure 2 and 3	
48	Al	47	46	46			
48	A2	41	40	40			
48	A3	167	380	212			
48	A4	57	58	55			
49	BI	67	84	66			
40	21	Heard	64 Hoard	Heard			
48	62	Heard	Heard	Heard			
48	C1	78	105	97			
48	C2	166	165	155	4	1 Heard before Measure 1, then 1 Heard between Measures 1 and 2, then 2 Heard between Measures 2 and 3	
48	C3	78	88	84	1	1 Heard before Measure 1	
48	וח	44	44	44			
/8	 D2	177	97	96	2	2 Heards between Measures Land 2	
40	11	157	65	50	2		
60	AI	56	57	58			
60	A2	51	51	50			
60	A3	197	197	199			
60	A4	61	62	77			
60	Bl	72	63	64			
60	D1	70	163	112	5	2 Heards before Measure 1 then 1 Heard between Measures 1 and 2 then 2 Heards between Measures 2 and 7	
60	BZ	70	162	112	5	2 Heards before Measure I, then I Heard between Measures I and 2, then 2 Heards between Measures 2 and 3	
60	C1	114	99	103			
60	C2	127	93	133			
60	C3	240	129	145	2	1 Heard before Measure 1, then 1 Heard between Measures 1 and 2	
60	D1	54	53	53	2	2 Heards before Measure 1	
60	D2	234	71	83			
72	A1	70	71	72			
72	A1	70	71	72			
-72	A2	-75	.78				
72	A3	342	299	189			
72	A4	89	94	89	1	1 Heard before Measure 1	
72	B1	84	127	95	1	1 Heard between Measures 2 and 3	
72	B2	Heard	Unheard	Heard			
72	CI	216	112	117			
72	c)	100	165	107			
12	CZ	001	201	201			
72	C3	144	133	159			
72	D1	68	64	66			
72	D2	165	172	170			
84	A1	83	83	83			
84	A2	84	85	85			
84	A3	354	353	354			
04	A.4	100	105	105			
64	-17 D1	106	105	105			
84	ы	94	86	83			
84	B2	81	83	83			
84	C1	114	120	245			
84	C2	250	181	264	1	1 Unheard before Measure 1	
84	C3	206	240	239			
84	נס	77	79	88			
04		Hoard	Hoard	Hoard			
84	U2	neard	пеаго	neard			
96	A1	105	99	102			
96	A2	84	88	84			
96	A3	215	265	217			
96	A4	105	106	106			
20	BI	Heard	Heard	Heard			
	51	Heard	Heard	Linhers 1			
96	62	Heard	Heard	unneard			
96	C1	255	131	252			
96	C2	192	186	258			
96	C3	171	255	254			
96	DI	91	87	91			
90	27	Heard	Unboard 07	Heard			
96		inearu	Dimearo	i tealu			
108	Al	103	106	103			
108	A2	97	97	100			
108	A3	359	363	223			
108	A4	15.3	150	118			
108	B1	178	193	.33	1	1 Heard before Measure 1	

108	B2	Unheard	Unheard	Unheard	
108	Cl	159	257	182	
109	<u> </u>	107	290	277	
100	C2	167	280	277	
108	C3	258	257	256	
108	D1	97	100	103	
108	D2	Heard	Unheard	Heard	
120	A1	115	116	117	
120	Al	115	110	117	
120	A2	113	113	113	
120	A3	376	376	373	
120	A4	156	162	155	
120	BI	194	205	169	
120	50	134	203	105	
120	B2	236			
120	C1	196	262	140	
120	C2	192	199	195	
120	C7	107	105	10/	
120		107	105	104	
120	D1	108	107	153	
120	D2	393	310	295	
132	A1	164	158	127	
132	Δ2	134	134	133	
132	AZ	7.0	7/2	7.0	
132	A3	342	342	341	
132	A4	166	136	166	
132	B1	180	168	168	
132	B2	Unheard	Heard	Unheard	
132	 Cl	2000	10010	100	
132	G1	208	167	186	
132	C2	221	283	200	
132	C3	266	336	333	
כדן	D1	161	129	160	
132		Hoard	Hoord	Heard	
132	UZ	пеаго	пеаго	rieard	
144	A1	175	238	238	
144	A2	139	207	207	
144	A3	349	349	350	
1//	A.4	2.5	100	100	
-	~~~	291	100	100	
144	B1	350	147	188	
144	B2	Heard	Unheard	Unheard	
144	C1	337	336	338	
144	C2	202	215	223	
144	67	202	215	223	
144	C3	270	204	201	
144	DI	149	150	224	
144	D2	Heard	Heard	Unheard	
156	Al	183	209	159	
156	A1	183	209	159	
156 156	A1 A2	183	209 178	159 172	
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156           156           156           156           156           156           156           156           156           156           156           156           156           156           156           156           156           168           180           180           180	A1 A2 A3 A3 B1 C1 C2 C2 C3 D1 D2 A1 A2 A3 A4 B1 C2 C3 C1 C2 C3 C1 C2 C3 C1 C2 C3 C1 C2 C3 C1 C2 C3 C1 C2 C3 C1 C2 C1 C1 C2 C1 C1 C1 C1 C2 C2 C1 C1 C2 C2 C1 C2 C2 C2 C2 C2 C2 C2 C2 C2 C2 C2 C2 C2	183           152           363           167           160           48           148           Heard           254           207           362           207           362           207           362           207           362           207           362           207           362           207           364           277           160           448           173           386           207           188           173           386           207           4687	209 178 359 168 168 168 275 281 153 Heard 207 207 389 207 389 207 389 207 389 207 389 207 389 207 207 389 207 207 389 207 207 207 207 207 207 207 207 207 207	159 172 359 167 147 Unheard 272 149 Heard 40 167 40 40 167 176 346 274 194 167 176 346 176 345 208 176 345 208 Heard	
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156           156           156           156           156           156           156           156           156           156           156           156           156           156           156           156           168           180           180           180           180           180           180           180           180           180           180           180           180           180           180	A1         A2         A3         B1         B2         C1         C2         D1         D2         A1         A2         A3         A4         B1         D2         A1         A2         A3         C1         C2         C3         D1         D2         A1         A2         A3         A4         B1         B2         C1         C2         C3         D1         C2         C3         D1         D2         A1         A2         A3	183           152           363           167           160           48           Heard           254           262           207           362           204           Heard           Unheard           386           207           366           277           362           204           Heard           Unheard           285           350           285           352           362           207           160           207           160           285           352           352           352           352           352           352           352           352           352           352           352           352           352           352           352           353           354           355      352	209 178 359 168 168 153 Heard 275 281 153 Heard 207 207 207 207 207 207 207 207 207 207	159           172           359           167           147           Unheard           272           149           Heard           209           Heard           400           209           Heard           400           167           440           167           440           167           441           167           442           167           443           167           444           167           195           176           345           106           107           108           109           101           110           110           110           110           110           110           110           110           110           110           110           110           110           110           110	
156         156         156         156         156         156         156         156         156         156         156         156         156         156         156         156         156         168         180         180         180         180         180         180         180         180         180         240         240	A1         A2         A3         A4         B1         B2         C1         C2         D1         D2         A1         A2         A3         A4         B1         D2         A1         B2         C1         C2         C3         D1         D2         A3         A4         B1         B2         C1         C2         C3         D1         D2         A1         A2         A3         A4         B1         B2         C1         C2         C3         D1         D2         A1         A2         A3         A2         A3         C1         C2         C3         D1         D2         A1         A2	183           152           363           160           162           285           286           400           207           362           207           362           207           362           207           362           207           362           207           362           207           362           207           362           207           362           207           363           208           386           207           468           207           362           207           160           173           386           207           488           373           386           207           489           207           489           207           380           381           382           383	209 178 359 168 168 275 281 153 Heard 281 207 165 207 207 205 Heard 205 165 207 205 207 205 165 207 205 205 165 207 205 205 205 205 205 205 205 205 205 205	159           172           359           167           147           276           272           149           142           143           272           149           183           209           Heard           4           167           Heard           194           167           Heard           194           167           Heard           195           208           Heard           Unheard           208           Heard           208           Heard           208           Heard           208           209           201           202           203           204           205           206           207           208           4           271           289           Heard	
156           156           156           156           156           156           156           156           156           156           156           156           156           156           156           156           156           156           168           168           168           168           168           168           168           168           168           168           168           168           168           168           168           168           168           168           168           180           180           180           180           180           180           240           240	A1       A2       A3       A4       B1       B2       C1       D2       A1       B2       C1       C2       C3       B1       B2       C1       C2       C3       B1       B2       C1       C2       C3       D1       D2       A1       A2       A3       A4       B1       B2       C1       C2       C3       D1       D2       A1       A2       A3       A4	183           152           363           160           167           275           286           74           148           Heard           254           207           326           204           Heard           346           277           160           448           173           346           277           160           171           188           173           386           207           Heard           188           173           386           207           Heard           208           Heard           209           386           386           393           384           384           384           384           384           384           384           384           384           384           384     <	209 178 359 168 369 187 400 187 187 187 187 187 187 187 187 187 187	159           172           359           167           276           277           147           Unheard           120           Heard           209           Heard           209           Heard           107           Heard           194           195           176           194           195           176           195           176           194           195           176           194           195           176           194           195           176           195           176           194           195           176           195           176           194           195           196           197           198           199           199           199           190           191      192	
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156           156           156           156           156           156           156           156           156           156           156           156           156           156           156           156           156           156           168           168           168           168           168           168           168           168           168           168           168           168           168           168           168           168           168           168           168           180           180           180           180           180           180           180           180           180           180           180           180           180           180	A1       A2       A3       A4       B1       B2       C1       C2       D1       D2       A1       B2       C1       C2       C3       B1       B2       C1       C2       C3       D1       D2       A3       A4       B1       B2       C1       C2       C3       D1       D2       A1       A2       C3       D1       D2       A3       A4       B1       B2       B1       B2	183           152           363           160           162           285           286           44           275           286           277           362           204           Heard           204           Heard           204           Heard           346           277           360           204           Heard           160           Heard           173           386           207           Heard           173           386           207           Heard           173           386           207           Heard           208           380           381           382           383           384           207           483           384           385           385           384           385           385	209 178 359 168 158 Heard 5 275 281 153 Heard 205 Heard 205 Heard 205 Heard 354 353 163 Heard 263 354 263 173 364 263 173 348 263 173 264 275 264 294 205 Heard 205 Heard 205 H	159 172 359 167 147 Unheard 4276 722 149 Heard 40 149 149 140 167 149 195 346 274 194 195 176 345 208 Heard 107 45 208 Heard 201 201 201 201 201 201 201 201 201 201	
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     A2       A3       A4       B1       B2       C1       C2       C3       D1       D2       A3       A4       B1       B2       C1       C3       B1       B2       C1       C3       C4       B1       B2       C1       C3       C4       C5       C6       C7       C7       C3       C4       C5   <td>183           152           363           160           162           285           286           400           148           Heard           254           400           207           362           207           362           207           362           207           362           207           362           207           362           207           363           207           364           377           362           207           363           207           364           373           364           373           364           365           364           365           364           365           365           366           367           368           369           364           464        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2	2 Heard before Measure 1
-	1 Jacob and 3 Jacksond before Managers 2 than 3 Jacob and 2 Jacksond
5	I Heard and I Unneard before Measure I, then I Heard and 2 Unneard
2	1 Heard before Measure 1, then 1 Heard between Measures 2 and 3
2	1 Heard before Measure 1, then 1 Heard between Measures 2 and 3
1	1 Heard before Measure 1
1	1 Heard before Measure 1
2	1 Heard before Measure 1, then 1 Heard between Measures 2 and 3
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2 5	Heard before Measure 1, then 1 Heard between Measures 2 and 3     Heards before Measure 1, then 3 Heards     Heard before Measure 1
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2 5 1 1 4 1 1	
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2 5 1 1 4 4 3 3 1	1 Heard before Measure 1, then 3 Heards 2 Heards before Measure 1, then 3 Heard after Measure 2 1 Heard before Measure 1, then 3 Heard after Measure 2 1 Heard before Measure 1 1 Heard before Measure 1, then 1 Heard between Measures 1 and 2 After Measure 1, 2 Unheard and 1 Heard 1 Heard before Measure 1, then 2 Heards between Measures 1 and 2 1 Heard before Measure 1, then 3 Heards 3 Heards after Measure 2 3 Heards after Measure 1 and 2
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2 5 1 1 4 4 3 3 1	

:	300	A1	324	326	326		
:	300	A2	307	301	304		
:	300	A3	Heard	Heard	Heard		
	300	A4	393	315	331	2	1 Heard between Measures 1 and 2, then 1 Heard between Measures 2 and 3
	300	B1	Unheard	Heard	Heard		
	300	B2	Unheard	Unheard	Unheard		
	300	C1	370	329	330		
	300	C2	Heard	Heard	Heard		
	300	C3	Heard	Heard	Heard		
	300	D1	317	364	345		
	300	D2	Heard	Heard	Unheard		
Bathroom		Sanity	Unheard	Unheard	Unheard		

The sanity check in the last row confirms that when the phones have their ultrasound blocked by distance and a door, the "Unheard" response triggers reliably. Indeed, the earliest objective of NOVID's Bluetooth-ultrasound framework was to reject interactions from different rooms.

It turns out that NOVID's iOS Version 2.1 implementation of the combined Bluetooth-ultrasound framework achieves significantly more than just that. The laws of Physics govern the travel of ultrasonic waves, and the baseline accuracy of a particular ultrasonic implementation can be assessed in terms of its performance on Settings A1 and A2. (Even then, the task is not completely trivial in the real-world environment of this experiment, which is far from anechoic, and has much multipath interference.) Those settings do turn out to be extremely accurate in Table 1.

Setting	Mean of Error (inches)	Standard Deviation (inches)
A1	-1.0	3.1
A2	-6.3	5.6
A4	14.4	10.7
D1	-4.9	3.9

Table 1: Accuracy of measurements ranging over true distances of 2, 3, 4, 5, 6, 7, 8, and 9 feet, in the settings where Physics would predict accurate results.





Figure 2: All distance measurements for Settings A1, A2, A4, and D1. Note that the region of highest accuracy extends up to 108 inches (9 feet), while measurements consistently provide upperbounds on the actual distance.

On the basis of the very high accuracy in Settings A1 and A2, the next-most-ideal setting from a Physics perspective is A4, because each small obstacle scatters ultrasound back towards the other phone. (Physics would predict that Setting A3 gives wild overestimates, because there is nothing nearby for the ultrasound to reflect off of, and that is confirmed in the experiment.) The fact that NOVID is able to return to accuracy in Setting A4 with just a small obstacle indicates that the multipath disambiguation processing methods are robust.

Already, Settings A1, A2, and A4 indicate that when phones are placed on tables (e.g., in an office environment or at home), NOVID is sensitive enough to pick out one of the shortest multipath ultrasound trajectories and accurately estimate its length. Taking reflections into account, this motivates imposing a proximity detection threshold of 9 feet (108 inches) for the purpose of capturing interactions which in reality are within 6 feet. It is here that the (geometric) triangle inequality shines: the shortest path between two points is the straight line, and so ultrasound is particularly robust to avoiding false positives. Indeed, if one used the 9-foot-threshold to differentiate between 6-feet-and-under and 12-feet-and-over interactions, then there was only one false positive.

True Distance (feet)	Number of Samples	Number Correctly Categorized	Percentage
$\leq 6$	187	103	55.1%
$\geq 12$	225	224	99.6%

Table 2: Accuracy of categorizing by thresholding the reported distance against 9 feet.

The fact that a substantial fraction of truly-under-6-foot interactions were successfully categorized by this threshold, even in a test suite that included many adversarial settings, shows that this very high level of robustness to false positives is not simply achieved by turning off all detection. Rather, many useful positive settings are correctly handled.

The particular percentages should be taken with a grain of salt, because they are as proportions of test settings in this experiment. However, a real-world correction may work in ultrasound's favor. In real-world settings, the correctly characterized percentage of 6-feet-and-under interactions could be substantially higher than the 55.1% above, particularly if Setting A4 is representative of the disproportionate norm. Indeed, in Setting A4, 15 out of 16 measurements of truly-under-6-feet interactions were correctly detected as under-9-feet, corresponding to a success rate of 94%. Setting A4 is particularly interesting because it represents accurate detection of the shortest multipath reflection with phones that are out-of-pocket. Further discussion will be in the Conclusion.

We then turn to study NOVID's ability to detect in obstructed situations. Table 1 shows that Setting D1 still has very good performance. From a Physics perspective, since the phone is entirely enclosed in a front pocket, the ultrasound will emanate from the entire pocket, and the effective detection indicates that NOVID's algorithms are sufficiently sensitive to handle some attenuation. In fact, the extremely accurate detections in Setting C1 at close ranges (2 or 3 feet) indicate that the signal processing methods are able to discern substantially attenuated signals through a 1/4inch foam core board, even in an environment which has many multipath reflections. Even when one phone is in a bag (Setting B1), detection is reasonable up to 7 feet (Table 3).

Setting	Mean of Error (inches)	Standard Deviation
B1	13.7	13.9

Table 3: Accuracy of measurements corresponding to true distances of 2, 3, 4, 5, 6, and 7 feet.

We now turn to the settings in which ultrasound was not effective. They are consistent with what one would anticipate based on the Physics of ultrasound. Setting D2 was the worst by far, and is likely because from a back pocket, there is no single-reflection transmission pathway off the ceiling, floor, or a side wall. The other setting which generally did not produce distances was B2 (both phones in bags), presumably because the signals were so attenuated that they were too diffuse to accurately calculate time-of-flight for. However, even then, among the B2 instances when the devices were within 6 feet, the ultrasonic ranging protocol only produced "Unheard" one time, out of a total of 20 trials, thereby detecting the presence of an ultrasound signal with 95% success. In light of the sanity check which confirmed that devices in different rooms reliably produce "Unheard," this indicates that if additional smartphone sensors are used in tandem (such as the proximity sensor to detect whether the phone is inside a bag), the "Heard" vs. "Unheard" signal could still potentially have value.

The remaining Settings C2 and C3 (one phone in a bag, but with a foam core board blocking line of sight) effectively turn out to be similar to Setting B1, because the ultrasound just reflects off of another object in the room. As expected, the measured lengths are then overestimates of the true length. However, it is interesting that the C2 measurements at each distance appear to be relatively self-consistent (as are the C3 measurements amongst themselves). Table 4 highlights this, showing that in many situations the standard deviation of the received measurements is small. Although the sample size is too small to draw significant conclusions, it would be interesting to further investigate whether NOVID's signal processing algorithm has locked onto a particular multipath reflection avoiding the obstacle.

Actual Distance (inches)	Measure 1	Measure 2	Measure 3	Standard Deviation
24	116	155	243	65
36	153	164	166	7
48	166	165	155	6
60	127	93	133	22
72	160	165	165	3

Table 4: Self-consistency of measurements in obstructed Setting C2, suggesting accurate detection of multipath reflection length.

### 5 Conclusion

This systematic experiment reveals the significant potential of ultrasound in controlling the falsepositive rate for contact tracing. The details of the signal processing implementation are important, in order to handle real-world situations with multipath interference, such as the various challenging environments in this test suite. In particular, this experiment indicates that bags and barriers do attenuate ultrasonic signals.

This experiment also shows a way out. In the context of COVID-19 contact tracing applications, it is important to identify interactions that represent close physical proximity (within 6 feet). This is why no experiment was done with many scattered obstacles in the line of sight between two phones at distance 15 feet. Instead this experiment already indicates that NOVID's ultrasound method is generally effective at ruling out false positives even in obstructed situations, because it consistently upper-bounds the true distance when there is no direct line of sight due to the triangle inequality. At close physical ranges, the 94% categorization accuracy in Setting A4 suggests that if people set their phones on a table next to them, in the vicinity of other common items (mouse, earbud charger, wallet, cup, purse, etc.), then ultrasound will find a way to reflect outward, possibly scattering off other objects and the ceiling to reach the other phone. This experiment did not set up such a situation due to the complexity of defining it with sufficient specificity for reproducibility, and so that will be postponed for subsequent experimentation. An example of a relevant test setting would consist of devices 6 feet apart, on tables, with a variety of objects nearby, some of which serve as obstacles but some of which (such as computer monitors or people's chins) facilitate pathways of reflection. In the interim, anecdotal observations indicate that when phones are out-of-pocket at close distance in real settings, there are often enough nearby objects to facilitate a short reflected ultrasonic pathway.

Fortunately, it is already a common behavior pattern for some people to set their phones on a nearby surface when they intend to stay in the same place for some time (e.g., office and home environments, or cafes and restaurants). These situations correlate with extended interactions with significant opportunity to transmit viral load. This, combined with the experimental validation of some level of robustness to obstruction in pockets and bags, lead us to conclude that ultrasound has high practical potential for sensing proximity for contact-tracing purposes.

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