

Ultrasonic range sensing enables measured social contact

ABSTRACT

Ensuring safe social distancing in the workplace is one piece of the puzzle to enable people to work safely in the age of COVID-19. Chirp's ultrasonic range sensors enable the range between workers to be measured with centimeter accuracy, providing the ability to immediately alert people who are closer than minimum social distance limits. Chirp's ultrasonic solution gives individuals a tool to track who they have contact with and avoid unnecessary contacts. While providers of existing tracking technology based on Bluetooth low-energy (BLE) or RFID trackers are attempting to position their solutions for social distancing, finer accuracy requirements narrow down the options to ultrasonic and ultrawideband (UWB), with ultrasonic delivering a greater accuracy of < 1 cm versus < 10 cm for UWB.

Relative to UWB, Chirp's ultrasonic range sensors consume much less power: a Chirp solution can operate at 1% of the power required by UWB chips, enabling a coin-cell tag to operate for an entire workweek. In addition, electromagnetic range sensing solutions such as UWB have a critical failing for social distancing solutions: UWB cannot natively determine whether people are separated by a barrier, such as a door, window, wall, or partition, without adding additional UWB markers near each barrier to estimate the position of each user. In a realistic work environment, UWB distance-sensing solutions without these fixed markers may produce hundreds of false-alarms in each work shift, making these solutions impractical and annoying for workers; fixed markers will require mains connections and will add significantly to the deployment costs and complexity of a UWB solution.

Because ultrasound propagates through air, only ultrasonic sensing can natively determine whether people are safely separated in the workplace. Tracking solution-providers can use Chirp ultrasonic range sensors to create social-distancing solutions that respect an individual's privacy but also permit an automated contact tracing capability to notify affected individuals and their emergency contact or direct management, providing a cost-effective way to minimize workforce disruption and stop chains of infection from propagating.

Key Features

- 2.4 m (8 ft) maximum range; detection range is configurable by the solution provider
- Range accuracy < 1 cm; ~10x lower than UWB and >100x lower than BLE
- Fast sample rate, up to 10 samples/sec at 2.4m max range to monitor social contact
- Ultralow supply current: 400 μ A average current during pairing phase through 1.8V supply
- Small size (3.5 mm x 3.5 mm LGA package), compatible with standard SMD reflow
- On-board ultrasonic DSP handles all ultrasonic signal processing
- Easy-to use sensor API enables fast time-to-market

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1 INTRODUCTION

COVID-19 presents a unique failure mode of the economy where once normal social contact can now lead to widespread infections that can overwhelm medical systems; social interaction may remain changed for some time to come. This white paper describes how tracking-solution providers can use Chirp's ultrasonic time-of-flight technology to measure when users come into contact and notify those who may have been exposed to SARS-COV-2 when an infection does occur. Chirp provides a complete sensor API and reference design to make it easy for solution providers to quickly incorporate ultrasonic range-finding technology into their tracking solutions.

Workers who get sick and spread infection in workplaces represent a hazard to supply chains [3] and, besides the considerable human costs, high-value (e.g. semiconductor and medical equipment) supply chains rely on sophisticated workers with many years of training who cannot be replaced easily if widespread infection does occur. Minimizing chains of infections is possible with rapid contact tracing [4]. Many businesses and governments are recognizing the need for wearable tags to automatically detect when individuals come within 6-8 feet of one another so that they can be alerted to maintain a safe social distance.

Tracking-solution providers can use Chirp's CH101 ultrasonic transceiver to accurately measure the range between wearable tags at ranges up to 8 feet with an accuracy of 1 centimeter. CH101 is a miniature, ultra-low power ultrasonic Time-of-Flight (ToF) range sensor. Based on Chirp's patented MEMS technology, CH101 is a system-in-package that integrates a PMUT (piezoelectric micromachined ultrasonic transducer) together with an ultra-low power SoC (system on chip) in a miniature, reflowable package. The SoC runs Chirp's advanced ultrasonic DSP algorithms and includes an integrated microcontroller that provides digital range readings via I²C [5]. CH101 is used for precision position-tracking in consumer VR systems today – in these systems CH101 measures the position and orientation of hand-held VR controllers with an accuracy of better than 1 centimeter [6] - [7]. It is also targeted for applications like liquid level detection in bottles, soap dispenser, faucets, and other devices that want to eliminate touch.

Chirp has software reference designs to enable tracking-solution providers to quickly integrate CH101 into their tracking products. Here we describe some example implementations that use CH101 along with a wireless link such as BLE or 802.15.4. To measure the distance between two people, two or more CH101 are used in pitch-catch mode, where the CH101 on the first person's tag transmits an ultrasonic pulse that is received by the CH101 on the second person's tag. Based on the time-of-flight of this ultrasonic pulse, the second person's tag records the distance to the first person and transmits a response pulse that is received by the CH101 on the first person's tag, providing the distance to the first person. Ultrasonic range measurements can be performed at 10 samples per second, and two people whose distance is less than 2.4m (8 ft) are notified within 1 second. The key to this quick response time is fast pairing between two nearby tags. CH101 must listen and transmit pulses of ultrasound to determine whether another tag is nearby. Incorporating two CH101 allows nearly 360 degrees of coverage, and the pairing process ensures users are detected with high probability if they are in contact for more than one second. Once two users' tags pair with each other, they stay in sync at regular intervals to monitor the duration of the contact.

A wireless link such as BLE or 802.15.4 enables the tag to exchange unique identifiers (IDs) which allow each user's tag to record which tags it has contacted. Contact tracing can be enabled without compromising user privacy by assigning each user a unique tag and keeping each tag's contact log local to the tag, which will compare its log against the list of infected IDs provided by a central database. In this way no central authority will have access to the user's contact list. The only central database required is that of the tag IDs of those users who test positive. Each UCT can locally determine when it has been exposed to an infected user's tag, what the severity of the exposure is, and relay only the recommended quarantine action to the central database through a fixed tag (FCT) that is internet connected and typically stored at the charging station. In this way user privacy and automated contact tracing need not be in opposition.

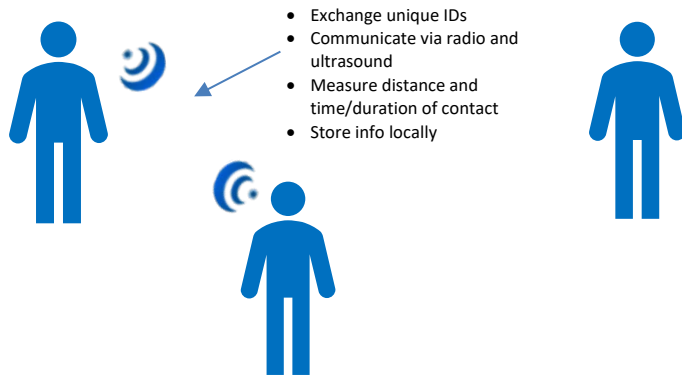


Figure 1. When users need to get close, their tags track the distance to each other and exchange IDs.

2 ULTRASONIC PEER-TO-PEER RANGEFINDING

Chirp’s software reference design for peer-to-peer range-finding, SonicSync [8], was originally developed for 3D tracking and home security applications but can be readily adapted to any tag-based tracking system. The basic principle is that two nodes should discover each other by exchanging pulses of ultrasound. A block diagram of a simple ultrasonic tag is shown in Figure 2. This block diagram enables the basic function of sounding an alarm when two users break social distance recommendations.

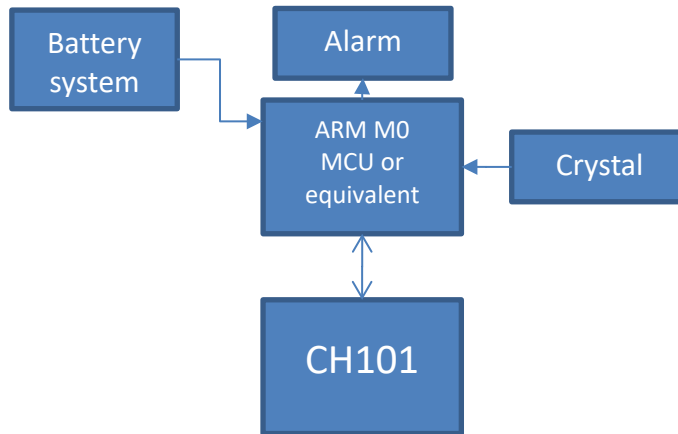


Figure 2. Basic block diagram of an ultrasonic tag for a social distance alarm

At power on, each node goes into pairing mode, where it will remain until the user comes into social contact with another user. During pairing mode, a node will transmit a burst of ultrasound at a pre-determined frequency (the search pulse), wait for echoes to reverberate, and then enable the receiver to listen for a reply pulse. If no reply is heard, the node will continue listening for other nodes’ search pulses for a random number of receive periods (each about 10 ms in duration) for an average of 250 ms. At this point the node will repeat the process. The duty cycle of the receive phase is ~80%, designed to ensure that two nearby nodes detect each other within 1 second with a probability of 99.8%. The average current consumption during the receive phase is about 400 μ A through 1.8V which enables one 40 hour workweek operation of two CH101 ultrasonic transceivers in search mode on a 23 mm coin cell battery [9].

The pairing process for two nodes is illustrated in Figure 3. Transmit phases are represented by an upright narrow rectangle and receive phases are represented by a shorter, nearly square rectangle. In the diagram, two nearby nodes are within range of each other. In some instances, the two nodes will pair immediately because the transmit and receive phases of the two nodes happen to coincide. This example illustrates a case where the pairing is not immediate and multiple search phases are required. At t=0 the asynchronous nodes happen to be nearly in phase, and their search pulses, represented by the diagonal arrows, pass each other and are undetected during the reverberation time. The nodes continue to receive frames of ultrasound for several hundred milliseconds. Each node happens to select the same random period, and the cycle repeats. In the 2nd cycle, node A happens to select a shorter random period and transmits to Node B while Node B is receiving, thereby triggering node B to prepare to respond.

After the tags have discovered each other, they begin synchronized (“locked”) communication. Figure 4 illustrates the behavior of locked tags. Node B waits for a predetermined reference time before sending a reply pulse. Meanwhile, Node A, after sending the search pulse, has waited for a predetermined reference time and then starts a receive period in time to catch the reply from Node B. Node A calculates the round-trip time-of-flight (ToF_A) by measuring the time from the start of the receive period to when the reply pulse from Node B arrives. Since Node A transmitted the search pulse that was discovered, Node A becomes the master node. Subsequently, after waiting another predetermined reference time, Node A transmits a reply pulse to Node B, which has waited for a predetermined reference time and then started a receive period in time to catch the reply from Node A and calculate the round-trip time-of-flight (ToF_B) by measuring the time from the start of the receive period to when the reply pulse from Node A arrives. At this point, both tags know they have contacted another tag and they know the distance to that tag. The nodes will continue to stay in contact as long as they are in range of one another. Node A will transmit at a fixed period and Node B will stay synchronized to that period by listening for Node A’s search pulse in a long enough window to compensate for clock drift or motion between the two nodes.

This method can be extended to measure the distances between a group of tags. As a tag joins the network, it communicates with the master node during a special window that is used for pairing. Subsequently, the master node will assign it a time slot using the tag's wireless (BLE or 802.15.4) connection.

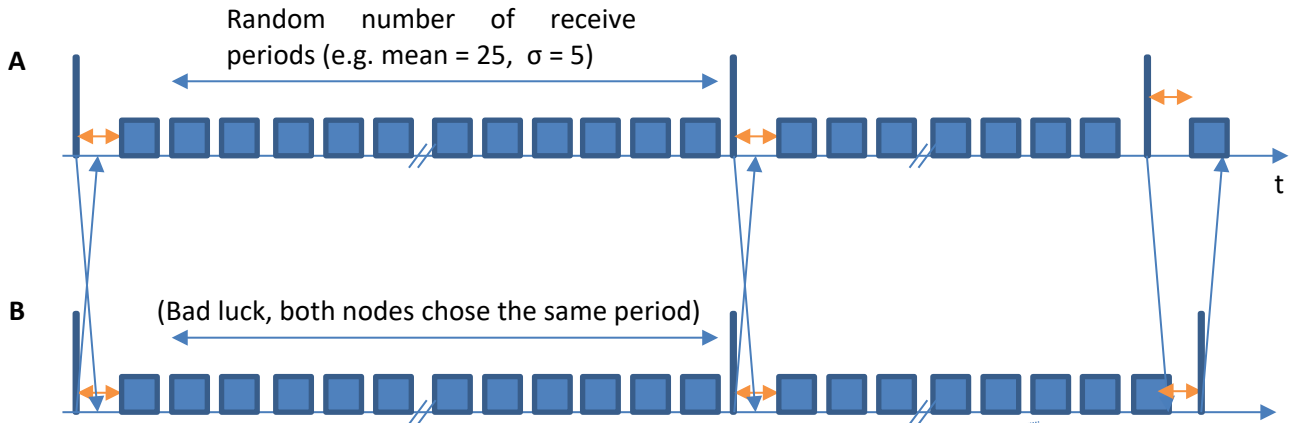


Figure 3. Pairing behavior of two nearby tags, showing the case where the two nodes need multiple search cycles to pair. [2]

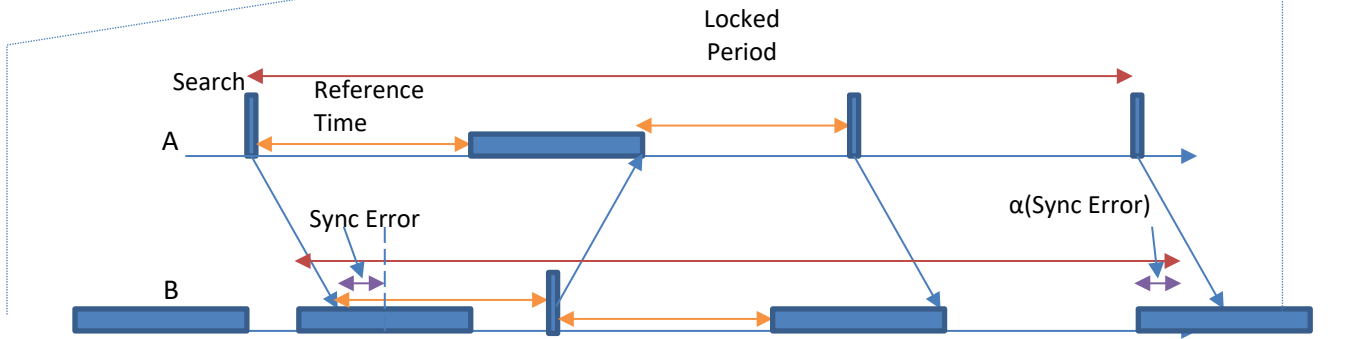


Figure 4. Operation between paired nodes. User movement changes the time-of-flight of the ultrasonic pulse, resulting in Sync Error. This error does not affect range accuracy and is nulled by adjusting the start time of the next receive phase so that the pulse always arrives approximately at the middle of the receive phase.

3 ADDING A SECOND CH101 TO ENABLE 360° FIELD OF VIEW

The field-of-view (FOV) of CH101 can be optimized for a particular application by engineering the acoustic opening that the sound travels through. For this application, the FOV needs to be as wide as possible in the horizontal axis in order to detect other tags approaching from any direction. However, the vertical axis does not need a wide FOV since user’s height does not vary that much and users can be instructed to wear the tag at a near-uniform level.

A horn with an asymmetric FOV is shown in Figure 5. The horizontal FOV is 150 degrees FWHM (full-width, half-maximum) and has substantial sensitivity all the way to ± 90 degrees while the vertical is about 50 degrees FWHM and beyond ± 40 degrees has very little signal.

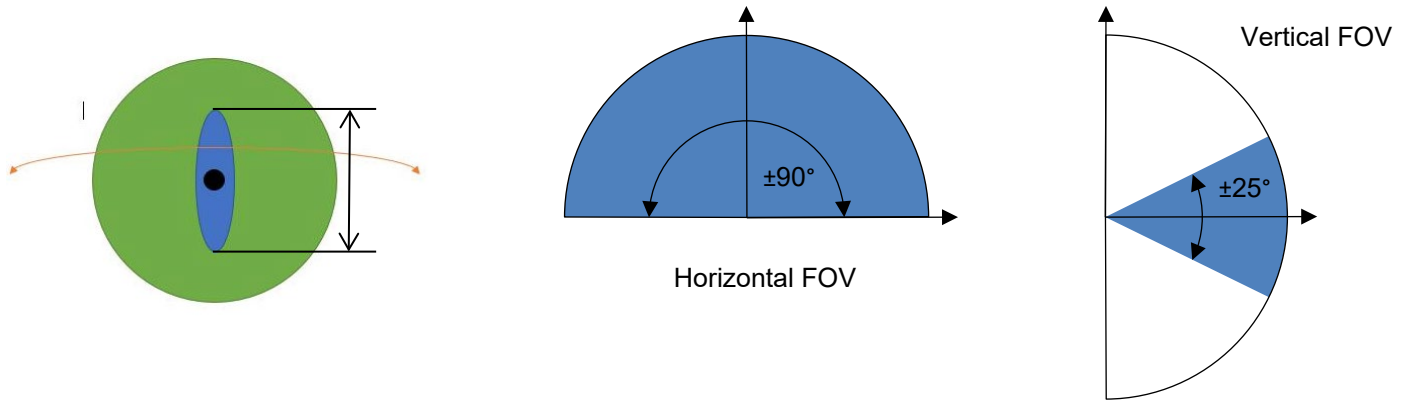


Figure 5. Asymmetric FOV horn. The horizontal axis, marked with the orange arrow, has a wide FOV while the vertical axis has a narrower FOV.

Clearly, to cover 360 degrees of detection, more than one CH101 is required. In some high-risk situations, three or more CH101 may be used, but for typical use-cases, two will be enough to ensure good coverage if the CH101 can be placed on the user’s body in roughly opposing viewpoints. For example, the user may choose to attach the sensor tags to their chest and back, especially if they are wearing a vest; those wearing a mask or a visor may be able to attach the tags on the right and left side of their head.

The two CH101 transceivers on the user should be used independently, since they may connect to different nearby tags. However, care must be taken not to trigger both CH101 to transmit within 10 ms of each other, as this could cause the two CH101 transceivers on the user to ‘discover’ each other. In the rare case that both CH101 transceivers are connected to different nearby tags with the same locked period and overlapping transmit phases, the wireless link (BLE or 802.15.4) can be used to reconfigure the network to avoid collisions.

4 CONTACT TRACING

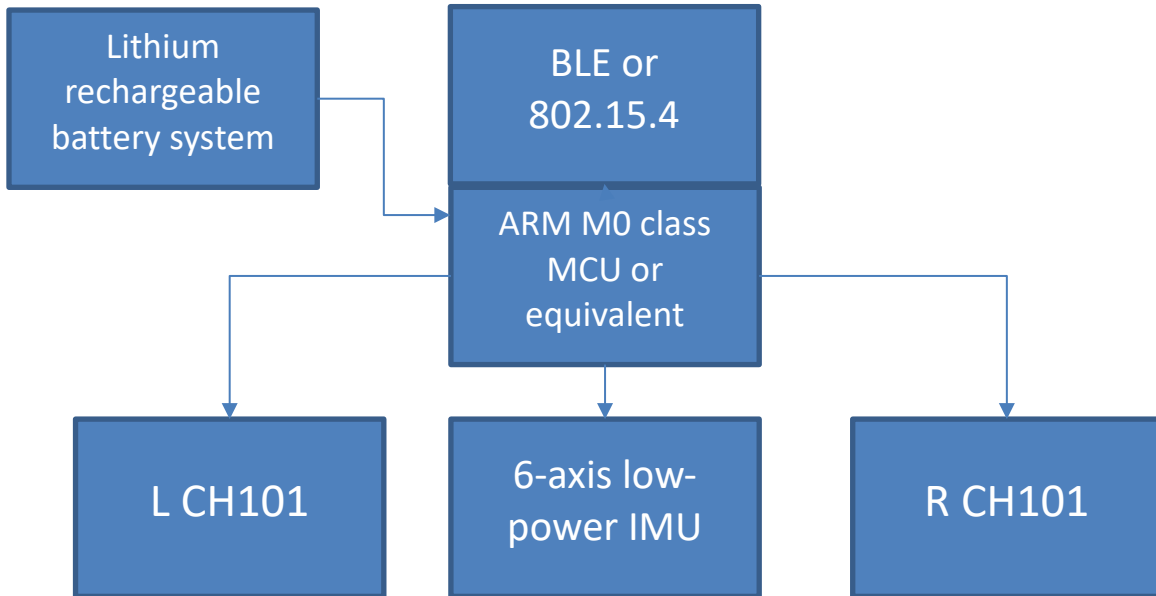


Figure 6. Overall block diagram for contact tracing solution

A system block diagram to enable automated contact tracing is shown in Figure 6. An ARM Cortex-M0 class MCU controls the system, starting the search for nearby tags when the IMU detects motion. The system also incorporates a wireless link, assumed to be BLE here, although alternative radios such as 802.15.4 may be used. When the left or right CH101 detects a nearby tag, a BLE connection is made between the tags and the tags verify that the time-of-flight measured by both sides is in good agreement (to prevent tags from pairing to the wrong nearby tag). The BLE can also configure the ultrasound network, establishing a contact period and timeslots such that multiple tags can interact at the same time.

Using the BLE in a mesh networked fashion allows the contact trace to be made and remain local to each tag without any central database of social contacts required; the only info required to be stored centrally is the ID of the tag of those users who have a suspected or confirmed case. Each tag can locally determine when it has been exposed to an infected user’s tag, what the severity of the exposure is, and relay only the recommended quarantine action to the central database. This process could be achieved by equipping each tag with a method to contact the central authority directly, such as a WiFi or LTE modem.

In many cases, it may be advantageous to deploy fixed tags in the environment which would typically be powered and have a connection to the server via WiFi or LTE. The fixed tags could be used to track presence in heavily tracked locations like break rooms, bathrooms, or kitchens, and pass relevant info to the user tags who encounter it. The user tags would receive tag IDs of infected users and upload whether they have had potentially dangerous contact with any of the positive IDs.

The automated contact tracing could be made more advanced as more research into transmission mechanisms becomes available, as shown in Figure 7. For example, in [2], the authors estimate the probability of transmission spans about two days before symptoms develop to about seven days or more after they do. This data is useful to an automated contact tracing app if the infected individual’s time of developing symptoms can be estimated accurately.

For example, an algorithm for estimating a user’s exposure is detailed here. In the top plot of Figure 7, an infected individual’s onset of symptoms at t_0 can be used to estimate the period when they were contagious and assign a base probability of transmission. In the center, a tag who had exposure to the tag of the infected individual had a long-duration exposure at long range and a shorter duration exposure at very close range. On the bottom, a probability of the tag’s user falling ill (P_+) is estimated based on the known contact windows. If the P_+ becomes high enough, the tag notifies the user and the central authority that the user has a high risk of contracting COVID-19.

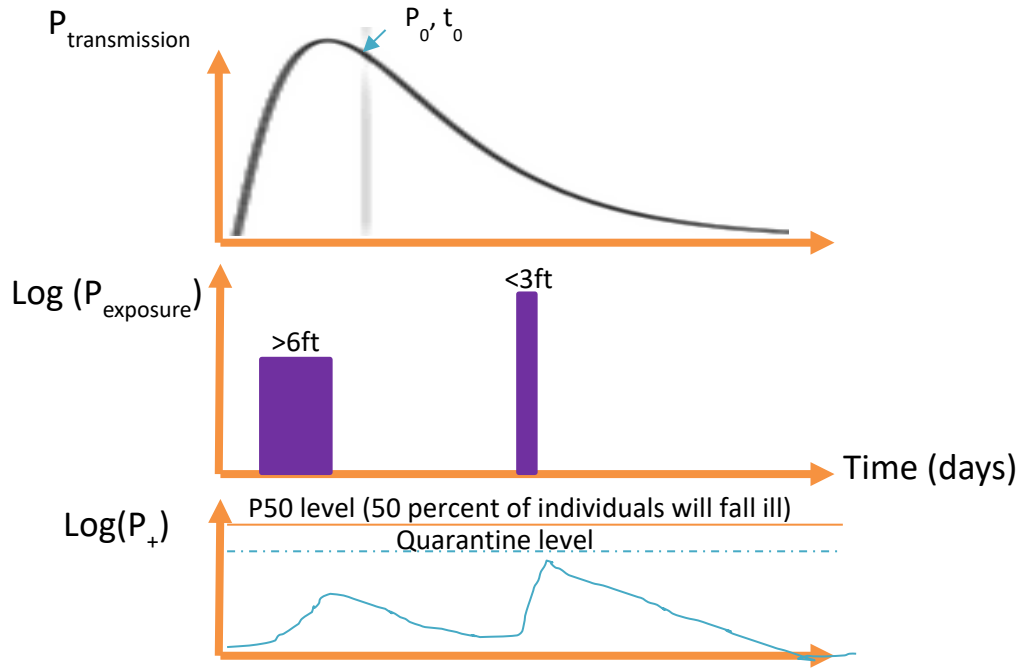


Figure 7. Estimating the probability of the user falling ill based on contact with a known positive case.

5 ADVANTAGES COMPARED TO OTHER TECHNOLOGIES

Chirp’s MEMS-based ultrasound technology is well suited to the problem of measuring social contact. The competing technologies are conventional ultrasound, ultra-wideband (UWB), and Bluetooth (or other RF based technologies). The comparison table is shown in Figure 8. RF technologies generally have high power consumption and low accuracy compared to ultrasound since the speed of light is nearly 1 million times faster than the speed of sound in air. Conventional ultrasound is bulky and expensive.





	 Conventional Ultrasonic	 UWB	 Bluetooth	 Chirp Miniaturized Ultrasonic
Solution Size	Large	Medium size (Needs antenna)	Small	Very Small
Accuracy	High <3cm	Low ~10cm	Very low 5-15m	Very high 1cm
Power Consumption	Mid-range	High	Mid-range	Ultra-low
Field of View	Up to 180 degree	360 degree	360 degree	180 degree w/1 sensor 360 degree w/2 sensors

Figure 8. Comparison table between other ranging technologies

Chirp technology is designed to be low-power from the bottom up. The piezoelectric material used to actuate CH101 is conducive to low power operation due to the high-impedance nature of the piezoelectric layer with its low permittivity and virtually zero dc conductance. The CMOS transceiver was designed with power efficiency as one of the primary requirements for the transmit and receive circuits, which only operate in the hundreds of kHz of range as compared with RF circuits that are typically operating with hundreds of MHz of bandwidth in the bands of 2.4 GHz or higher. As a result, the receive power consumption is between 2-3 orders of magnitude less power consumption than an RF solution, and the transmit power consumption is 1-2 orders less.

Low power consumption is especially important for the social distance application, as most devices will remain in the pairing phase, searching for other devices, for most of the battery lifetime. As any cell phone user who has been far from a cell tower knows, searching for other devices quickly drains the battery because the receiver must remain on for a substantial duty cycle in order to ensure discovery happens within the allotted time. For social distance, the allotted time is only ~1 second, so the receive duty cycle will be nearly continuous if a transmit period of 3-5 Hz is used during the search phase. This means that for a given battery lifetime (e.g. one week), the battery used in an RF solution should be 2-3 orders of magnitude larger than that used for a solution based on CH101. In practice, solutions using CH101 will be able to go for multiple weeks between charging whereas solutions using RF will need to be charged every day while using a much larger capacity battery, making tags bulky and inconvenient to use every day.

Ultrasound has the distinct advantage over RF based solutions that it can measure the presence of barriers that may be protecting users from one another. For example, if there is a barrier separating two users as shown in Figure 9, ultrasound will reflect off the barrier regardless of the material properties, and no social contact will be recorded unless there is a path through the barrier through which air can travel. On the other hand, for RF based solutions, the RF wave will not be reflected by the barrier unless it is conductive. Users on opposite sides of solid walls or glass partitions will record false positive social contact, which could lead to unnecessary quarantine and psychological stress if a user’s false positive contact(s) were to fall ill. Only by augmenting the environment around the barrier with additional fixed tags (adding significantly to the installation costs and solution complexity) will an RF solution be able to avoid the kind of false positives that ultrasound will natively reject.

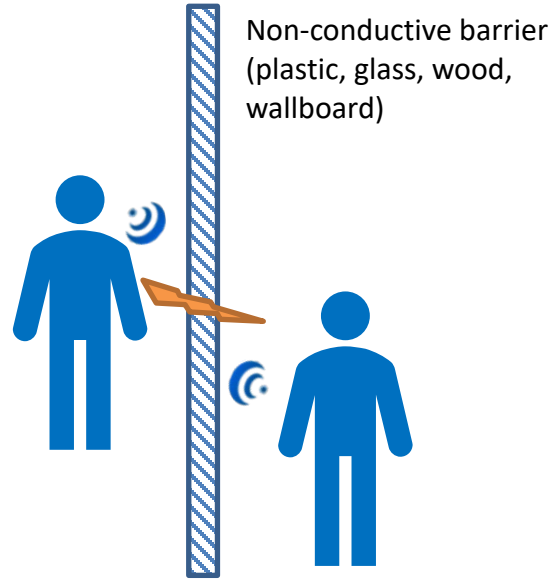


Figure 9. RF technologies readily penetrate non-conductive barriers such as walls, windows, and partitions, causing false positives where there is no social contact

6 CONCLUSION

Social interaction as we knew it has changed with COVID-19, and drastic changes into the way we interact are required at workplaces and in public settings. Using ultrasonic time-of-flight technology from TDK, we offer the most robust social distance metering system that empowers workers to stay a safe distance from one another and which enables automated contact tracing when social distance is not possible. The system has a range of 8 ft and does not detect false positives through walls or barriers. Low-power operation allows a coin-cell battery to power the system for one workweek.

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8 REVISION HISTORY

Revision Date	Revision	Description
06/01/2020	1.0	Initial release

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