UbiquiTouch: Self Sustaining Ubiquitous Touch Interfaces

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We present UbiquiTouch, an ultra low power wireless touch interface. With an average power consumption of 30.91μW, UbiquiTouch can run on energy harvested from ambient light. It achieves this performance through low power touch sensing and passive communication to a nearby smartphone using ambient FM backscatter. This approach allows UbiquiTouch to be deployed in mobile situations both in indoor and outdoor locations, without the need for any additional infrastructure for operation. To demonstrate the potential of this technology, we evaluate it in several different and realistic scenarios. Finally, we address the future application space for this technology.

CCS Concepts: • **Human computer interaction (HCI) → Interaction devices**; • **Human-centered computing → Ubiquitous and mobile computing**.

Additional Key Words and Phrases: Low power computing, Backscatter communication, Touch interaction, Power harvesting

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1 INTRODUCTION

Touch interaction is a fundamental interaction technique for computing interfaces. However, touch interaction is currently limited to devices such as phones, laptops, smartwatches, etc. Extending touch sensing from devices to objects and surfaces in everyday life can enhance them with interactivity and improve day-to-day interactions. The research community has explored a number of ways to extend the interaction space using acoustics [12, 48], RF sensing [7, 19], and capacitive sensing [11, 45]. Most of these solutions either require dedicated infrastructure

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or battery-powered hardware to sense and communicate back touch input to a computing entity that can respond appropriately. The logistics of providing power and a communication path is what limits the surfaces that can support touch interaction.

One way to address these challenges is to develop self-sustaining approaches that power the sensing and communication needed to support touch input. Previous battery-free approaches have used RFID [20, 34, 49] or other wireless powering methods [35, 43] but require additional infrastructure to be present in the environment (e.g., an RFID reader). Power harvesting solutions, such as solar cells, do not provide enough continuous power in many indoor artificial light settings to support the conventional sensing and communication channels (e.g. Bluetooth Low Energy (BLE) [22]). To address this, we developed UbiquiTouch (Figure 1), a low power sensing solution that can detect touch input and then communicate that input wirelessly to a nearby FM enabled smartphone by backscattering ambient FM radio waves. This approach works without the need for any additional custom infrastructure in the environment. It consumes 31 μW of power on average, enabling it to work both indoors and outdoors with most commodity solar cells.

In this paper, we discuss the relevant related research that inspires and informs UbiquiTouch. We provide an overview of our technical approach, with detailed descriptions for the implementation of the touch sensing, encoding of the touch event in a form that can be wirelessly communicated, and the use of ambient FM backscatter to communicate passively to a nearby smartphone. We describe the results of evaluations to explain how the prototype works in practice. We then explore the potential application space for UbiquiTouch.

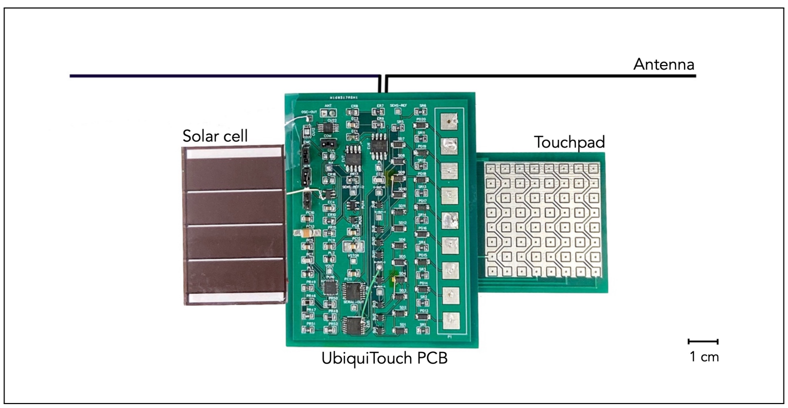


Fig. 1. UbiquiTouch System

Contributions

- **System design for ultra-low power wireless touch interface**: UbiquiTouch demonstrates an end-to-end pipeline for building self-sustainable interactive touch surfaces. It consists of a touchpad whose layout is dictated by the target application, a custom ultra-low-power circuit to sense and transmit the touch location leveraging ambient FM radio waves, and a software program that decodes the transmitted data in real-time.
- **Feasibility study in different settings**: We conduct an evaluation of our system with 20 participants in both indoor and outdoor locations to demonstrate that UbiquiTouch can be used in practical application scenarios. We also discuss in detail how different parameters affect the system's performance and their trade-offs.

- **Exploration of interesting usage contexts**: UbiquiTouch opens new possibilities for interaction on everyday objects and surfaces. We demonstrate the potential of UbiquiTouch in setting where a self-sustainable touch input would be relevant, e.g. input on clothing while using AR/VR, touch input on paper for interactive public poster, etc.

2 RELATED WORK

The choice of touch sensing interface is driven by its target application with trade-offs between performance (e.g. reliability, latency, precision), scalability (e.g. single-point, multi-touch and multiple device detection), ease of deployment, and power consumption. Our related work section intersects with three key research areas. First, we discuss touch sensing methods for everyday objects and surfaces with focus on functionality, power consumption and scalability. Next, we look at system design trends in the domain of self-sustainable sensing and communication. Lastly, we combine both the themes together and critically look at the current field of the self-sustainable touch sensing systems for everyday objects, analysing it carefully for functionality, instrumentation overhead and performance trade-offs.

2.1 Touch Sensing over Everyday Objects and Surfaces

A spectrum of techniques has been explored in the last decade to achieve reliable touch detection on surfaces of different sizes and geometry. Light sensing techniques using optical fiber [47], laser range finder [3] and depth-sensing camera [24] have been employed to determine grasp, touch, and movement. Large surfaces like tables or walls augmented with glass can be made touch-sensitive using FTIR sensing technique [1]. Even though these light-based methods allow for granular detection of touch interactions, they are extremely power-intensive and require expensive instrumentation of the infrastructure.

Another way to detect touch events on everyday surfaces is based on sound, by carefully placing microphones on or near the surface of the object [12, 17, 18, 32]. Wimmer et al. [48] applied time domain reflectometry to curved surfaces in order to enable touch interactions on them. These auditory methods are cheaper than light-based techniques but are still quite power intensive. They require a microcontroller which consumes mW-W of power for data communication, processing or storage. The same limitation is true for touch detection solutions that have resistive [13], capacitative [28, 33, 37] or piezoelectric [29] sensors embedded in the object itself. Recently, inexpensive do-it-yourself techniques [51–53] have been demonstrated in the literature for augmenting any surface with touch sensing capability. Even though these solutions have a low power requirement and are thus versatile for touch sensing, they are still far from a practical solution where everyday surfaces can be interactive. There is a need to consider system architecture level along with an application mindset to build a practical, interactive touch detection solution that is optimised for power and functionality.

2.2 Self-sustainable Sensing and Communication Systems

Improvements in the efficiency of power harvesting (e.g. solar [10], wireless power transfer) with a simultaneous decrease in the power of operation [16, 23, 31, 41] has resulted in making self-sustainable systems a reality. One of the earliest systems, Wireless Identification and Sensing Platform (WISP), augmented RFID tags with sensors so that the tag itself can send sensed data(e.g. camera, audio, accelerometer) to nearby reader [36, 49]. WISP works by first digitizing the sensed data and then using a state machine to perform data computation or communication using low-power micro-controller like MSP 430. WISP consumes < 10mW of power, thus lasting for a considerable amount of time when duty-cycling is applied. A recent wave of battery-free sensing systems optimizes power even further by shifting the digital tasks to the receiver and keeping the tag as a purely analogue system with cleverly designed encoding schemes to communicate the information reliably to a receiver. Such systems consume power on the order of 100 mW [26, 35, 43]. To save the infrastructure cost for the RF transmitters and receiver, another trend in the self-sustainable communication domain is to find clever ways of using existing infrastructure to transmit data. Cohn et al. [4] utilized powerline coupling to communicate sensed data in a home setting. One recent trend has been to utilize readily available radio frequency waves like FM [44], WiFi [2, 50] or TV signal [21, 30] for ambient backscatter communication. This makes the system more practical to use and deploy. We leverage these two technology trends to build UbiquiTouch, an ultra-low-power touch sensing system.

2.3 Self-sustainable Touch Sensing

Power is a major bottleneck in scaling touch interactions to everyday objects. There has been other previous work *that enables* self-sustainable touch and gestures detection based on inexpensive passive RFID tags to facilitate new-style interaction interfaces [20]. PaperID [19] and RapID [40] demonstrated RFID-based touch interaction possibilities for objects by detecting change of the backscattered signal. RIO [34] recently improved its performance detecting subtle changes in antenna impedance when a human finger touches the surface of an RFID tag. Live Tag [7] used thin, flexible chipless RFID with commodity WiFi to eliminate the need for using expensive transceivers. ZeroPowerTouch [25, 42] demonstrates a receiver design that operates only from the energy harvested from the received message to work as a touch sensor. All of these systems rely on dedicated RF equipment to be present for their operation, restricting availability to a certain location and contributing to deployment costs. UbiquiTouch overcomes this requirement by using existing resources present in the ambient environment for operation.

Inspired by the technology trends and lack of a practical self-sustainable interactive touch detection system in the existing literature, we propose UbiquiTouch as a low-power system for real-time touch detection without the need for significant infrastructure to be deployed.

3 TECHNOLOGY

3.1 Overview

The UbiquiTouch system consists of a touchpad, a custom ultra-low-power circuit to sense and transmit the touched location, and a software program to decode the transmitted data. The touchpad consists of a 2D grid of single touchpoints that causes a voltage potential change when touched. The detected location on the touchpad is encoded as a binary data packet and transmitted by backscattering ambient FM radio waves. This transmission is received as an audio signal by a commodity smartphone with a built-in FM receiver. The audio is then processed to identify and decode the data packets.

3.2 Touch Sensing Principle

The sensing technique is based on the mild conductivity of human skin which allows for electrical signals to propagate through it. The resistance of human skin is generally between 1-100 kΩ and depends on factors like skin moisture and body temperature [6]. When skin simultaneously touches two electrodes at different voltage potentials, it creates an electrical path between them, causing a flow of current between the electrodes. The presence or absence of this current can be used to detect human touch.

In our setup, we use two electrodes, one as a positive potential and another one as a voltage sensing electrode. When skin simultaneously contacts these two electrodes, it induces a current flow between them, resulting in voltage change at the sensing electrode, which is measured to sense touch. One such electrode pair makes a single touchpoint. We create a 2D arrangement of such electrode pairs or touchpoints for our system. Figure 2 shows the sensing principle.

3.3 Touch Pad Design

Our touchpad design consists of rows and columns which act as sensing electrodes. Both rows and columns are exposed as square-shaped conductive pads and are laid out, as shown in 3. The rest of the medium on the touchpad is an electrode maintained at a positive voltage. This layout tightly packs the touchpoints and evenly distributes both rows and columns.

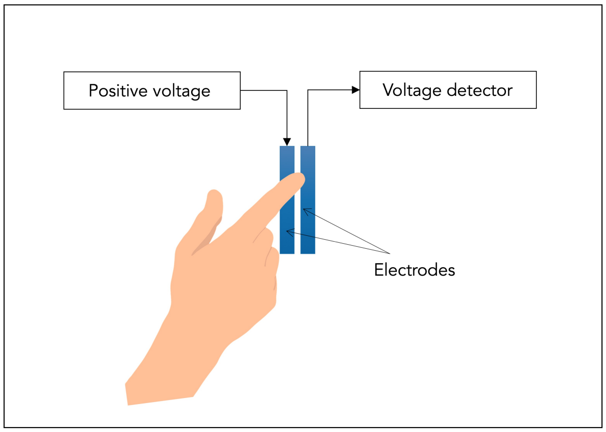


Fig. 2. Sensing principle

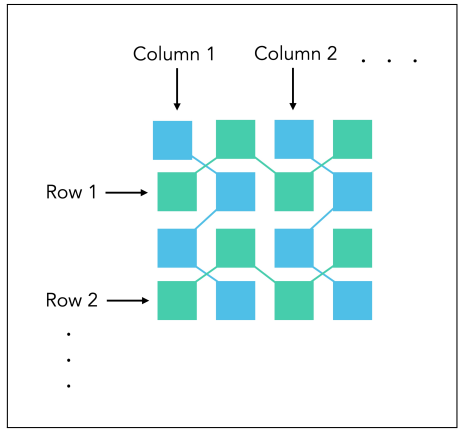


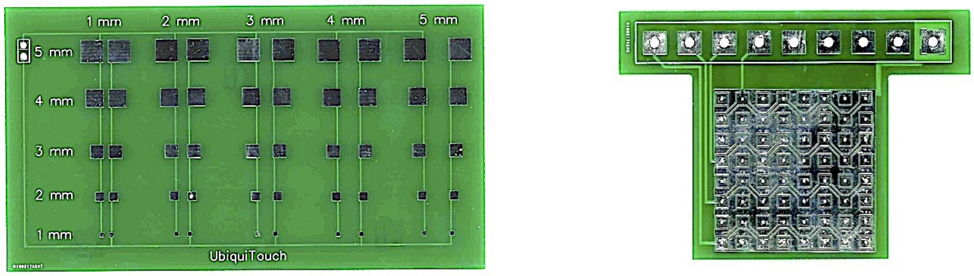
Fig. 3. Touchpad layout

In this design, the intersection of a row and column is one touchpoint on the touchpad. For a user's touch to be correctly detected, the finger must touch both the column and row at the contact point and induce a positive voltage in it. For this to happen, the dimensions of the row and column should be such that an average human fingertip should be able to touch at least one row and column pad. Furthermore, the voltage on the positive potential electrode should be sufficiently high to produce a positive voltage for different user's skin resistances on the row and column electrodes.

To determine the best physical dimensions of the row and columns pads, we performed a pilot study among the researchers in which we tested several combinations of electrode pairs with different surface areas and distances between them. All combinations were repeated for different values of the positive voltage. 4(a) shows the evaluation board used in this investigation made with tin-coated copper electrodes. From our analysis, we found that increasing the surface area of electrodes while decreasing the distance between electrodes increases the probability of touch detection. Based on these results, we designed our touchpad with a pad size of 2.5mm x 2.5 mm and maintained the positive voltage at 4 V. Figure 4(b) displays the touchpad with four rows and four columns.

3.4 Touch Location Encoding

Each touchpoint on the touchpad is represented by a unique binary address combining the address of the touched row and column. The rows and columns are addressed independently by two separate priority binary encoders where the rows and column lines are inputs to the two encoders. The choice of binary encoders for addressing helps to save power as binary encoders can read all inputs simultaneously and avoids the need to poll individual inputs. Polling inputs one-by-by would require more circuitry which will consume more power. A binary encoder takes 2^N bits of input and encodes it into an N-bit output. Since our touchpad prototype has four rows and columns, we use two 2-bit encoders, the output combination of which is a 4-bit location that has been touched.



(a) Touchpoint evaluation board

(b) 4x4 Touchpad

Fig. 4. Touchpad PCBs

This approach has the limitation that binary encoders can only read one input at a time—implying that if multiple rows/columns are touched simultaneously, the encoders will output a wrong result. This problem is solved by using a priority encoder which assigns priority to inputs and ensures that if multiple rows/columns are touched simultaneously, only the one with the highest priority is recorded. This, in terms of the design, means that the rows and columns pads can be made smaller and tightly packed to provide a higher touch resolution.

3.5 Communication

3.6 Overview

Communication is one of the most power-intensive operations in wireless devices, especially for low-power devices. This higher power requirement is due to the need to generate high-frequency RF signals that consume several watts of power. To save energy on communication, we use the technique of backscatter communication. Backscatter communication eliminates the need to produce high-frequency RF signals by modulating and reflecting existing RF radiation.

A typical bistatic backscatter system consists of a backscatter node, a continuous wave emitter, and a receiver. The backscatter node receives a carrier signal from the emitter and reflects a part of it to the receiver. By modulating the reflection of the incoming RF signals, the backscatter node embeds its information on the existing signal without generating the carrier wave itself. For UbiquiTouch, we use ambient FM signal as the signal source instead of a dedicated transmitter, as most locations have FM radio stations which are widely accessible and transmit continuously. Wang et al. have shown that this ambient FM signal is strong enough for supporting backscatter communication [44]. On the receiving side, the backscattered signal is captured by a commercial mobile phone with a built-in FM receiver. By using the receiver and transmitter as existing resources in the environment, UbiquiTouch runs without requiring any dedicated infrastructure. This is critical for supporting the goal of ubiquitous availability of the passive communication channel.

3.7 Transmission

The sensed location on the touchpad is transmitted wirelessly as a binary data packet to a nearby FM receiver by backscattering information on ambient FM radio waves. Since the backscatter communication link is weak due to the low signal to noise ratio of the backscattered signals, we take two measures for improving the communication quality. First, until a point is touched on the touchpad, the touchpad hardware continuously re-transmits the packet corresponding to the touched point. If a packet is corrupted in transmission, the next packet could be used for decoding location. Second, in each transmission, we create redundancy by including the detected location twice in the packet for error checking at the receiver. By simply including a second copy of the data in the packet, we avoid generating error-correcting codes and save power. Each data packet starts with a 7-bit header (1010111) which helps the receiver to find the start of the data packet. The header is followed by two copies of the 4-bit binary address of the location. Fig 5 shows a data packet.

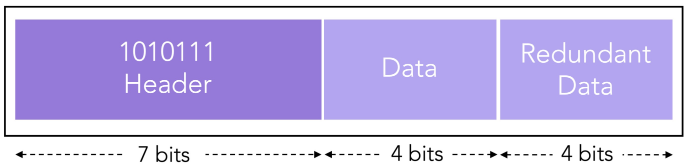


Fig. 5. Data packet structure

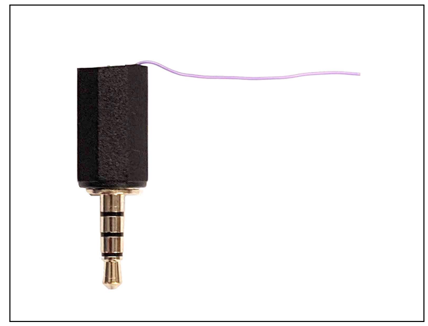


Fig. 6. Headphone Jack

We encode our binary data on the FM wave using an On-Off Keying (OOK) modulation scheme. In this scheme, binary one is represented by the presence of a backscatter signal while its absence represents a binary zero. A backscatter signal is generated by modulating the radar cross-section of an antenna in the presence of a carrier wave. We perform binary modulation in our prototype and hence switch our antenna between two discrete impedance states. The rate of this switching also determines the frequency of the produced backscatter signal. If the backscatter antenna is switched at frequency f_{back} to backscatter an ambient FM signal centered at frequency f_c, then the backscattered signal generated will be at a frequency of $f_c + f_{back}$ [44]. This implies that the FM receiver will need to tune at the center frequency of $f_c + f_{back}$ to receive the backscattered signal.

3.8 Receiver

The transmitted data is received by a nearby smartphone with a built-in FM receiver. Most smartphones have an FM radio integrated into their hardware [8], which makes them a commonly available receiver in the environment. The phone's FM radio does not provide access to the raw RF signal but instead decodes it and provides it as an audio stream. We process this audio stream in software to detect and decode data packets.

FM receivers in smartphones generally do not have an internal FM antenna, requiring the users to plug in their headphones to receive the FM signal. We do not want to require the use of headphones for UbiquiTouch to work, so we designed our system to work with only a small headphone jack inserted into the phone without any long headphone wire connected to it. This small jack, as shown in figure 6, can be used continuously without hindering regular use of the phone.

Figure 7 shows the system overview.

3.9 Power Management

UbiquiTouch touchpad hardware is self-sustaining and works only using the energy harvested from ambient light through a photovoltaic cell. It achieves this through its low power circuitry and passive communication technique. To optimize usage of the harvested energy, the hardware has a sleep mode. When the touchpad is not

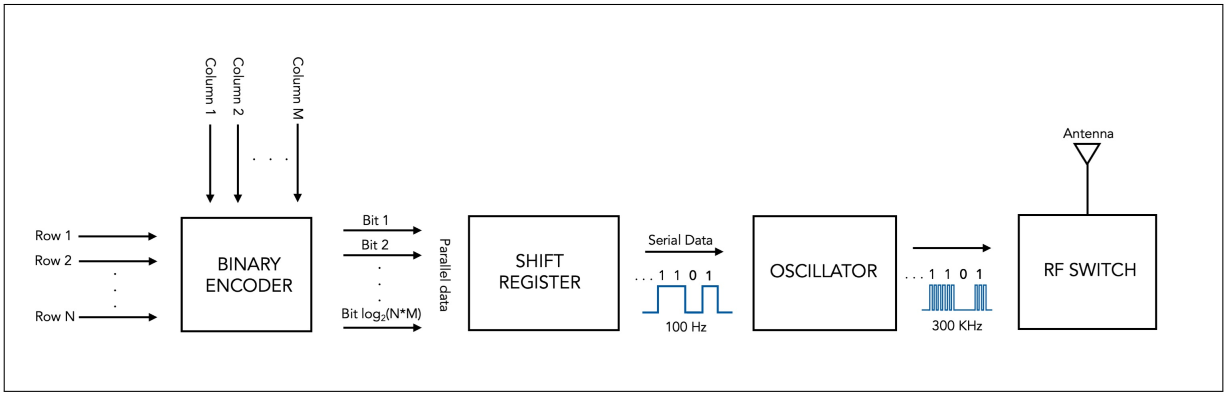


Fig. 7. System Overview

being used, the electronics components for data encoding and transmission are switched off. Human touch is then used as a trigger to turn the complete system back on.

4 SYSTEM IMPLEMENTATION

4.1 Hardware

The raw input to the touchpad hardware is the four rows and four columns which develop a positive voltage when touched by the user. This developed voltage differs across users and based on our test analysis when the positive electrode is at 4 V; this voltage is above 200 mV for all users.

Because the rows/columns are inputs to a priority encoder which operates at voltage levels consistent with digital logic, we use voltage comparators [14] to convert the changing analogue input into a sharply defined binary output. We analyze the voltage on the rows/columns for touch or no touch scenario by comparing it to a reference voltage of 150mV. This reference voltage value also helps to filter out false positives which may occur because of the voltage induced in the rows/columns due to ambient AC line noise or other RF disturbances.

The four rows and columns are each connected to the inputs of a 2-bit priority binary encoder defined by the following Boolean equations and represented in Table 1.

$$O_1 = I_1 + I_2 \tag{1}$$

$$O_0 = \neg(I_2 + \neg I_1) + I_3 \tag{2}$$

Table 1. Truth table for 2-bit priority binary encoder (X = Don't care)

Input 3 I_3	Input 2 I_2	Input 1 I_1	Input 0 I_0	Output 1 O_1	Output 0 O_0	Valid V
0	0	0	0	X	X	0
0	0	0	1	0	0	1
0	0	1	X	0	1	1
0	1	X	X	1	0	1
1	X	X	X	1	1	1

The boolean OR operations are implemented by combining the OR inputs through diodes (1N14148) to a common cathode as output, and the boolean AND operation was performed using the voltage comparator [14] in an inverting configuration. The two priority encoders output 2 bits each, representing the row and column touched by the user. To serialize these four bits for wireless transmission, we use a parallel-load serial-out shift register [27]. We daisy chain two 8-bit shift registers where the first 7 bits have a hardcoded header (1010111) and the next 8 bits are the 4-bit encoder output repeated twice. The shift register serially outputs one bit per clock cycle and is fed by an external clock provided by a CSS555 timer running at 100 Hz [39]. The inputs of the shift registers are loaded about five times per seconds as determined by another CSS555 timer, which sets the refresh rate of the touchpad as 5 Hz.

The serial output of the shift register is the input to the backscatter communication part of the circuitry. The backscatter portion consists of a square wave oscillator (TS3002) and an RF switch [5]. The RF IC is used to switch the impedance of a dipole antenna used in our system in two difference impedance states. The RF switch is fed by the output of the oscillator. Hence, the output frequency of the oscillator determines the switching frequency of the RF switch; in other words, the frequency f_{back} for our backscatter communication. The oscillator runs at 300kHz so f_{back} is 300kHz.

The oscillator output is controlled by the serial output of the shift register and is enabled for a binary one or disabled for a binary zero. The rate at which the shift registers outputs bits defines the rate at which the bits are transmitted, hence the shift register clock sets the transmission rate, and for our system, it is 100 bits per second.

All of the circuitry is powered by a photovoltaic cell (Panasonic - BSG AM-5412CAR) of dimensions 50mm x 33mm and the harvested energy is managed by Texas Instrument's BQ25570 chip.

4.2 Software

We built a real-time software pipeline to decode the data received from the touchpad hardware by the FM receiver. In our setup, we use a Motorola One smartphone with a built-in FM receiver chip as our receiver and use the default FM radio app on the phone to tune to the transmit frequency $f_c + f_{back}$. The phone outputs the received signal as audio data which we stream over Bluetooth to a Macbook Pro laptop for processing. Processing data on the laptop is done for ease of debugging, but this processing can also be done locally on the phone itself.

The raw audio received from the phone is stored in a buffer and processed using a sliding window approach in a Python program. Each sliding window is of length 7 bit and slides with a 50% overlap. For every window, the data is first passed through a Random Forest machine learning classifier to detect any active transmission from the touchpad. The classifier is trained using audio data recorded on the phone when there was an active transmission of random bits and while there is no transmission. The signal recorded during active transmission has a distinct frequency response compared to static noise recorded during no transmission. Therefore, we use features in the frequency domain (spectral spread and spectral centroid) while training the classifier. The trained classifier demonstrated 99.7% 5-fold cross-validation accuracy.

On detecting an active transmission in a sliding window, the window is searched for the start of the packet. This is done by passing the window through a bandpass filter to have frequencies between 15000-18000 Hz and then cross-correlating the known pattern of the header (1010111) with the sliding window. The position of the max value in this cross-correlation result indicates the start of the packet. After knowing the beginning of the packet, the location of all the bits can be calculated using the known length of each bit.

The next step in this process is to decode the payload. To do this, the individual energies of all the bits in the payload are calculated. For a single bit, energy is calculated by summing the magnitude of all the values representing that bit in the raw signal. Then the bit energies are compared to the bit energy of the known ones and zeros in the header to identify them. The decoded packet is then checked for bit errors by comparing the redundant bits in the packet. Finally, a packet without any bit error is accepted.

5 EVALUATION

5.1 Overview

Our evaluation measures the overall system performance and assesses the factors which affect performance. We quantify system performance in terms of three metrics:

(1) ***Accuracy*** of touch detection as the percentage of time a touch interaction occurred and was correctly registered by the system.
(2) ***Response time*** as the time between a touch interaction at the touchpad and the system correctly registering it the first time.
(3) ***Power*** consumed by the UbiquiTouch hardware.

During this evaluation, we also collect metrics on factors affecting the system performance.

5.2 Factors Affecting System Performance

The overall touch detection chain consists of three parts—touch detection by the touchpad hardware, transmission of that information over the wireless link, and decoding it at the receiver/phone. Each of these can affect overall system performance.

1) Touchpad hardware: The power consumed by the sensing circuitry can differ across users as the sensing works by passing a small current through the skin of the user, and the skin resistance can vary across users which affect the current.

2) Communication channel: Our system communicates by backscattering ambient FM radio waves, which is a weak communication link due to the low signal strength of the backscattered signal. It is also affected by the varying signal strength of the ambient FM signal at different locations and hence can introduce inaccuracies in the system.

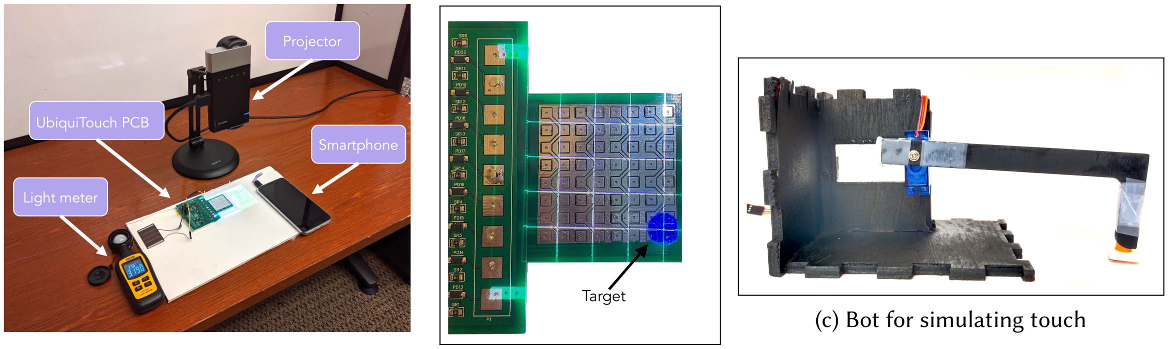
3) Receiver: The receiver relies on a machine learning classifier to detect an active transmission and a decoding algorithm to locate and decipher the packet. The individual performance of these can affect the overall performance.

5.3 Evaluation Procedure

To evaluate the system in common real-world situations, we evaluated the system in two scenarios—when the user is holding the phone (receiver) in their hand and while the phone is in the user's pocket. We replicate these two scenarios in both outdoor and indoor settings. The outdoor sessions were conducted on a patio during daylight hours with the light intensity ranging from 200 lux to 5000 lux. The indoor sessions were held in a fluorescent lighting office environment with a light intensity of about 300 lux. In all sessions, the touchpad was kept in front of the user on a horizontal flat surface while the user was interacting.

The user's initial task was to touchpoints on the touchpad, visually indicated to the user, one by one for a total of 16 points in every setting. The point to be touched was generated randomly from a uniform distribution and was projected by a portable projector onto the touchpad. The projector was operated by a laptop computer, and the projected target was a circle of radius 5 mm (Figure 8(b)). The 16 targets were each displayed one by one for 3 seconds, followed by a 2-second break in between. The projection was also accompanied by an audio cue played on the laptop that informed the user to start and stop touching the target. The user study setup is shown in Figure 8(a)

During the interactions, the phone logged the detected locations, processing times and other events for post-analysis on the performance of transmission (Packet Error Rate(PER)) and receiver software (Processing time). We also recorded raw audio from the interactions as received by phone.



(a) User Study Setup

(b) Projection on UbiquiTouch

(c) Bot for simulating touch

Fig. 8. User Study Setup

For measuring response time precisely, we built a bot shown in figure 8(c) to simulate human touch on the touchpad. The bot helped avoid the non-constant reaction time of the user in performing a touch action. We use a slow-motion camera to find the latency of the bot and included it in our calculations. Although the bot did the touch, we asked the users to hold the phone in their hands while the bot was touching. This enabled the human body's effect on RF fields to be maintained while receiving a transmission on the phone as in our other experiments. In both indoor and outdoor settings, we ran the bot for 16 points per user.

Finally, to measure the current consumption for sensing for each user, we asked them to touch every point on the touchpad one by one and recorded the average current. Other user-independent current consumption such as for encoding, communication, etc. was recorded independently.

6 EVALUATION RESULTS

6.1 Accuracy

The average accuracy achieved by the system is over 95% across all scenarios. Table 2 shows the highest, lowest and average accuracies in different situations. Figure 9 indicates the individual accuracies for all participants.

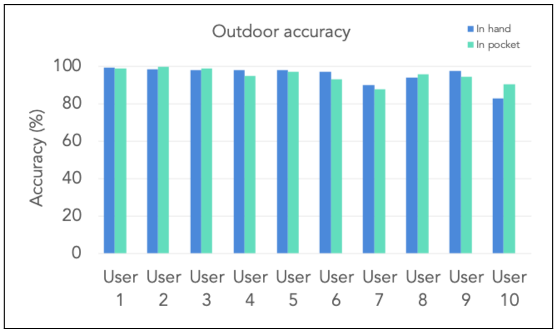
Table 2. System accuracy (in percentage)

		Max accuracy	**Min accuracy**	**Average accuracy**
In hand	Indoor	99.31	93.81	97.43
	Outdoor	99.34	82.75	95.36
In pocket	Indoor	99.63	91.67	96.98
	Outdoor	99.61	87.86	95.04

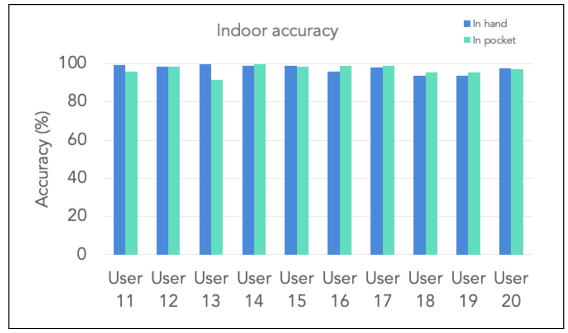
On average, for both indoor and outdoor situations, the accuracy when the phone was in hand was slightly higher than when the phone was in the pocket. The potential explanation for this observation is the possible dampening of the backscattered signals while propagating through the user's clothes, which reduces the signal quality of the received signal on the phone.

Despite the high accuracy of the system, even a few errors can lead to unexpected output in end-user applications. To mitigate this, one strategy is to utilize the packets re-transmissions done by the UbiquiTouch system.

From our analysis of the user study data, two successive receptions of the same location ensure that the location is touched. Checking for this pattern at the receiver can enable UbiquiTouch system to support accurate touch interactions.



(a) Outdoor System Accuracy



(b) Indoor System Accuracy

Fig. 9. User Study Results

6.2 Response Time

The average response time of the system over 20 users is 773.6 ms. The response time of the system can be broadly broken down into multiple sub-parts. Starting at the hardware level, since the refresh rate of the touchpad is 5 Hz there can be a 0-200 ms latency in detecting touch. A subsequent transmission of the sensed location, 15 bits at 100 bits per second, takes 150 ms to send the location. This might take more time if the packet received is incorrect or identifiable. User study data analysis shows that it takes up to a maximum of two packets to correctly detect a position. This, therefore, sets the maximum transmission time to 300 ms. On the receiving end of the phone, as we forward the raw data to a laptop, it adds a Bluetooth transmission latency of about 300 ms. Finally, the laptop processes one packet in about 99.8 ms. Table 3 lists breakdown of response time and 10 shows the average system response time per user.

The response time of the system is higher than the standard touch interfaces used in daily life. This higher than usual response time is a result of a tradeoff between speed and energy consumption of the hardware. The speed is sacrificed for low energy consumption to open up new possibilities of interaction. The slower response time can be masked by making the touch interactions longer. For example, a single touch to a point can be changed to stretching the point as a line and replacing the single touch with a swipe on the line, thus increasing the time of interaction. In the following application section, we provide design examples based on a similar approach for building applications using UbiquiTouch that can account for the higher response time while providing good user experience.

6.3 Communication Quality

To measure how wireless communication affects the system performance, we recorded the number of received packets for each user, for both outdoor and indoor, for both the in hand and in pocket scenarios. Table 4 shows the Packet Error Rate (PER) in different scenarios and Fig. 11 shows the distribution of received packets for each user.

From table 4, it can be seen that the PER is higher outdoors compared to the indoor environment, which means more incorrect packets are received in the outdoors. Another finding is that while holding the phone in hand, it

Table 3. Breakdown of response time.

System task	Time taken (ms)
Detection of touch	0-200
Transmission of touch location	150-300
Transmission of audio data from phone to laptop	300
Processing of a data packet	99.8
Average response time observed in user study = 773.6	

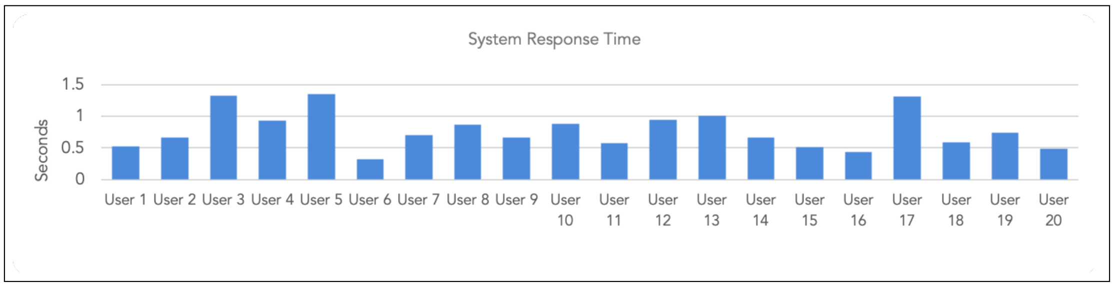


Fig. 10. System Response Time.

Table 4. Packet Error Ratio (PER) in different scenarios.

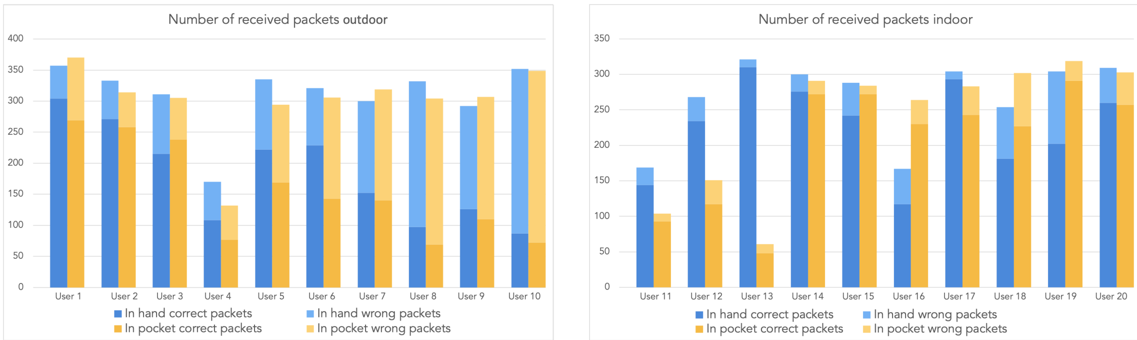
		Packet Error Rate (PER)
In hand	Indoor	15.67
	Outdoor	41.61
In pocket	Indoor	12.76
	Outdoor	48.50

usually receives more packets than when the phone is in the pocket, irrespective of whether outdoors or indoors, as the backscattered signal is attenuated when propagating through clothing.

The communication quality was also observed to vary according to environmental conditions. From fig. 11 (a) it can be seen that the number of correct packets for user7 to user10 (average number is 116 for in hand and 98 for in pocket) is much lower than the number of correct packets for User 1 to User 6 (average number is 225 for in hand and 192 for in pocket). This is because that we conducted an outdoor user study of User 1 to User 6 on one day, and conducted a study of User 7 to User 10 on another day. For the same reason, Fig. 11 (b) demonstrates that the number of correct packets received for User 11 to User 13 is lower than the number of correct packets received for User 14 to User 20. Although the communication quality differed on different days, from Figure 9 it can be seen the accuracy of the system remained consistent.

6.4 Power

We measured the power consumption of the different parts of our circuit while the system was being actively used. Table 5 lists the average power measurements. From these measurements, it can be seen that most of the power is consumed by the communication module. Specifically, the oscillator used to shift the frequency of the backscattered signal consumes the most power. The power consumption for touch sensing is slightly different



(a) Outdoor (b) Indoor

Fig. 11. Number of Packets received.

for different users because of the variance in skin resistance across users. Figure 12 shows the user-dependent sensing power consumption for each participant.

Table 5. Power consumption by different circuit components

Circuit component	**Average power consumed in active mode (μW)**
Encoding	5.4
Sensing - user independent	3
Sensing - user dependent	5.76
Communication	12.75
Power Management	4
	Total = 30.91μW

We tested the system under different light conditions to see the minimum amount of light required for our system to work in realtime. We found that the system required a minimum of 200 Lux of light to work reliably with the current photocell. With this lighting requirement, according to the IES Lighting Handbook [38], our system would work reliably in indoor environments like homes, offices, restrooms, libraries and also outside in daylight.

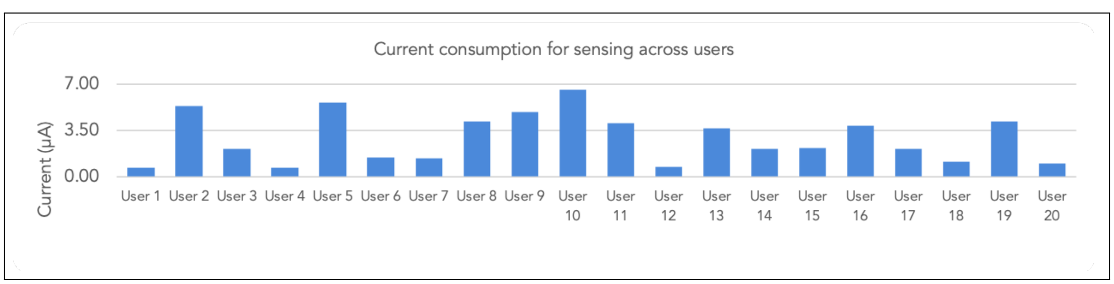


Fig. 12. Touch sensing current consumption for each participant.

7 EXAMPLE APPLICATIONS

We envision UbiquiTouch to be used in everyday life, adding self-sustainable interactivity to everyday surfaces. The following applications concepts highlight how UbiquiTouch can be used in the future.

7.1 Input on Clothing

Input on clothing provides a medium to interact with wearable devices such as AR/VR headsets. Current solutions, such as Google's Jacquard [9], provide such interaction capabilities but come with the logistical challenge of maintaining batteries in the clothing to support the functionality. This creates the inconvenience of charging batteries and carrying the battery's extra weight and volume. To solve this problem, a touch interface can be built into clothing using UbiquiTouch, as shown in 13. UbiquiTouch provides a touch interface without the need for a battery and no need for external operating infrastructure allowing it to function in the clothing-related mobile scenarios.

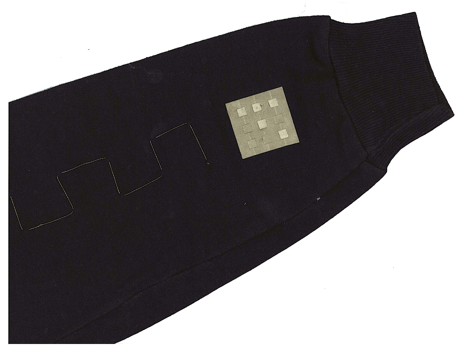


Fig. 13. UbiquiTouch touch interface on clothing

The touchpad in 13 is made using conductive fabric sewed into the sleeve of a jacket and a conductive thread stitched in the arm as an antenna. The PCB and solar cell could be packaged and put on the clothing in a small waterproof package in the future. This interface could be used for micro-interactions such as swipes (Up, Down, Left, Right) for navigation and long press for selection with AR/VR headsets or other wearables like Bluetooth headsets.

7.2 Touch Input on Paper

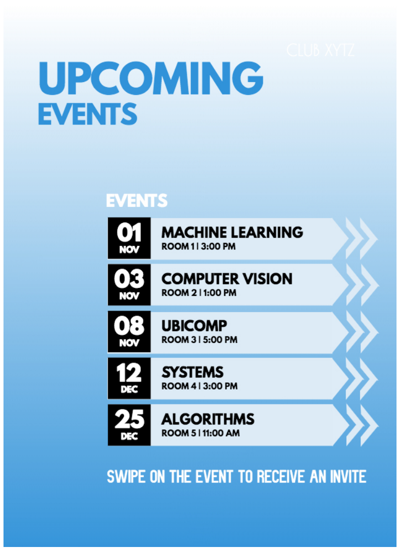
Touch input on paper opens up new possibilities for interaction. We demonstrate a few scenarios where adding interactivity to everyday paper material enhances the user experience.

- Posters communicate visually and provide quick access to information. Posters sometimes include a QR code to get related information, but it is often up to the user to find it. Here, we present a scenario in which users are presented with digital information by interacting with a physical poster.

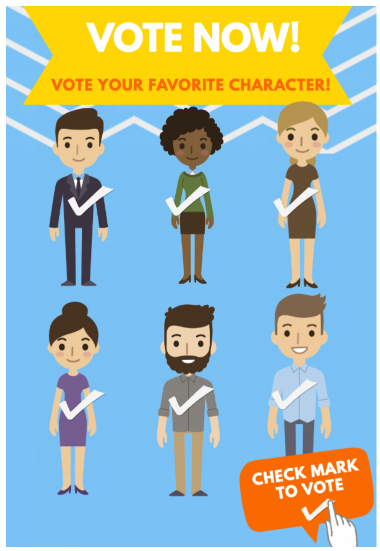
  Scenario Figure 14(a), a display of multiple events happening in the university over the week attracts a student's attention. The student, while going through the list of events, finds an event of interest and would like to be notified about it. To do this, the student swipes the event on the poster, which sends a calendar invitation for the event to the student's phone.

- Posters may also be used to receive information from users using UbiquiTouch, in addition to providing information.

  Scenario 1 A user walking on a street notices an advertisement poster Figure 14(b) about a TV show of interest, asking the users to vote for their favourite characters on the show. The user swipes directly onto a character in the form of a checkmark to vote for the role. The poster communicates the voting information to the TV show servers via the user's phone.



(a) Events poster for receiving event information on user's phone



(b) Poster to gather user votes

(c) Poster for collecting user feedback

Fig. 14. Application examples of UbiquiTouch on paper

  Scenario 2 People on the way out of the clothing section in a mall are presented with a poster 14(c) asking them about their shopping experience. By swiping on the appropriate emoji on the poster, the users can register their feedback. Similar posters can be used to gather other types of feedback, such as on cleanliness in public toilets, quality of food in restaurants, etc., which can help improve the quality of public services.

These paper-based interfaces can be put up both indoor/outdoor or at public/private spaces without requiring any additional technical infrastructure or maintenance. Previous work like [44] used FM backscatter to make posters broadcast information. UbiquiTouch adds onto that functionality by adding real-time input on the posters such that users can selectively receive or provide information.

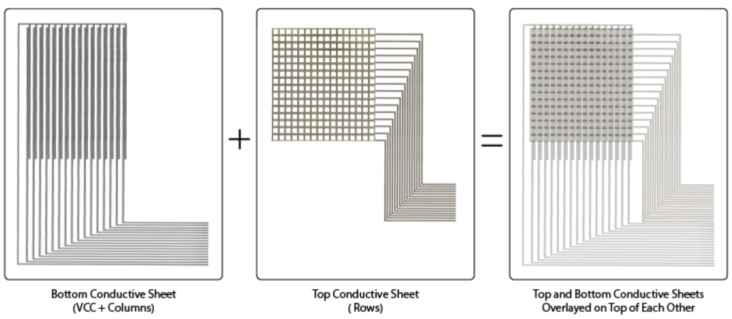
In all the application examples, the interactions were designed as swipes or long-presses which makes them longer to perform. Also, the interaction area for swipe was just one touchpoint in an elongated shape. For example, Figure 14(b) the point was in the shape of a tickmark, in Figure 14(c) the point was presented as an emoji, etc. These design decisions support the interactions to be longer which helps mask the system latency. The longer interaction time also means that the user is in contact with a single touchpoint longer, enabling the system to perform multiple retransmissions per point which add robustness to the communication through redundancy.

8 DISCUSSION

8.1 Different Touchpad Design and Fabrication Techniques

The layout of rows and columns presented in Figure 15 is one of the several possible designs of the touchpad. The touchpad can be laid out in other patterns or shapes to suit different applications. Also, the touchpad can be fabricated in different materials with different form factors. To illustrate different fabrication aspects, we present two touchpad prototypes build with different fabrication techniques and materials.

(1) First, we present a paper-based interface with the rows and columns printed on with conductive inkjet printing. Figure 15 shows this prototype. To create insulation between rows and columns, we print them on separate sheets of paper and laser-cut holes on the top sheet to expose the conductive lines on the bottom sheet.



(a) Fabrication steps in inkjet printed touch interface

(b) Flexible form

Fig. 15. Inkjet printed 2 layer design for UbiquiTouch touchpad

(2) The next prototype is developed with a more DIY approach requiring only basic equipment and materials. This interface is made on a regular sheet of paper with rows/columns created on with copper tape. Insulation is conceived between the rows and columns by separating them with scotch tape. Additionally, as an optional step, the contacts between different pieces of copper tape were reinforced by soldering them together. This prototype is shown in Figure 16.

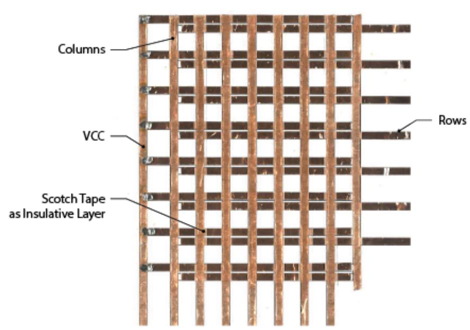


Fig. 16. Touchpad using copper tape and non-conductive Scotch tape

Throughout the usage of these two interfaces, the copper tape-based design was found to be more stable with frequent bending and unbending. While the printed touchpad initially worked fine, but with repeatedly touching by the finger, the ink began to come off. So the printed touchpad looks more suitable for limited-time applications.

8.2 Scaling the Touchpad

The touchpad can be scaled in terms of touch resolution, surface area or both. The main parameters which affect the touchpad are the number of touchpoints and the size of each touchpoint. The size of a touchpoint is independent of the UbiquiTouch circuitry and is application-driven, and the encoders define the number of touchpoints, the system can support. For an R-bit row encoder with a C-bit column encoder, the max number of points the system can support is $2^{(R+C)}$. In this section, to shed light on scalability, we contrast between different parameters such as the number of touchpoints, touch resolution, etc. when the size of the touchpoints and the number of bits in the encoders vary. The relationship is presented in the table 6.

Table 6. Relationship while scaling touchpad

	Number of touchpoints	**Touchpad resolution**	**Surface area of touchpad**	**Response time**
Number of encoder bits increase while size of touchpoint remains same	Increases exponentially	Remains constant as the resolution is define by the size of touch points	Increases exponentially as number of touch points increase exponentially	Increases linearly due to the increased transmission time of extra bits.
Size of touchpoints increase while number of touchpoints remain same	Remains same	Decreases	Increases	Remains same as the time of transmission remains constant

8.3 Multi Touchpad Environment

Some scenarios may require the deployment of multiple touchpads in the same location. If more than one touchpad transmits at the same frequency, it can cause interference in communication between touchpads. To avoid this interference, the transmission frequency $f_c + f_{back}$ must be selected to be unique for each touchpad, allowing multiple touchpads to co-exist.

8.4 UbiquiTouch as a Communication Platform

In this paper, we sense touch input, package it in a binary format and transmit it to a nearby receiver. Nevertheless, digital information can also be fed into the system from other sensors and used as a low-power communication platform. UbiquiTouch can thus be used as a ubiquitous and infrastructure-less communication platform.

9 FUTURE WORK

9.1 Decoding Packets on the Phone

Currently, the audio data from the phone is streamed to a laptop computer over Bluetooth for processing. This processing can be done by the phone itself, which will make the system more mobile and reduce the response time by avoiding Bluetooth transmission latency. One of the challenges in achieving this, on Android OS, is that the Android OS does not give third-party applications access to live FM audio streams. A possible solution might be to root the phone to gain system-level permissions and then access the FM radio stream. Another problem may be that the lower computing power on the phone compared to a laptop computer may mean slower data processing speed. Still, the time saved in avoiding Bluetooth latency may compensate for it.

Running processing on the phone also means doing computation on a battery constraint environment which would require more efficient implementation of algorithms and platform-based optimizations to save power.

9.2 Alternate Modulation Schemes

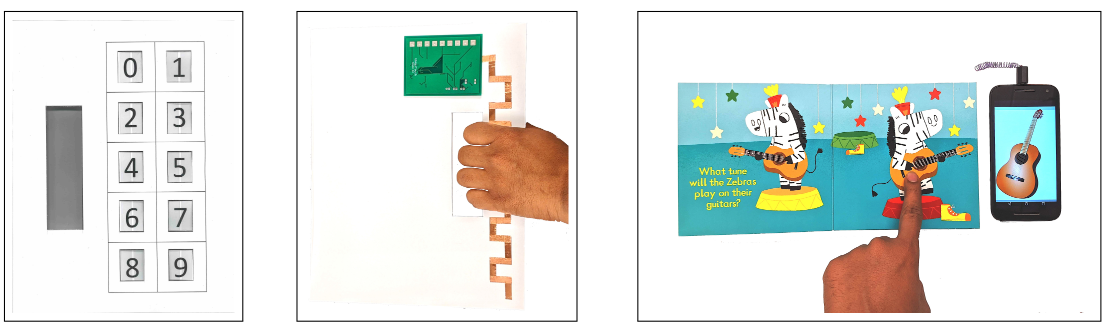
Different modulation schemes can be used to achieve higher bit rates in data transmission to reduce transmission time. With the current binary modulation scheme, the system can represent one bit per symbol - either 1 or 0. However, using schemes such as Quadrature amplitude modulation (QAM) or 4 Frequency shift keying (4-FSK), it is possible to represent two bits per symbol, doubling the transmission rate.

9.3 Antenna Size

Antenna size for the FM Range is on the order of feet, which limits the UbiquiTouch touch interfaces to larger objects and surfaces to accommodate for the long antenna. There are two possible approaches to solve this problem -

(1) We can exploit the fact that the human body can partially act as an FM antenna [15]. Thus if we electrically couple our system with the user's body, it can help with the RF transmissions which would mean requiring a smaller FM antenna. Based on this idea, we propose a design for an interactive keypad using UbiquiTouch. The keypad presented in Figure 17 (a) and (b) contains numbers 0-9 which, when touched, can communicate this information to an FM enable smartphone nearby. The handle on the keypad in Figure 17(b) is designed as an affordance to help couple the user's body with the system while providing a way to hold the keypad.

(2) For FM backscatter, a smaller antenna would mean less effective transmission, which would effectively decrease the range for wireless communication. But in cases where long-range is not required, such as when the phone(FM receiver) is placed next to the UbiquiTouch interfaces, a small antenna can also provide functionality. An initial exploration into this suggests that UbiquiTouch system can work with a monopole antenna as small as a 7cm when the phone is kept in close contact with it. Based on this aspect, we present an interactive storybook concept, as shown in Figure 17(c). Touching on an image in the storybook can present the associated content with it on the phone. In this example, touching on the guitar can play a guitar melody on the phone.



(a) Keypad front (b) Keypad back (c) Interactive storybook

Fig. 17. Future applications for UbiquiTouch

10 CONCLUSION

UbiquiTouch is a touch interface which can sense and wirelessly transmit touch events in a very low power budget. With an average power consumption of 30.91μW, UbiquiTouch can harvest the energy required for realtime operation from ambient light even in indoor lighting conditions. We did a feasibility study to evaluate the UbiquiTouch system with multiple users in indoor and outdoor settings with more than 95% accuracy for touch detection in both scenarios. We later explored the potential applications for this technology - input on clothing or touch input on paper. UbiquiTouch promises to open new interaction opportunities for everyday objects, allowing computation to be truly woven in the fabric of everyday life[46].

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