PACT: Scalable, Long-Range Communication for Monitoring and Tracking Systems Using Battery-less Tags

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The food and drug industry is facing the need to monitor the quality and safety of their products. This has made them turn to low-cost solutions that can enable smart sensing and tracking without adding much overhead. One such popular low-power solution is backscatter-based sensing and communication system. While it offers the promise of battery-less tags, it does so at the cost of a reduced communication range. In this work, we propose *PACT* - a scalable communication system that leverages the knowledge asymmetry in the network to improve the communication range of the tags. Borrowing from the backscatter principles, we design custom PACT Tags that are battery-less but use an active radio to extend the communication range beyond standard passive tags. They operate using the energy harvested from the PACT Source. A wide-band Reader is used to receive multiple Tag responses concurrently and upload them to a cloud server, enabling real-time monitoring and tracking at a longer range. We identify and address the challenges in the practical design of battery-less PACT Tags using an active radio and prototype them using off-the-shelf components. We show experimentally that our Tag consumes only 23μJ energy, which is harvested from an excitation Source that is up to 24 meters away from the Tag. We show that in outdoor deployments, the responses from an estimated 520 Tags can be received by a Reader concurrently while being 400 meters away from the Tags.

180

CCS Concepts: • **Hardware → Communication hardware, interfaces and storage**; • **Computer systems organization → Embedded and cyber-physical systems**.

Additional Key Words and Phrases: battery-less, passive tag, RF harvesting, backscatter

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1 INTRODUCTION

Data-driven optimization is slowly revolutionizing various industries. This, however, calls for pervasive sensing to generate the necessary data, which has so far been led by the evolving technologies in IoT. For example, humidity and temperature control in food and dairy industry is a crucial topic of academic and commercial significance due to the industry's direct impact on economy and the health and safety of consumers [1, 2]. Roughly one third

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of current global fresh produce is thrown away; a bulk of it is due to non-optimized post harvest handling and storage losses that are estimated between 0.5% - 10%[3, 4]. The perishable goods transportation market, which is expected to register a growth of $6.43 billion in the next 5 years[5], is a critical point for such smart monitoring to reduce food loss. Over the years, the Food and Drug Administration (FDA) has implemented strict regulations on humidity and temperature (quality) control in the food supply chain to prevent the spread of food-borne illnesses. However, the actual implementation of such sensing and traceability is a work in progress as technology evolves to meet strict cost requirements. The FDA's follow-up initiative on "Smarter Food Safety" explores low-cost technologies to quickly trace a food product throughout the system to prevent large-scale spread of food-borne illnesses and retain nutrition of food products [6, 7]. This ability to track and discard "bad apples" quickly also has a significant impact on the economy [1, 7, 8]. Keeping the sensing cost low at large scale is crucial in the food industry due to the already low profit margins. A number of startups and commercial stakeholders that utilize cloud-based IoT platforms [9–14] have emerged to deliver smarter food safety. most of the monitoring is still manual, prone to error, and does not scale. Simple, low-cost sensing and tracking in real-time with data storage from a large-scale of food products remains an open challenge [15].

The key requirements for practical implementations of such large-scale, low-cost monitoring systems are,

- Low-power and low-complexity network: In the case of a large number of low-power sensors deployed for data-driven applications, there is a need to keep the technology environmentally sustainable.
- Long-range and scalable communication: Specifically in the agriculture and food industry, the communication range of sensing can be over hundreds of meters, such as across warehouse/fields. Being able to easily communicate with multiple sensors in real time is crucial for process and cost optimization.
- Low-cost and long battery life at scale: With the low profit margins of the global food industry, keeping the monitoring and maintenance costs low with long battery life helps easy adoption of the technology.

While Bluetooth-Low-Energy (BLE) is popular among commercial solutions [9–14], backscatter communication is an emerging alternative technology to address the low-power and low-cost needs of monitoring applications [16–24]. However, since information is conveyed by scattering back existing signals, the communication range of traditional backscatter systems is constrained, limiting practical deployments [19–21, 25]. We identify three key reasons for the **short range** of a passive backscatter system: (1) RF **Energy harvesting range** to power the tag, (2) **Reader sensitivity** in receiving the backscattered signal in the presence of self-interference from the excitation signal, (3) **Dual path loss** faced by the backscattered signal. While research on energy-harvesting [26, 27] and alternate architectures [28–31] have addressed (1) and (2), dual path-loss is an inherent characteristic of backscatter due to the distance traversed by the backscattered signal [32]. The limited range due to dual path loss in turn demands the use of more readers to communicate over larger areas, which affects scalability. Hence, backscatter-based systems do not meet all the needs of large-scale, low-cost monitoring systems.

In this work, we propose PACT (Passive communication with ACTive radio), a scalable communication system that improves the energy efficiency and communication range of battery-less Tags by leveraging the knowledge asymmetry in monitoring and tracking systems. Consider a smart temperature monitoring system in a food storage unit, where each product is sensitive to a certain range of temperature. A food safety concern arises when the temperature is outside its sensitive range [33, 34]; which is typically known apriori [35, 36]. PACT leverages this prior knowledge and designs the Source to send a specific Query, which has the dual purpose of powering the Tag as well as querying the Tag. As illustrated in Figure 1, our proposed system consists of a Source ①, a Tag ③, and a Reader ⑤. A PACT Source is an RF excitation source that broadcasts a Query ② using an active radio transmission. The Source Query is designed to power the battery-less Tag, which harvests energy from the Query itself. It also includes specific questions to the Tag e.g., "*Is the temperature below 30 F?*". A PACT Tag compares the sensor data with this Question and responds with a *yes* or a *no* using an active radio ④. A PACT Reader listens to the Tag response, and uploads it to a cloud server. **A PACT Tag, thus, improves**

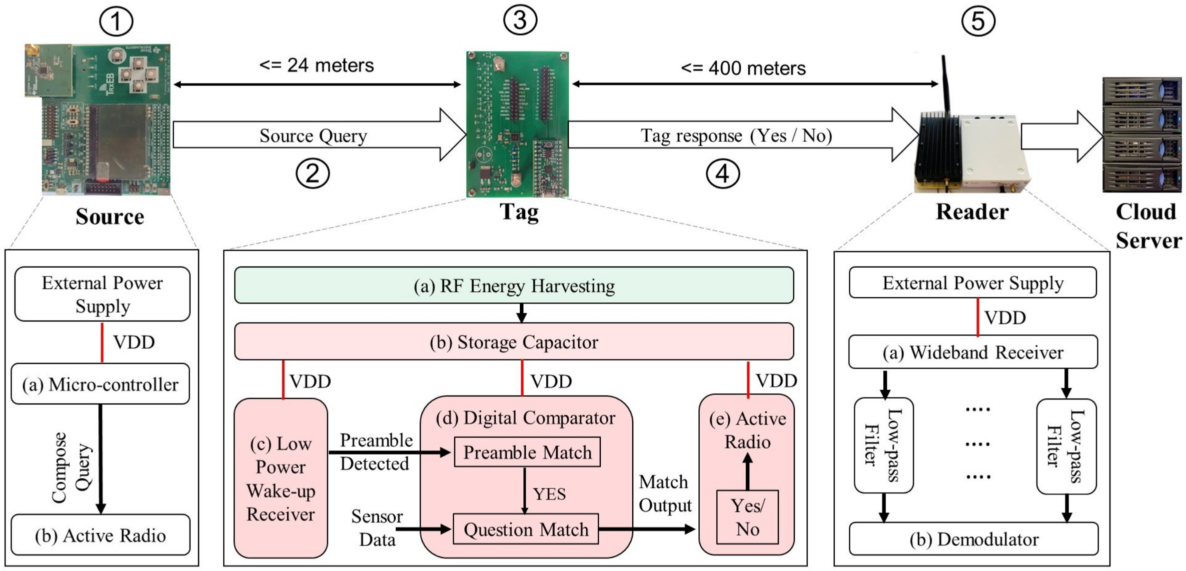

Fig. 1. PACT framework. ① Source, a transmit-only active radio ①b, broadcasts the Query at 14dBm to the Tag. ② Source Query supplies power to the Tag and asks a specific Question for the Tag to compare. The harvesting range of PACT determines the maximum distance between the Source and the Tag. ③(a) RF harvesting unit on the Tag stores energy on the ③(b) 6.8μF storage capacitor and supplies power to the ③(c) low power wake up receiver, ③(d) FPGA, and ③(e) the AX5043 active radio on the Tag. The wake up receiver detects the Preamble and Question which are compared digitally on the FPGA and the output of the Question match triggers the active radio. ④ Tag response from the active radio transmitted at 0dBm is FSK modulated with 15kHz BW at 1.2kbps baud rate and a 2dBi whip antenna. (5) Reader with a sensitivity of -95dBm to support 400m communication range receives Source Query and the Tag response. It uses a 25 dB gain power amplifier. The wideband USRP receiver ⑤(a), using digital filters, receives Tag response from multiple channels ⑤(b) and relays it to cloud.

the communication range by transmitting a short yes/no response using an active radio, while still operating only on energy harvested from the Source query, rendering the Tag battery-less.

Although the yes/no responses are short and consume lesser energy than sending the actual sensor data, the active radio is energy consuming. In order to power this active radio, we design an energy harvesting circuit to maximize the harvesting range and efficiency. Additionally, the Q&A format of PACT provides the desired flexibility for monitoring and tracking systems to ask different questions (frame different queries) for different products and environments. Finally, offloading the data encoding to the Source through queries simplifies the Medium Access Control (MAC), one of the major challenges in practical deployments of RFID [37, 38]. PACT network is divided into Tag groups, where the Source queries all the Tags in a Group using their Preamble. Each Tag concurrently responds in a unique channel (up to 520 channels with 15kHz BW) in the 902-928 MHz band, leveraging Frequency Division Multiple Access (FDMA). As the network grows, new groups with distinct Preambles are created and queried sequentially. By leveraging Time Division and Frequency Division Multiple Access, PACT allows hundreds of Tags to co-exist and the network to scale without affecting latency or energy efficiency. **We perform real-time evaluations to show that a PACT Reader can communicate with an estimated 520 battery-less Tags in a single group placed at distances of up to 0.4 kilometer concurrently.**

In summary, we leverage the knowledge asymmetry in monitoring and tracking systems to query Tags that respond with a yes or no, towards realizing a scalable, low-cost, and long-range communication network of battery-less Tags. Specifically our contributions are the following:

- We propose a scalable, ultra-low-power communication paradigm that uses prior knowledge at the excitation Source to Query a battery-less Tag that harvests RF energy from this query. Our proposed Tag consumes energy as low as $23\mu J$ for its operation. This includes the energy consumption of an active radio on the Tag that improves the communication range of the passive Tag to nearly 400 meters.PACT combines the strengths of active radio communication and passive tags operating on harvested energy.
- We design a custom energy harvesting front end to enable battery-less operation of a PACT Tag. We design an ultra low power envelope detector and a digital comparator to demodulate and decode the Query from the Source. We implement and experimentally verify the RF energy-harvesting circuit that powers the PACT Tag.
- We propose and implement a hybrid Time-Frequency division MAC to allow the co-existence of large scale of Tags avoiding collisions and reducing network latency compared to state-of-the-art. We show that a group of 520 Tags can communicate with one Reader concurrently, increasing the network throughput.
- We prototype a PACT Source, Tag, and Reader using commercial off-the-shelf (COTS) components on a PCB and experimentally demonstrate an RF energy-harvesting range of 24 meters to operate a Tag that consumes $23\mu J$ energy, and achieves a communication range of over 400 meters.

The rest of the paper is organized as follows: section 2 presents an overview of PACT system design. In section 3, we present in detail the Source Query design, Tag Design, Tag Response, and expected throughput of PACT. In section 4, we propose a hybrid MAC protocol that allows PACT to scale and Tags to coexist in a network, followed by section 5 where we describe our implementation, hardware, and settings used. section 6 evaluates the range, energy, latency, and coexistence performance of PACT. We identify use cases of PACT in section 7, related works in section 8, limitations and future work in section 9 and conclude in section 10.

2 AN OVERVIEW OF PACT SYSTEM DESIGN

The goal of this work is to develop a communication paradigm that can address the low-cost, long-range, and large-scale needs of real-time monitoring systems. Building on top of low-power backscatter communication principles, we design and prototype PACT, a communication system that leverages knowledge asymmetry to improve the range of a large-scale network of battery-less Tags. PACT is particularly useful in applications where it is critical to understand the range of data and not its absolute value.

As illustrated in Figure 1, our proposed system consists of a Source, a Tag, and a Reader. The Source is a transmit-only active radio, that broadcasts an Amplitude Shift Keying (ASK) Power-up sequence (train of bit 1s) followed by an ASK modulated Query. The Tag harvests energy from the power-up sequence. On harvesting sufficient energy from this sequence, the Tag wakes up, listens, and demodulates the Query from the Source using an envelope detector. It then compares its sensor data with the received Query and responds with a *"yes"* if there is a match, and a *"no"* otherwise. The Reader is a simple receiver that listens to both the Query from the Source and the Tag response. The Tag response is transmitted using an active radio and faces only one-way path loss from the Tag to the Reader; the active radio avoids the dual-path loss and thus overcomes the range limitation of backscatter. The communication range of a PACT Tag, therefore, depends only on the distance between the Tag and the Reader and the Tag's modulation characteristics. The improved communication range of PACT allows us to deploy a single Reader to communicate with hundreds of Tags concurrently. We design a 3-node architecture with a decoupled Source and a Reader to simplify the infrastructure and reduce costs. Source being a transmit-only radio that broadcasts ASK modulated queries, can be battery-powered and low-cost as it goes to low-power sleep mode between queries. The Reader on the other hand, requires a continuous power supply as it is always on and listens for Source queries and Tag responses. Additionally, the Reader is computationally more complex than the Source as it receives from multiple channels to process Tags concurrently, making it more expensive than the Source. Therefore, by separating the Source and the Reader and improving the Tag-Reader communication distance, we reduce the number of power-hungry Readers, in turn reducing the overall infrastructure cost. In

Table 1. Comparison of State-of-the-art ultra lower power communication technologies

Technology	Battery less tag	Comm. range > 10m	Number of concurrent tags>10
Active RFID [42]	✗	✓	✓
WiFi Backscatter [43]	✓	✗	✗
BLE Backscatter [44]	✓	✗	✗
Passive RFID [26]	✓	✓	✗
HitchHike [20]	✓	✓	✗
PLoRa [30]	✓	✓	✗
LoRa Backscatter [28]	✓	✓	✗
LoRea [29]	✓	✓	✗
PACT	✓	✓	✓

addition, energy harvesting limits the Source to Tag distance but not the Tag to Reader distance. Hence, the decoupled system allows strategic coverage of large areas with distributed inexpensive Sources and Tags, while using a single Reader to cover the entire range.

Two main design choices pave way for the battery-less operation of PACT Tags employed with active radio. First, the Tag responses (yes or no) are short and hard-coded on the Tag; since the answer to a Query is either yes or no, Tag response is independent of the length of the sensor data. Therefore, despite the higher power consumption of active radio, its **on-time is much smaller**, resulting in a **lower energy** consumption than that of backscatter tags. Second, to reduce the on-time of the Tag, we leverage a low-power envelope detector as a **wake-up receiver** that activates the rest of the Tag only when a valid Query is received. This in turn reduces the overall Tag energy consumption. Thus a PACT Tag (with active radio) can operate in real-time using only the energy harvested from an off-the-shelf RF transmitter as the Source and a decoupled receiver as the Reader.* All the circuit diagrams, PCB files, and software to recreate PACT have been made publicly available [39]†.

PACT Source Design: We implement a PACT Source using TI CC1125 [40] as the radio with MSP430 [41] as the microcontroller (MCU) interface. Periodically, the MCU triggers the Source to transmit an ASK modulated Power-up sequence and a Preamble, to wake up the Tag, followed by the question; e.g., "Is the input less than 30?". For outdoor range experiments, the Source EIRP is set to 16 dBm - maximum transmit power of CC1125 is 14 dBm, along with an antenna gain of 2dBi. This is within the FCC limits of 30dBm. The Source operates in the 902 - 928MHz ISM band at a baud rate of 9.6kbps. In section 3.1, we present our Query design in detail.

PACT Tag Design: Figure 1 summarizes the prototype of a PACT Tag that includes an energy harvesting module, an FPGA (Digital Comparator) for Preamble and Query matching, and an active radio that responds to the Reader. The Tag includes a half-wave rectifier with a 15-stage Dickson charge pump with Skyworks SMS7630-040LF [45] Schotkky diodes. These diodes have a low forward voltage drop and hence function even at low incident powers. The Tag is able to harvest energy from incident RF power as low as -21.67 dBm. The antennas on the Tag are impedance matched using an LC Ell network and the L and C values are obtained from ADS Smith chart utility. The storage capacitor is 6.8 μF, designed to meet the energy needs of our PCB with the FPGA and the active radio.

The Tag includes a wake-up circuit and digital comparator to check for valid Query. We implement the low-power wake-up circuit using Skyworks SMS7630-040LF [45] diode in the envelope detector and the comparator [46] to decode the received bit. Our digital comparator circuit is designed on Lattice Semiconductor's iCE40LX FPGA chosen for its low power consumption and its easy-to-use development toolchain. The comparator ensures that the wakeup circuit activates the Tag on the reception of a valid Preamble. The output of this comparator

*The number of queries and the maximum length of a Query depends on the application; an optimal Query design is part of future work.
†https://github.com/UW-CONNECT/PACT

triggers the active radio for transmission of Tag's response. We use ON Semiconductor's AX5043 transceivers [47] operating in the 902-928 MHz ISM band using FSK modulation as the radio. AX5043 is chosen for its low current of 7.5mA at 0dBm transmit power and consumes 14.85μJ of energy at an operating voltage of 1.8V to transmit a 2-byte payload. We discuss this in detail in section 3.2.

PACT Reader Design: Our proposed Reader can be implemented using any off-the-shelf RF receiver with ASK and FSK demodulator to receive the Query and the response respectively. However, in order to evaluate multi-channel operation of the proposed MAC protocol, we design an FSK demodulator using USRP B200 that can filter multiple channels, demodulate Tag response in each channel, and thus support multiple Tags simultaneously as shown in Figure 1. Our implementation can support 520 unique channels concurrently.

In summary, PACT combines the strength of RF energy harvesting with the benefits of active radio to improve communication range of battery-less Tags. In Table 1, we present the energy-range-scale tradeoff of recent ultra-low-power communication. Technologies that support battery-less tags using ambient signals have low range (rows 2-3). While backscattering using dedicated excitation source can improve the range of battery-less tags, they cannot support a large number of tags due to collisions and interference (rows 4-8). Although active RFID can communicate over long range and accommodate large scale, it requires battery to power tags.

3 PACT SYSTEM DESIGN

In this section, we present in detail the algorithm and system design of the PACT Source, Tag, and Reader, towards our goal of improving the communication range of the battery-less Tag with an active radio.

3.1 Query Design at the Source

PACT Source delivers energy to the Tag as well as assist in data encoding by querying the Tag with a specific Question. The proposed Query format consists of three segments as shown in Figure 2 (b). The first segment is a *Power-up Sequence*; a train of bit 1s that provides sufficient energy to power the Tag which then demodulates the Query to respond. In order for the Source to be energy-efficient with a low-latency Q&A session, we derive the shortest Power-up Sequence required to charge the Tag. The sequence length (in bits) depends on the baud rate (R bps) of the Source and the time to charge the Tag to the desired voltage. For a known charging time, t_c, to charge to the desired voltage, V_D, the optimum length of power-up sequence is,

$$\texttt{Power-up sequence length (bits)} = t_c * R. \tag{1}$$

We design and optimize an energy harvesting unit to reduce t_c and decrease the Power-up Sequence length.

The next segment is a *Preamble* that is used by the Tag to verify the validity of the query; it also serves as the Tag address. If each Tag has a unique Preamble, its length is at least $\log_2$(Number of Tags). Such long Preambles are not desirable as it requires long digital comparators at the Tag. Additionally, querying each Tag sequentially will increase the network latency. To overcome this, we propose a MAC protocol, discussed in detail in section 4, to query and receive from hundreds of Tags concurrently and reduce network latency. The last segment of a Query is the Question itself. We leverage the prior knowledge about the sensor at the Tag to ask questions of the format "Is sensor data below X?" by sending **X** whose length exactly matches the resolution of the Tag data.

In other words, the Tag is designed to receive **X** and proceed to answer "Is sensor data below X?" by comparing **X** to its sensor data. In order to determine if the sensor data is below X, we introduce *Control bits*, which serve as a mask for each bit of the Question. For example, the Source can ask the Tag if the data is less than 128 by sending an 8-bit Question with the Most Significant Bit (MSB) set to "0". A successful comparison of MSB is sufficient to conclude if the sensed data is less than 128. All the other bits are masked by enabling the control bit corresponding to the MSB and disabling comparison of all other bits. More details on control bits are presented in section 3.2.3. The proposed Query format with control bits offers flexibility in the resolution of the data being queried with an optional choice of all 1s as control bits to know the exact match.

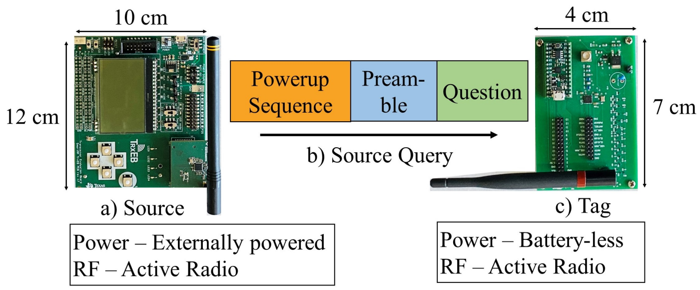

Fig. 2. (a) Externally powered PACT Source transmits a (b)Query that consists of a power-up sequence to charge the battery-less Tag, Preamble to check for Query validity, and Question to be compared with the sensor data. (c) Battery-less Tag responds with an active radio.

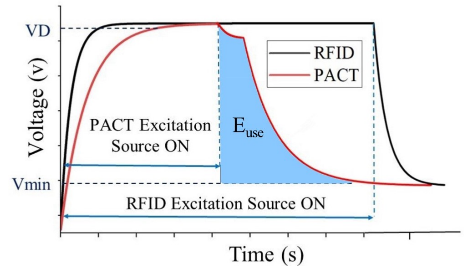

Fig. 3. PACT vs RFID capacitor charge-discharge pattern. Backscatter excitation source is ON throughout the operation. PACT Source is ON only till the capacitor charges to V_{max}.

3.2 Tag Design

The Tag is activated by harvesting energy from the Query following which it demodulates and receives the Question, compares it with the sensor data and responds accordingly using an active radio. Since the query reception and the active radio are powered by the harvested energy, it is crucial that the Tag design is extremely energy efficient. In this section, we present our design of each component in the Tag block presented in Fig. 1.

3.2.1 Energy Harvesting Unit: The harvesting circuit of the Tag includes a half-wave Schottky diode-based rectifier to convert the incident RF energy to DC voltage. It is then amplified by the following stages of Dickson charge pump. Schottky diodes with low forward-bias voltage enable the Tag to operate at low incident powers [48, 49].

The energy harvesting unit of PACT differs from backscatter systems in one key aspect: backscatter tags harvest energy throughout their operation, while PACT Tags harvest energy for a predefined duration and then use it to operate the Tag. In other words, the incident RF power at the backscatter tag must be above a threshold such that the storage capacitor can be charged in real-time. At distances over 15m, although it is possible to harvest the necessary energy, the time to harvest increases due to the reduced harvesting efficiency at lower incident power. Based on our experiments, this increase in harvesting time affects real-time operation. On the other hand, a PACT Tag first harvests energy from the power-up sequence and then turns the rest of the Tag ON to process. At higher distances with lower incident power, it can still harvest sufficient energy from a longer power-up sequence. Therefore, by designing the power-up sequence to match the charging time of the capacitor, we improve the harvesting range of PACT.

This decoupling of energy harvesting and Tag operation changes the demands on the storage capacitor of a PACT Tag. We illustrate the charging and discharging pattern of an backscatter tag and PACT Tag in Fig. 3. We note that a backscatter tag need not store energy, as the excitation source is on throughout the operation. Hence, a small capacitor that can charge/discharge quickly is preferred for backscatter tags. The PACT Tag , however, has two unique requirements: - **the time taken to charge** must be **small** to optimize the power-up sequence length and **the total energy stored** in the capacitor must be **high** to operate the active radio. However, these are conflicting needs, as the total energy stored and the time to charge have a conflicting relationship to the size of the capacitor: smaller capacitors charge faster but store less energy.

Additionally, the voltage across the storage capacitor must be at least V_{min}, the minimum voltage required to operate the Tag components, including the active radio. We design the energy harvesting circuit to meet the energy and voltage needs of the Tag. To enable faster charging, we optimize for the storage capacitor to be the smallest capacitance that can charge to the desired voltage, $V_D > V_{min}$ AND store enough energy to ensure

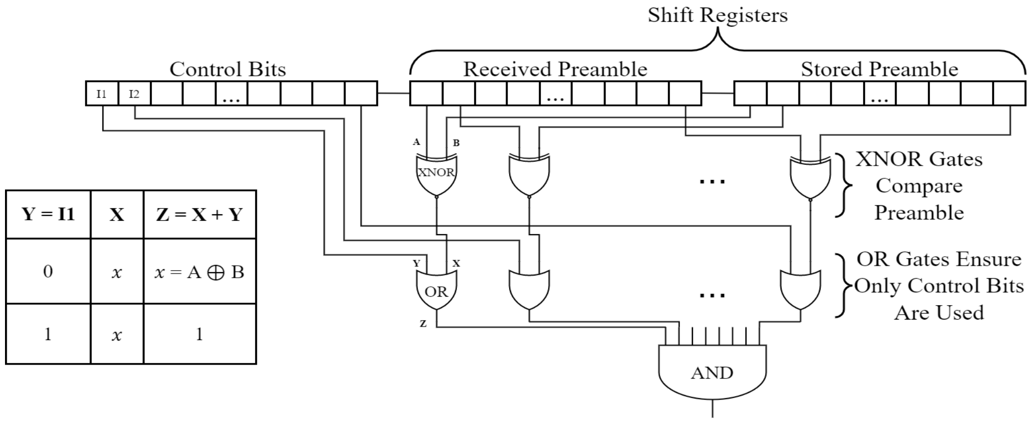

Fig. 4. Digital comparator circuit with control bits for Preamble and Question comparison implemented on the FPGA. Control bits mask Preamble/Question bits not to be compared allowing real time changes in the resolution of sensor data.

error-free Tag operation. Charging to a higher than required voltage ensures that the Tag will have responded by the time the capacitor discharges to V_{min}. We refer to the total energy supplied by the capacitor in discharging from V_D to V_{min} as the *usable energy* as shown in Fig. 3. The energy consumption of the Tag, E_{tag}, must be less than the *usable energy*, E_{use}, given by:

$$E_{tag} < E_{use}, \quad \text{where,} \quad E_{use} = \frac{CV_D^2}{2} - \frac{CV_{min}^2}{2} \tag{2}$$

We first determine the capacitor satisfying this inequality. Then, we increase the number of amplification stages from 4 (typical in backscatter [18, 48]) to 15 to generate the adequate voltage for operation, V_{min}, while keeping charging time low [48]. This optimization improves the harvesting range by allowing our storage capacitor of $6.8\mu F$ to charge to the desired voltage even at low incident powers. While an RFID tag requires atleast -15dBm incident power, a PACT Tag can charge from -21.67dBm incident power by harvesting for a longer duration.

3.2.2 μW Power Wake-up Receiver and Demodulator. On harvesting sufficient energy, the Tag must start receiving samples. Since our Tag is battery-less, an ultra-low-power demodulator is required. Following the design principles of other low-power wake-on radios in RFIDs and WISP [18, 50–56], as shown in Figure 1, the next stage of the Tag is an envelope detector. We design the Preamble and the Query transmitted by the Source to be amplitude modulated. On the Tag, a Schottky diode-based envelope detector and an ultra-low power comparator is used to detect, demodulate and digitize the received samples to bit0 or bit1. To do so, a voltage divider holds a threshold on the negative input of the comparator to half of the input power that is received on the antenna. This allows the circuit to adapt to various power levels and receive at longer distances. The received bits from the comparator are stored in shift registers and compared with the known Preamble at the Tag to verify the validity of the received query. In order to conserve the harvested energy, the rest of the Tag is ON only upon detecting a valid Preamble.

3.2.3 Digital Comparator to Validate Preamble and Question: The digitized Preamble bits are compared with the Preamble assigned to the Tag to check its validity. This preamble check should have low false negatives so as not to miss any Query from the Reader and it must also have low false positives to ensure that the Tag is not triggered ON unnecessarily. We propose a digital comparator that is resilient to fluctuations in incident power while consuming low energy to conserve the harvested energy [57]. The received Preamble is compared **bit-wise** with known, tag-specific preamble using XNOR gates as illustrated in Fig 4. Upon a match, the XNOR gate sets the output high (bit "1"). The result of each bit comparison is input to an AND gate. When all the bits match, the output of all the XNOR gates and hence the AND gate is high. Even if one of the Preamble (or Question) comparison fails, the AND gate output is pulled down (bit '0'). Therefore, a bit "1" output of the comparator indicates a valid query, triggering demodulation of the rest of the query.

The Question follows the Preamble in the Query. The above digital comparator for checking preamble validity is reused for bit-wise comparison of the Question segment with the Tag data. For Question comparison/match, the received question bits replace the Preamble bits and the Tag data replaces the stored Preamble in Figure 4. A Source Query is of the format "Is sensor data below X?" In order to perform this greater than or less than comparison, we propose a modified comparator circuit with control bits.

We design the Source to send a set of control bits for each corresponding Preamble (and question) bit. For example, in order to ask a 16-bit question or preamble, a Source would send 16 control bits ahead of the question or preamble. The **control bits are active low** i.e., a control bit '0' indicates that the corresponding question bit must be compared. A control bit set to '1' implies that the corresponding question or preamble bit is not to be compared. The output of the XNOR gates that indicate whether there was a match, along with the control bits, is fed to the OR gate. When the control bit is set (bit value of '0'), the output of the OR gate is equal to that of the XNOR gate. This means that the OR gate outputs '1' if the corresponding bits match and '0' when there isn't a match. When the control bit is not set (bit value of '1'), the output of the OR gate is always '1'.

Consider the truth table in Fig 4. Y is the control bit and X is the output of the XNOR gate that indicates a match (or not). Any time Y, the control bit, is '1', the output is masked to '1', irrespective of the value of X. When the control bit, Y, is '0', the output of the OR gate is the value of X, which is the output of the XNOR gate. The control bits can thus override the output and in doing so, provide bit-wise question flexibility to the Source; the Source can query the Tag on whether the sensor data is below a value by masking appropriate question bits. Irrespective of the XNOR output regarding bit match, the output is masked and is not considered. The addition of a few OR gates doesn't affect energy substantially but provides for immense flexibility and bit-wise granularity to the matching circuit. This digital circuit can be implemented with a small budget of 794 transistors. The proposed Tag with mostly passive components for Query reception and comparison is energy-efficient and we show that it operates only on harvested energy even at distances up to 24 meters.

3.3 Tag Response and Reader Design

To improve the communication range of a battery-less PACT Tag, we propose the use of active radio for the response. However, an active radio is power-hungry; most Commercial Off The Shelf (COTS) radios draw between 5 and 50mA current depending on the transmit power. For instance, CC1125 [40] consumes 220mJ of energy to transmit a 16-bit payload (and a 2-byte header) at a baud rate of 9.6kbps. RF harvesting will be insufficient to power the Tag. In this section, we design the response format to be energy-efficient in order for the Tag to be battery-less. To reduce Tag energy ($power \times duration$), we design a short response that renders the radio ON time (and hence energy) low enough to be operated using harvested energy, in turn allowing the Tag to be battery-less. In our prototype, a 16-bit, FSK modulated response is sent at 915MHz at 1.2kbps baud rate and 0dBm power.

First, we assign a unique bit sequence to transmit *yes* and *no* in response to the question from the Source. On receiving a Query and matching the data, the Tag activates the active radio to send the corresponding response (yes or no). Therefore, irrespective of the Query length and/or the number of queries, the duration of a Tag response is constant, and is equal to the length of *yes* or *no*. Second, we estimate the energy required by the active radio to send a response prior to system setup. Using this estimated energy as E_{tag} in Eqn 2, we determine the overall energy consumed by the Tag which will determine the energy harvester configuration. It can be noted that the Tag energy is directly proportional to the duration of the Tag response. If each Tag is assigned a unique bit sequence for yes and no, the response length will increase with the increasing number of Tags. We leverage FDMA (described in detail in section 4) to maintain short response length. Additionally, with the help of wake-on radio and digital comparator, the active radio remains in sleep/dormant mode until the comparison is complete. We further decrease the energy consumption of the Tag by reducing the transmit power of the active radio to be close to 0 dBm. Due to the simplicity of the active radio, any COTS radio that satisfies the energy budget can be integrated with the proposed Tag. We discuss the Tag implementation and its components in detail in section 5.

3.4 System Throughput

Due to the question and answer format of PACT, the network throughput characterization is not straightforward. It depends on the number of queries, baud rate of the query, baud rate of response, and the length of the sensor data. While reducing the power-up sequence can improve network throughput by reducing the duration of the Source query, it will lead to lower harvesting range. Therefore, for a given harvesting range, the maximum number of queries that can be broadcast per second by the Source is determined by the minimum power-up sequence length. We evaluate this relation in detail in section 6.1. Network throughput also depends on the baud rate of the response. While higher baud rate allows the Tag to respond faster, the BER (bit error rate) performance of the response suffers at higher baud rates, limiting the communication range. We evaluate the BER performance of Tag responses for different baud rates at increasing communication range in section 6.3. Finally, smart Query design can reduce the total number of queries required, in turn improving the network throughput to obtain sensor information with the fewest number of questions. In conclusion, due to the question-answer format, we expect the data rate of a single PACT Tag to be lower than most comparable technologies. However, the overall network throughput can be improved by optimizing the number of queries, modulation characteristics of the Query and response. In the next section, we present our MAC protocol that can accommodate hundreds of PACT Tags to coexist and communicate concurrently to a Reader, further improving the network throughput.

4 SCALABLITY AND CO-EXISTENCE OF PACT TAGS

So far, we have focused on a single link with a Source, a Tag, and a Reader. In this section, we focus on the co-existence of multiple Tags in a network with one Source and one Reader, a common topology in practical deployments of applications discussed in Section 7. When multiple Tags are within the harvesting range of the Source, more than one Tag could receive the Query and respond. Since the Tags are powered by the Query, the time to harvest, process Preamble and Question, and then respond, is comparable; hence their responses are transmitted concurrently, leading to collisions. A MAC protocol is thus required to uniquely identify each Tag as well as overcome any collisions that may occur as a result of concurrent responses from the Tags.

One of the widely used anti-collision protocols in RFID is based on Time Division Multiple Access (TDMA), where the Reader interrogates the Tags sequentially [58]. Tag-Driven and Reader-Driven TDMA have also been proposed in backscattering systems [58]. While TDMA-based querying can eliminate collisions, it increases the overall latency. FDMA is not widely used due to the need for oscillators for frequency shift [59]. FDMA also limits the bandwidth (BW) per Tag; lower BW increases the ON-time and energy consumption of the Tag.

We propose a hybrid MAC protocol that is energy efficient at the Tag and the Source; it combines the advantages of TDMA and FDMA to reduce collisions. During system setup, we assign each Tag a unique two-tuple address: **(Preamble, Center Frequency)**. The Tags are divided into non-overlapping Groups; each Group has a Preamble i.e., all the Tags within a Group share the same Preamble. Each Tag within a Group is then assigned a unique center frequency (Channel) for the response. When a Source queries with a specific Preamble, all the Tags in the vicinity harvest and perform Preamble comparison. Only those Tags whose received Preamble match their stored preamble proceeds to demodulate and compare the Question. Depend on the match outcome, the Tags respond a yes or no in their assigned Channel, leveraging FDMA. The Source then continues to Query the next Group with its corresponding Preamble, similar to TDMA. Since each Tag with the same Preamble is assigned a unique frequency, their responses do not collide and are received successfully at the Reader. As the frequencies

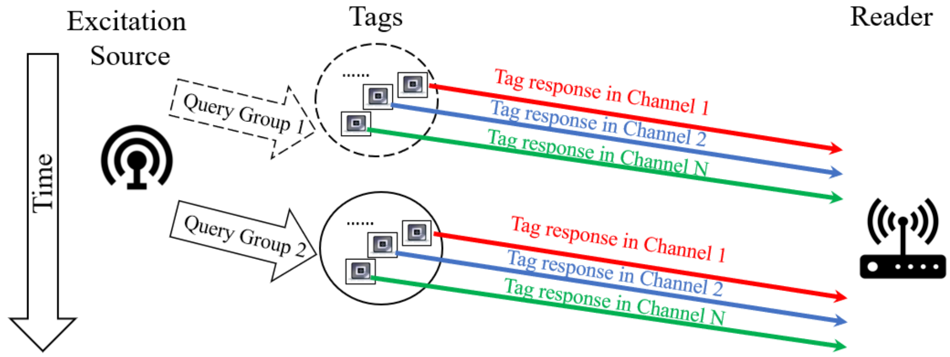

Fig. 5. Illustration of PACT's Hybrid MAC protocol : The Source queries a Group, where all the Tags share the same Preamble. The Tags respond concurrently in unique channel which are received by a wide band Reader. The Source proceeds to repeat this for each Group sequentially. Arrow colors in the Tag response indicates a unique frequency channel

are reused across Groups, the bandwidth per Tag is higher than that of standalone FDMA. A broadband Reader listening to all the Tags performs FFT to identify all the Tags that replied simultaneously. **Thus, the Source utilizes TDMA to query Groups sequentially and the Tags utilize FDMA to respond concurrently.**

Fig 5 illustrates our proposed MAC protocol in a network with one Source, one Reader, and six Tags divided into two Groups. Source first broadcasts a Query with the Preamble set to $Preamble_1$ to query all the Tags in Group 1; Tags can be in arbitrary locations within the harvesting range. After the Query match, Tags in Group 1 reply *yes or no* at their pre-allocated center frequencies, indicated by Channels 1, 2, and 3. The Source then broadcasts the next Query with the Preamble set to $Preamble_2$ to query the Tags in Group 2. Tags in this Group reuse Channels 1 to 3 to respond. Since the two Groups are queried separately, there will be no collisions between Tags across Groups. We optimize the address allocation to maximize the number of Tags without compromising the energy efficiency of each Tag. We propose the following approach to choose the number of channels (and hence Tags) per Group such that the energy consumption of the Tag is minimized. The energy consumption of a Tag (E_{tag}) as shown in Eqn 3 depends on the voltage (V_{min}), the current consumption (I), and Δt, the time period for which the Tag is ON. To conserve energy, we choose radio modules that can work at low V_{min}, consume a lower current (I), and/or reduce the "on" time of the radio. For a given radio, V_{min} and I are fixed. Since the ON time of the Tag's active radio is inversely proportional to its BW of operation (as baud rate is directly proportional to the BW) [60], a higher baud rate has lower ON time and hence lower energy consumption.

$$E_{tag-radio} = V_{min} * I * \Delta t;\ \ \Delta t \propto \frac{1}{BW};\ \ \texttt{BaudRate} \propto BW \quad (3)$$

We first determine the energy budget of the Tag radio, $E_{tag-radio}$ to be the difference between the tag energy (except radio) and harvested energy. By substituting the voltage and current drawn by the active radio in Eqn 3, we determine the acceptable response duration Δt. The maximum number of Channels that can be assigned with a baud rate such that the response duration per Tag is ≤ Δt determines the number of Tags per Group. The number of Groups is then the ratio of the total number of Tags to the number of unique frequencies. Such a design allows co-existence of multiple tags while maintaining the energy efficiency and range of a single link. We evaluate the tradeoff between the number of frequencies, latency, and energy consumption in section 6.5.

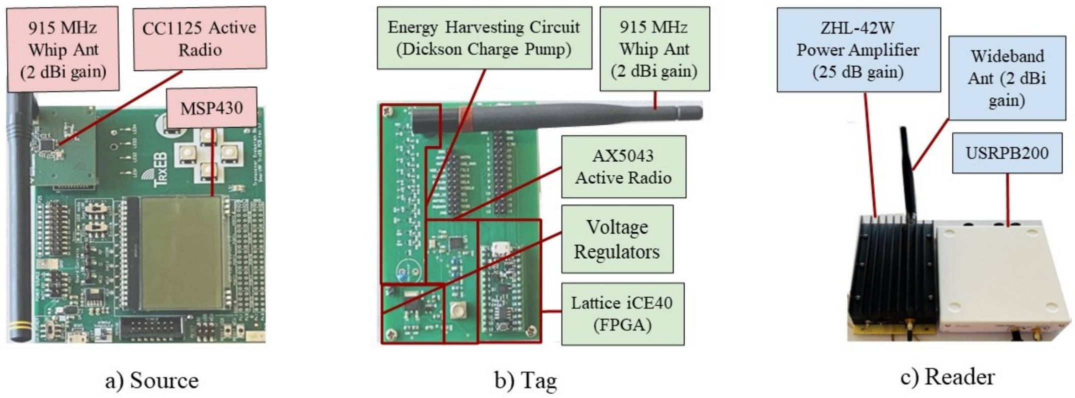

Fig. 6. (a) Source implemented on CC1125 with 2dBi whip antenna (b) PCB prototype of battery-less PACT Tag: RF front end with 2dBi whip antenna is impedance matched. Harvesting unit stores energy on the 6.8μF capacitor, which supplies power to the wake-up receiver, Lattice iCE40 TinyFPGA, and the AX5043 active radio. AX5043 transmits a 2-byte FSK modulated response at 0dBm and 15 kHz BW. (c) USRP B200 with ZHL-42W power amplifier and 2dBi gain whip antenna as Reader

5 IMPLEMENTATION

We implement the PACT system shown in Figure 1 using COTS components and verify the end-to-end performance through simulations and real-world experiments. The prototype used in our experiments is shown in Figure 6. All the software, PCB files, and circuit diagrams to recreate the prototype have been made publicly available [39].

Source Implementation: PACT Source is prototyped using an MSP430 [41] connected to CC1125 [40] radio. The MCU maintains the radio in ASK transmit mode and transmits a Query consisting of the power-up sequence, Preamble, and Question. The power-up sequence is a train of bit 1 whose length is determined by the charging time requirement of the Tags. The Preamble and the Question are 8 bits long; along with 8 control bits each, these are transmitted as a 16 bit value. We use a 2dBi gain, quarter-wave whip antenna and the power level at CC1125 is set to its maximum value of 14dBm, thereby achieving an EIRP of 16dBm, well within the FCC limits. The code used for CC1125 transmitter is located at Source/Software [39].

Reader Implementation: PACT Reader is implemented on USRP B200 as radio, programmed using GNU Radio. ASK demodulator in the USRP receives the Query transmitted by the Source. FSK demodulator in the USRP receives Tag responses in the 902 - 928 MHz band at a baud rate of 9.6kbps. In experiments that use a single Tag, the USRP receives a signal bandwidth of 200kHz at a sampling rate of 200 ksamples/s. We use a band pass filter aligned to the center frequency of the Tag response with 30 kHz passband and 100dB stopband attenuation. Demodulation is done using the quadrature demod block set to deviation of 5kHz to match the Tag response. However, in experiments where multiple Tags transmit in different channels, the USRP receives a wide band signal at a bandwidth of 2.4MHz and a sampling rate of 2.4 Msamples/s. Parallel band pass filters aligned to the center frequency filter the received samples and downconvert samples in each channel to 120 ksamples/s, which are demodulated to infer the Tag response in each channel. A wideband whip antenna with less than 1dBi gain is connected to a power amplifier [61] providing 25dB gain to the USRP Reader. The PACT design files are being open sourced at [39]. GNU Radio files and other software for Reader implementation may be found under Reader/Software [39]

Tag Implementation: Figure 6(b) summarizes the prototype of a PACT Tag that harvests energy from the Query to operate. PCB files of the Tag and FPGA code may be accessed under Tag/Hardware and Tag/Software [39].

Energy Harvesting (EH) module: The first module in the Tag is the EH circuit. Our proposed EH circuit (section 3.2.1) includes a half-wave rectifier with a 15-stage Dickson charge pump. ADS (Advanced Design System) simulations were used to study the impact of the number of stages and storage capacitor. We use the SPICE model of the Skyworks SMS7630-040LF [45] diode for accurate simulations (Figure 6(c)) which enabled us to easily modify the number of stages from 4 to 15 and storage capacitors in the range of nF to μF, and choose the optimal capacitor. We choose V_D and V_{min} as 1.8V and 4V to provide sufficient energy at the capacitor whose transient response is shown in Fig. 3. The antennas used on the Tag were impedance matched using an LC Ell network; the optimum values of the LC matching circuit, 6.5nH inductor and 1pF capacitor, are obtained using Keysight ADS' Smart Component functionality[‡].

The choice of $C_{storage}$ depends on the total Tag energy and V_{min}. The total energy largely depends on the active radio. For our choice of active radio (described later in this section), V_{min} is 1.8V. TI TPS7B88 and ON Semiconductor NCP718 Low-dropout (LDO) voltage regulators are used for 3.3V and 1.8V supplies to the FPGA and radio respectively and require 300mV as the minimum input. ADS simulations indicated that the smallest capacitor needed for a Tag with AX5043 is 6.8μF; hence, we use that in our hardware implementation.

Wake-up and digital comparator circuit: Following the EH block, the Tag checks for valid Preamble and Query. We implement the low-power wake-up circuit using Skyworks SMS7630-040LF [45] diode in the envelope detector and an ultra-low power comparator[46] to decode the received bit. The comparator operates without any feedback and the output is pulled up to VDD or down to 0 depending on the result of the comparison. Our prototype of the digital comparator is designed on the TinyFPGA BX using Lattice Semiconductor's iCE40LX FPGA [57]. We chose the iCE40LX for its low power and its easy-to-use development toolchain. The digital matching circuit ensures that the wakeup circuit activates the Tag if and only if a valid Preamble is received.

Active radio on the Tag: We use ON Semiconductor's AX5043 transceivers [47] for the active radio; it operates in the 902-928 MHz ISM band using 2-FSK. We use AX5043 for its low current of 7.5mA at 0 dBm transmit power, consuming 14.85μJ of energy. The response consists of an 8 bit header (alternating 0s and 1s) followed by an 8-bit response (yes or no) to the Query. Upon a match, a *yes* response is transmitted by all bit-1 s and a *no* response is transmitted by all bit-0 s. Upon receiving and successfully matching the Preamble, the FPGA turns the radio ON and transmits the 16-bit response. In outdoor experiments where multiple Tags transmit concurrently, we use MSP430 to emulate the FPGA. In these experiments, the MSP was externally powered through a battery and did not use harvested energy. The 2-FSK modulated Tag response is transmitted at a baud rate of 9.6 kbps and 0dBm power. Multiple Sources associated with various Tag groups can be placed up to 400m from a single Reader. In our experiments, we test the worst case by placing the Source and the Tags 400m from the Reader.

6 EVALUATION

We use the hardware prototype described above and evaluate the functionality and correctness of our proposed communication system. We evaluate and present our experimental results on the following metrics:

(1) Coexistence and Communication Range : We evaluate the maximum achievable communication range between a PACT Tag and a Reader, when the Tag is within 24 meters from the excitation Source (maximum harvesting range). We also study the coexistence of 5 Tags in this experiment.
(2) Harvesting Range and Communication Range : We characterize our EH unit at various harvesting distances from the Source and evaluate the relation between harvesting and communication ranges. We experimentally evaluate the sensitivity of the Tag at decreasing incident powers.

[‡]To optimize the impedance matching circuit below -15 dBm power, a variable capacitor is needed to account for manufacturing tolerances of capacitors affecting the precise matching required for optimal harvesting efficiency.

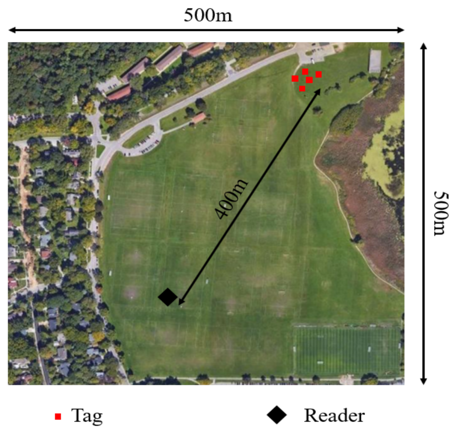

Fig. 7. Experimental outdoor set up in a 500 m x 500 m open field to evaluate communication range.

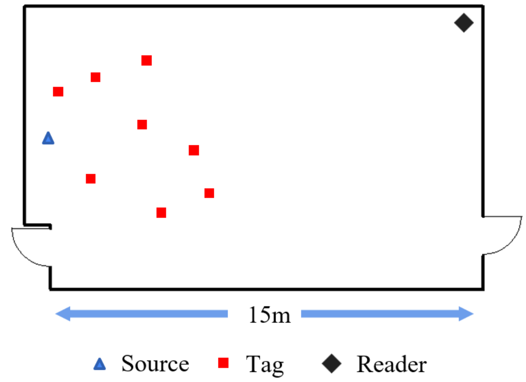

Fig. 8. Indoor Setup in a 15m x 10m lab space with up to 8 Tags distributed within 24 meters from the Source

(3) Throughput and RF Energy Harvesting Range : We evaluate the maximum number of queries that can be transmitted by the Source to a battery-less Tag, which determines the per-node throughput. We experimentally show the dependence between throughput and storage capacitor on the Tag. We also evaluate the impact of achievable response throughput at increasing distance between Tag and Reader.
(4) Energy Consumption: We evaluate the energy consumed by a PACT Tag and Source to convey a 2-byte payload and compare it against state-of-the-art backscatter systems and Active RFID.
(5) Network Latency : We evaluate the network latency for increasing number of Tags and compare against state-of-the-art battery-less tag networks.

Experimental Setup : Our experiments were conducted in Line-of-Sight (LOS) conditions in indoor lab space as well as outdoor environment for long-range evaluations. In Figs. 7 and 8, we mark the locations of the Source, Tags, and the Reader in outdoor and indoor settings respectively. Outdoor experiments were conducted in a large open field of size 500mx500m under LOS conditions. As discussed in section 5, in the outdoor settings, the Tags are battery powered and do not harvest energy. Hence, no Source was deployed in Fig. 7. Active radios in the Tag are set to transmit at 0dBm, to emulate Tag functionality when battery-less. At each distance, over 1000 rounds of query-response pairs were recorded from the Tags on the USRP over a period of 2 hours. The Tags and the Reader were both elevated from the ground by 1m. Indoor experiments were conducted in 15mx10m labspace. The Tags were placed in random locations around the Source. We used up to 8 Tags, each using an AX5043 radio to transmit its FSK response with 15kHz bandwidth at a unique center frequency with a transmit power of 0dBm.

Baselines compared : We compare the performance of PACT against state-of-the-art Passive RFID tag (SMARTRAC Sensor DogBone [26]), active RFID tag (TAGSENSE-ZT-ZR [42]), pLoRa [30], HitchHike [20], and LoRea [29]. The RFID tags chosen above are commercially available and are considered ultra-low-power for passive and active RFIDs. Although Gen2 passive tags from SkyRFID [62] operate up to 16m range, they do so at the highest EIRP. However, they are not commercially available as yet. Passive backscatter systems with long communication range are chosen as baselines. pLoRa, xSHIFT, and HitchHike use a three-node communication model by incorporating a dedicated excitation source, similar to PACT. LoRea uses a two-node communication model by relying on ambient signals to backscatter data. To provide a fair comparison, we consider the maximum range reported for pLoRa and Hitchhike and use the corresponding bit rate for energy calculations. We compare against the 2.4GHz

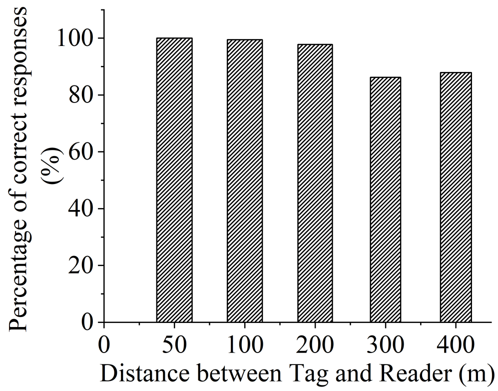

Fig. 9. Concurrent responses received from 5 Tags at the Reader. Each Tag responds in a unique channel, with 15 kHz bandwidth and 1.2kbps baud-rate.

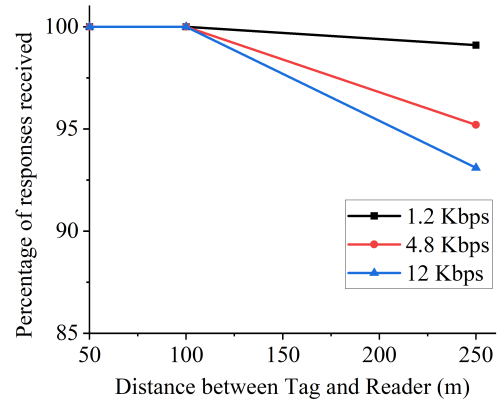

Fig. 10. Responses received by the Reader at increasing distances for three different FSK baud-rates used by the PACT Tag for transmitting its response.

implementation of LoRea because it relies on ambient RF signals from WiFi routers as excitation. We recreated Hitchhike tag using the publicly available code-base [63]. For other works, we utilize the power consumption and communication range results as reported in the respective papers.

6.1 Coexistence and Communication Range

We evaluate the achievable communication range of 5 PACT Tags, each sending its response at a baud rate of 1.2kbps. Tags were deployed in an outdoor field with LOS to the Reader. In Fig. 9, we plot the average rate of correct responses across all Tags as a function of communication range in the x-axis.

We observe that the Reader decodes 100% of the responses from the Tags at 50 meter and over 99.7% of the responses at 100 meters. As the distance increases, the SNR decreases, in turn reducing the percentage of responses decoded correctly. At a distance of 400 meters, the average rate of correct responses across all 5 Tags is about 88%. It must be noted that the transmit power of the AX5043 active radio is set to 0dBm. Despite this low power, PACT Tags are capable of communicating to the Reader that is about 400 meters away. This is due to the use of ultra-narrow bandwidth of 15kHz, which decreases noise floor and improves SNR. In addition to improved range, ultra-narrowband operation improved scalability by increasing the number of available channels. The achievable communication range of PACT also depends on the baud rate of the Tag response, as shown in Fig. 10. As the baud rate of the response increases, the success rate decreases beyond 100 m. The communication range-throughput tradeoff is discussed further in section 6.3.

Due to the high cost of the FPGA (over $200), we prototype only one Tag with the FPGA. However, an FPGA is closer to chip design than an MCU so despite the FPGA prototype being expensive, a chip form factor at scale (much like RFID tags) will bring down the cost of each Tag. To evaluate the co-existence of Tags, we implement PACT Tags on MSP430 with AX5043 as the radio. In this setup, we only evaluate the Tag to Reader communication range, and do not implement the energy harvesting component of the Tag. We independently verify that at the maximum energy harvesting range of 24 meters, the Tag harvests sufficient energy to operate AX5043 radio at a transmit power of 0 dBm. Therefore, to emulate networks with maximum harvesting range, the Tag radio transmits at 0 dBm, while the MSP430 is powered using the laptop.

In summary, use of active radios with ultra narrowband operation improves the communication range by enhancing the SNR at the Reader. Additionally, it allows multiple Tags to transmit concurrently in the 902-928

Table 2. Communication Range (Tag to Reader distance) at increasing Harvesting Ranges (Source to Tag distance) and the received signal strength (RSS) at the Reader.

Technology	Communication Range : Tag- Reader Distance (m)				Max. Harvesting Range (m) (Theoretical)	Max. Harvesting Range (m) (Experimental)	RSS at Reader (dBm)
	Source to Tag ≤ $1m$	1m < Source to Tag ≤ $5m$	5m < Source to Tag ≤ $10m$	10m < Source to Tag ≤ $20m$			
PACT	400	400	400	400	24	24	-31.6
LoRea [29]	225	160	140	90	22*	-	-44.4
pLoRa [30]	600	200	150	-	10*	-	-61.2
HitchHike [20]	54	20	8	-	6*	-	-67
Passive RFID [42]	10	10	10	-	10	10	-32
Active RFID [26]	300	300	300	300	5*	-	-46

MHz ISM band without interfering with each other and hence allowing PACT networks to scale. We note that the active radio decouples the communication range from the harvesting range. In other words, a communication range of 400 meters is feasible even at the highest harvesting range of 24 meters.

6.2 Harvesting and Communication Range

The use of a separate excitation source to improve communication range has been proposed by other works such as Hitchhike [20], LoRea [29], pLoRa [30]. In existing architectures, the communication range is improved by bringing tags closer to the Source (decreasing the harvesting range). Here, we compare the communication range at different harvesting ranges of PACT and other battery-less, long range communication systems.

Table 2 compares the communication range between the Tag and Reader of PACT with other backscatter systems and RFIDs at various harvesting ranges (between Source and Tag). The communication range of PACT does not vary with harvesting range; it only depends on the transmit power of the active radio on the Tag. At a Tag transmit power of 0 dBm, PACT communicates to distances of about 400m (also showcased in Fig. 9). This impressive communication range is attributed to the use of ultra narrowband active radio, which faces only one-way path loss. PACT achieves 7× improvement over HitchHike and 40× over Passive RFID tags at a Tag-to-Source distance of 1m for PACT and Passive RFID and 0.2m for HitchHike. 3-node backscatter systems such as HitchHike enhance communication range by compromising the harvesting range i.e.,keeping the excitation source closer to the tag. pLoRa and LoRea have the distinct advantage of using chirp spread spectrum(CSS), which inherently offers greater sensitivity on the Reader, improving communication range up to 225m (LoRea) and 600m (pLoRa). However, to reach these long ranges, pLoRa requires the excitation source to be 20cm away; when the excitation source is 5m away, the communication range drops to around 200m. We observe that a PACT Tag can be adapted to implement CSS to further improve range. Except at harvesting ranges below 1m, PACT Tags achieve the highest communication range (highlighted cells in Table 2).

Column 6 shows the maximum harvesting range estimated using the Friis free space propagation model to account for path loss. We achieve an impressive harvesting range of 24m, over 2× improvement over passive RFID. We experimentally verify that PACT Tags require a minimum estimated incident power of -21.67 dBm to charge its storage capacitor over 300mV. The voltage regulators on the Tag can then provide 1.8V to all the Tag components as long as a minimum of 300mV is supplied to the regulators. Assuming the maximum Source EIRP as stated by FCC regulations (30dBm output power through a 6dBi antenna) and minimum incident power of -21.67dBm, we estimate the maximum range possible by using the Friis free space propagation model to be

*Harvesting range estimated from the tag power consumption to transmit a 2 byte payload.

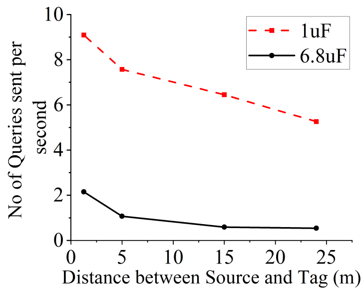

Fig. 11. Maximum # of queries that can broadcast by the Source and processed by the Tags Vs harvesting range

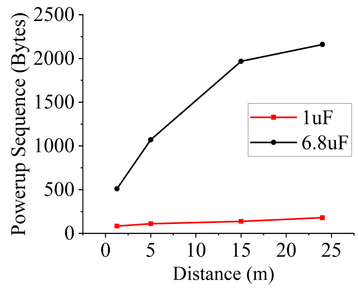

Fig. 12. Minimum Power-up Sequence to charge a PACT Tag with AX5043 for two capacitors : 1μF and 6.8μF.

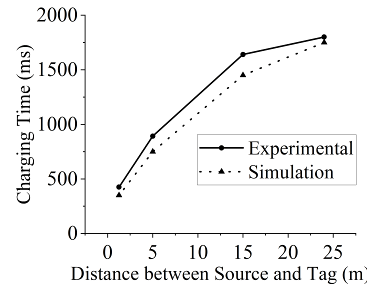

Fig. 13. Experimental and simulated verification of the time to harvest and charge Tag with 6.8μF capacitor.

24m. The improved harvesting range is made possible by the low Tag energy consumption (evaluated in the next subsection) of about 23μJ. Unlike backscatter, which requires the presence of a continuous excitation source for energy harvesting as well as communication, PACT Tags only harvest energy from the Power-up sequence and expend it in a fraction of the charging time to operate the Tag. For the other technologies compared, we estimate the harvesting range based on their tag energy, minimum operational distance from the Source, and Frii's path loss model. It must be noted that these experiments to determine the sensitivity of the Tag do not include MSP430 on the Tag. We use PACT Tag implemented on the FPGA to perform these experiments.

In summary, PACT decouples the communication and harvesting range by using an active radio. The improvement in communication range can also be observed by the RSS (received signal strength) of various technologies when the Source and the Reader are 1m from the Tag. We assume the maximum Source power as stated in the respective papers. On an average, the RSS at the PACT Reader is 25dB higher. pLoRa uses ambient RF signals to backscatter which results in a low RSS. HitchHike and LoRea use a dedicated Source but the RSS on the Reader suffers due to two way path loss. Even though the RSS of passive tags is comparable to PACT, the SNR is still significantly lower due to self interference by the excitation signal. By incorporating a low power radio on the Tag, PACT is able to increase the RSS, and hence the SNR at the Reader. This allows us to use any COTS transceiver as the Reader without additional components for interference cancellation, making PACT a low-cost solution.

6.3 Query Throughput and Harvesting Range

In a PACT network, the overall network throughput depends on the number of query-responses per unit time, baud rate of the Query and the Tag response. In this section, we evaluate the impact of each of these individually.

In Fig. 11, we plot the maximum number of queries that can be sent by a Source in a second at increasing distances between the Source and the Tag (harvesting range). As the Tag moves away from the Source, the harvesting efficiency deteriorates and requires longer duration to charge the storage capacitor. Therefore, the Source has to supply a longer power-up sequence to meet the Tag's energy demands. This in turn increases the duration of the Query and decreases the number of Queries per second. The increase in estimated power-up sequence length (bytes) at increasing harvesting ranges is shown in Fig. 12. Additionally, the power-up sequence length varies with the storage capacitor as the charging time depends on the capacitance. As shown in Fig. 12, a smaller capacitor (1μF) has a lower impact than a larger one. PACT Tags with lower power active radios will use smaller capacitors and can operate with power-up sequences of few 10s of bytes. We evaluate the charging time of a 6.8μF capacitor experimentally and through ADS simulations in Fig. 13. In our experimental evaluation, we vary the transmit power of CC1125 radio to emulate varying distances. On an average, the experimental charging

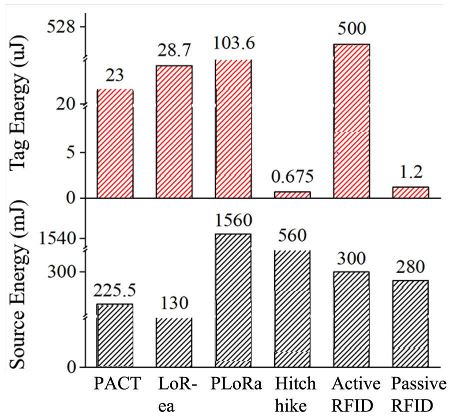

Fig. 14. Comparison of the average energy consumed by a Source (bottom) and a Tag (red) transmitting a 2-byte payload by different technologies

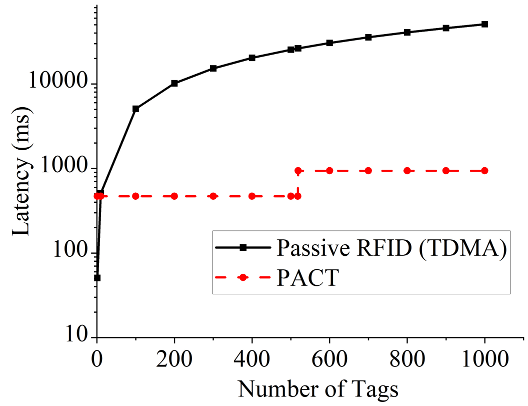

Fig. 15. Estimated Network Latency as network size grows : PACT results are based on the experimental setting of Tags using FDMA with 15kHz BW

time is within 87% of the simulation. Since the LC matching circuit in our implementation has been designed for best-case matching at low incident power conditions (i.e., larger Tag-Source distance), our simulation results for larger Tag-Source distances match the experimental evaluation more accurately compared to smaller distances.

We thus show that the Tag energy, storage capacitor, and the expected harvesting range determines the power-up sequence length and hence the number of queries per second. PACT Tag using a 6.8μF capacitor can receive up to 2.15 queries/second when it is 1.2m away from the Source. This number drops to 0.54 queries/second at the maximum harvesting range of 24m away, due to the longer charging time. However, a PACT Tag implemented with a 1μF capacitor can receive 9.09 and 5.26 queries/second at harvesting ranges 1.2m and 24m respectively. While the harvesting range does not affect the communication range of PACT Tags, it affects the network throughput. The longer the distance between the Source and the Tag, lower is the per-node throughput.

The second factor that impacts the throughput is the baud rate of the Tag response. We plot the percentage of Tag responses that were decoded accurately by the Reader at increasing distances between the Tag and the Reader (communication range); we evaluate the decoding accuracy when the responses are transmitted at baud rates of 1.2kbps, 4.8kbps, and 12kbps in Fig. 10. Tag response at a higher baud rate reduces the transmission time and hence improves throughput. However, higher baudrate leads to higher probability of symbol errors. As shown in Fig. 10, at distances of 50 and 100m, a PACT Reader demodulates 100% of the responses at all three baud rates. As we move further to 250m, the packet decoding accuracy drops to 93% for 12 kbps.

In summary, the network throughput of PACT can be improved by increasing the baud rate of Tag response at the cost of reduced communication range. It can also be improved by decreasing the power-up sequence length, which increases the Query throughput by trading off the maximum harvesting range.

6.4 Tag and Source Energy Consumption

We evaluate the energy consumption of PACT Tag as low energy consumption is necessary for its battery-less operation. Since the active radio is the most power-hungry module of a PACT Tag, we also analyze the Tag energy when using active radios with lower power than that of AX5043. We identify Langevelde [64] as a potential low-power active radio that draws 1.8mA at 1.2V. We measured the current consumed by our prototype with AX5043 using a 6.5 digit Keysight multimeter and the benchvue tool. Benchvue also lets us verify the ON time of the Tag for energy calculation. We also present the energy consumed by the PACT Source. Unlike backscatter systems where the excitation source is ON throughout the communication, a PACT Source is ON only for the duration of the Query and then goes back to sleep, thus conserving the Source energy. Reducing the Source energy renders PACT to be a sustainable network with the potential to power the Source from a battery, making PACT more accessible for applications such as transportation tracking, livestock monitoring among many others.

Fig. 14 plots the Tag and Source energy for PACT and other passive systems. The energy consumption of a PACT Tag implemented with AX5043 is higher than that of other passive systems. However, when implemented using Langevelde [64], it is 33% and 74.9% lower than pLoRa and LoRea respectively, because the Langevelde radio operates at a 2x lower voltage, and draws over 3x lesser current than AX5043. We recreated and experimentally verified the Tag energy of Hitchhike. For fairness, we compare the PCB implementation of each technology and not ASIC. Majority of existing work focuses on reducing the Tag energy at the cost of increasing the Source energy. On an average, the Source energy of PACT is at least 23% lower than that of various backscatter technologies compared in the Fig. 14. LoRea relies on ambient RF to backscatter and hence has low source energy of 130mJ, compared to 225.5mJ consumed by the AX5043 implementation of PACT. However, the Langevelde implementation of PACT reduces the Source energy to 5.5mJ due to reduced power consumption of the radio. It must also be noted that the Source energy in PACT is amortized over all the Tags that transmit concurrently. In our evaluation, even though the overall energy consumed by the Source is 225.5mJ, all 5 tags are charged simultaneously and no additional energy is incurred. Hence, as the system scales up, the energy consumption of the Source remains constant. On the contrary, other backscatter tags that do not transmit simultaneously increases their source energy consumption linearly as the system scales. This is of particular significance in applications where the Source could be battery powered.

6.5 Network Latency

We evaluated the coexistence of 5 PACT Tags experimentally in section 6.1 and showed that they communicate with a wide-band USRP Reader placed up to 400 meters away. In this section, we show that over 500 concurrent Tags can operate in a single group with the bandwidth setting in section 6.1 in the ISM band. Additionally, the network size can be increased further by adding new Tag groups with minimal impact on network latency.

In our experimental evaluation with 5 Tags, each Tag is assigned a unique center frequency and is programmed to transmit the response using 15 kHz bandwidth 2-FSK response. Nearest adjacent channels were designed to be 50 kHz apart i.e.,the difference between the center frequencies of any two Tags is an integer multiple of 50 kHz. With a bandwidth of 15kHz, this above difference allows a guard band of 35 kHz between two adjacent channels. We validate experimentally that at this guard band, the energy leakage from one channel to the other is little to none. Additionally, with a 100 dB attenuation loss in the Low pass filter at the Reader, a 50 kHz difference between center frequencies ensures no interference from adjacent channels. Given the 26 MHz spectrum between 902MHz and 928MHz, up to 518 channels that are spaced 50kHz apart can be received concurrently by the Reader. Therefore, a Source can broadcast its Query over 500 Tags and the Reader can receive all of them simultaneously in one group. However, the computational complexity of the Reader to receive a 26 MHz wide spectrum and process over 500 low pass filters and demodulators is significantly higher than that of a Reader processing a single Tag. Wide band software defined radios for [65–67] IoT applications have been a growing research area that we believe offer low-cost design for PACT Reader. Our current implementation using USRPB200 is limited to 2.4MHz spectrum, due to the limitations of sampling rate that can supported by the computer.

To illustrate the advantage of our hybrid MAC protocol, we compare the network latency of PACT network as a function of number of nodes in Fig. 15. We define network latency as the overall time to obtain data from all the Tags in the network. We compare against TDMA, a commonly used MAC protocol by RFID systems. While TDMA is easy to implement and can scale up to 10s or even 100s of devices, in addition to higher Source energy, it has the disadvantage of increasing network latency. The latency of TDMA and our proposed MAC approach for a varying number of Tags is shown in Fig 15. PACT's latency remains constant for a group of up to 518 Tags. It

Table 3. Comparison of PACT prototype using COTS components with Passive RFID.

	PACT	RFID
Harvesting Range	24 m	10 m
Communication Range	400 m	10 m
Tag Energy	23μJ	1-2 μJ
Source Power	150 mW	-
Reader Power	700 mW	1 W
Latency	470 ms	5083 ms
Tag cost	$50 - $290	$0.1 - $20
Source cost	$50	-
Reader cost	$1175	$1250 - $2700 [68]

increases linearly with the number of groups i.e. the latency increases only when the network size steps up by an additional 518 Tags in this setting. This is in contrast to passive backscatter, where the latency increases linearly with the number of Tags. The advantage of our hybrid MAC protocol is evidenced by the fact that the latency of a network of 500 - 1000 PACT Tags is the same as the latency of a network of 10 passive backscatter tags. Such low network latencies even in a large-scale deployment leads to faster tracking, which in turn improves throughput.

6.6 PACT v/s Passive RFID Comparison : A Case Study

Let us consider a warehouse shelf with 100 cartons each containing perishables that could be spoiled below 8 °C. A PACT Tags per carton is placed on the shelf and a Source to Query these Tags is deployed within 24 meters of the shelf. The Reader is located in the corner of the warehouse, listening to the Source and the Tags. The Source asks the Question “Is the temperature less than 8 °C?” and all the Tags respond concurrently on their respective channels. The Reader records all the responses and uploads them to a cloud server. For an RFID deployment, a minimum of 2 RFID readers are required to cover the entire shelf. We assume that the tags don’t move and that the reader position is optimized based on the tag locations. The tags transmit the recorded temperature to the reader in a TDMA fashion. All the tags (RFID and PACT) are equipped with a temperature sensor that has an 8-bit resolution.We tabulate the range, energy consumption, communication latency, and cost of all components in Table. 3. Passive RFID tags are limited in their communication range due to backscatter based transmission. Only tags that are located within a 10m radius of the reader can communicate with it. To cover larger areas, more readers must be used. PACT decouples the harvesting and communication range; all Tags located within a radius of 400m from the Reader can transmit to it, so long as they are within 24m of the Source. Since all PACT Tags respond concurrently, the overall network latency of the PACT deployment is 470ms. Hence, the Reader and the Source only consume about 400 mJ of energy. On the other hand, due to TDMA based communication, the network latency of an RFID deployment is about 5s which leads to an energy consumption of about 5J. The reduced network latency from concurrent reception at the PACT Reader amortizes the Reader and Source energy consumption over all the Tags, thereby reducing the Reader and Source energy per Tag.

In terms of cost comparison, a bulk of the PACT Tag’s cost depends on the FPGA used which can range from $19 [69] to $260 [70]. Hence, a PACT Tag can cost between $50 and $290. However, this is the price of a Tag prototype implemented using COTS components; we expect the price to reduce considerably when implemented as an ASIC. The Source implemented using CC1125 Radio costs about $50 [40] and the Reader implemented using USRPB200 [71] costs $1175. It must be noted that cheaper software-defined-radios such as RTL-SDR can be used as the Reader which brings the price down to $30 [72]. The total cost of the deployment is $1225, excluding Tags. RFID tags usually range between $0.1 [73] and $20 [74]. Assuming $1250 per reader [75], the total cost comes out to be $2500, excluding tags. Note that PACT measurements are from a COTS prototype. The Tag power and cost will be significantly lower per unit at scale in custom chip form.

7 APPLICATIONS

7.1 Smarter Food Safety and Traceability

The FDA's "New Era of Smarter Food Safety" blueprint identifies Technology-based traceability, the ability to track a food product throughout the system from the manufacturing unit, transportation, and distribution, as a key problem to be solved to reduce the spread of food-borne illnesses [2, 6]. The winners of the FDA's low-cost or no-cost to the end-user traceability challenge highlight the interest and need for end-to-end digital record of food products [76]. As has been seen with outbreaks in fresh leafy greens and other foods over the past decade [77], anonymity and lack of traceability in the food systems hinder progress in efforts to identify contaminated foods. PACT fits in this architecture seamlessly by leveraging the simple and flexible query design on a Source and Reader that are implemented using general purpose transceivers that can be modified in real time. Moreover, the same Source and Reader can be used for digital tracing of different foods with no changes required in the system architecture. In a distribution center, the same Source can query "Is temperature below 40 F?" for food products to be refrigerated and "Is temperature below 0 F?" for those to be frozen [13, 35, 78]. With a simple change in the query, PACT can trace a vast variety of sensor Tags attached to packages. Since the Tags are battery less, its lifetime does not depend on the temperature, unlike BLE tags with limited battery life.

7.2 Remote Monitoring for Smart Storage and Transit

Temperature is one of the six factors that affect bacterial growth in food that could result in foodborne illnesses due to Potentially Hazardous Foods. Similarly, temperature monitoring is a crucial part of "cold chain", the supply chain of temperature-sensitive biotechnology and pharmaceutical products [79–82]. However, the specific temperature requirements depends on the product - food, vaccine, medicine. The World Health Organization estimates that about 50% of vaccines may be wasted gloablly every year due to temperature control, logistics, or shipment related issues[83]. According to UNICEF, $1.5 million worth of vaccines were lost in 5 months often due to difficulty in maintaining the cold chain supply [84]. A flexible query-based temperature monitoring system like PACT will be of great use in monitoring the temperature of each product without changing the infrastructure. The granularity of sensing can be varied by varying the number and specificity of questions. PACT can be integrated into existing data analytics infrastructure with the only requirement of attaching a PACT sensor Tag to the product of interest. It must be noted that although temperature monitoring is key in many applications, PACT can be modified to accommodate other sensors such as humidity without any change in Source and Reader.

7.3 Temperature Monitoring for Smart Buildings and Data Centers

Millions of dollars could be saved in energy costs using IoT-based predictive maintenance [85, 86]. However, the cost and infrastructure overheads of battery operated sensor tags and readers limit the wide deployment of temperature sensors [87]. Remote monitoring of buildings, Green House, and Datacenter [88, 89] poses a critical need in the age of green and sustainable engineering. Varying needs for temperature, air pressure, humidity among many other factors impacts the energy demands of these structures. Today's uniform one-size-fits-all solution is energy inefficient. However, IoT based monitoring solutions have not been adopted owing to their limitations on battery life and scalability. Use of scalable, long-range communication using batteryless tags in PACT will enable easier adoption of IoT for remote monitoring and energy efficiency for building and structures.

8 RELATED WORK

Commercial BLE: A majority of the current commercial solutions [9–14] utilize Bluetooth-Low-Energy (BLE) enabled real-time monitoring. However, the short life and bulkiness of batteries needed for BLE poses a challenge, particularly in cold storage units, and is not sustainable at scale.

Passive Backscatter communication: Battery-less communication using backscatter - inspired by passive RFID tags - has been proposed as a viable technology [16–21] to provide connectivity to low-power sensors. Backscatter tags have a small form-factor and are low cost, making them easily scalable. A backscatter tag offloads communication to a remote source/reader. Variants of backscatter transceivers have been proposed [20, 25, 28–30, 43] to improve their communication range. Majority of the existing approaches decouple the excitation source from the reader. We compared PACT with many of the recent works in section 6 and showed that we improve the communication range and the number of concurrent battery-less Tags that can be supported in a network.

Backscattering ambient wireless signals: Hitchhike [20] proposes backscattering commodity 80211.b WiFi packets, and conserves the tag energy by removing the oscillator at the tag. However, it increases latency when trying to reduce destructive interference. Also, it requires additional hardware to decode the backscattered packets. FM Backscatter [25] utilizes ambient FM signals that are in the order of -30dBm. However, the RF energy harvesting at such powers is extremely inefficient, making the charging time impractical for wearable sensors or monitoring applications. xSHIFT [19] offloads power hungry demodulation to the reader by modifying the excitation signal. However, its range is still limited by the dual path loss.

Energy harvesting circuit designs : Ambient RF harvesting from cellular and broadcast transmitters has been proposed [23, 90] but it requires the tags to be deployed outdoors and limits the application scope. Moreover, the charging time is in the order of a few seconds and the communication range is limited. MAC algorithms have been proposed to reduce wastage [24] but the practical challenges of designing the framework are not addressed. Battery and power management schemes [22] have been introduced to improve harvesting efficiency but the communication range is limited to a few meters. Finally, studies on energy consumption of sensor nodes [91] aim to create theoretical models which may provide insight to building smart cities. However, these do not address practical deployments or the problems of scalability. Also, efficient RFID tag designs [26] and rectennas (rectifying antennas) [27] have been proposed to maximize the energy harvesting range and efficiency. Low power preamble detection has been proposed in [20, 50–56, 92, 93] to reduce tag energy. To increase the range from more than 10s of meters, higher receiver sensitivity is desired on the tags. Advancements in energy harvesting is complementary to PACT and can be integrated to further improve its harvesting range.

ID Modulation in RFID: Alternative means of data modulation like interleaving repetition mechanism [94] and shorted/non-shorted tag states [95] aim to increase the decodability by reducing the error rates. However, they rely on backscatter for communication and not to increase the communication range of the tags.

Spread spectrum to improve range: PLoRa [30], LoRa Backscatter [28], LoRea [29] propose to leverage existing LoRa deployments to enable long-range backscatter and design power-efficient tags by introducing a third node. Existing approaches [96] are unable to solve the near-far problem as they both require the activation signal source to be in close proximity. Despite decoupling the excitation source and the Reader, the excitation signal suffers significant path loss depending on the distance between the excitation source and tag.

Asymmetric Communication protocols: Asymmetric communication protocols have been proposed to leverage the knowledge asymmetry in communication systems [97]. This work is inspired by the theoretical analysis on asymmetric communication that utilizes knowledge asymmetry to address resource asymmetry [97, 98]. To the best of our knowledge, this is the first step towards a practical deployment of asymmetric communication protocols in a wireless network.

9 LIMITATIONS AND FUTURE WORK

To the best of our knowledge, PACT is the first practical deployment of batteryless communication that eliminates dual-path loss and improves communication range without compromising harvesting range. Offloading computation to the Source and the Reader renders the Tag ultra-low-power and the active radio enables long range. We discuss here some of the limitations and potential future research directions of this work.

Throughput analysis: While the network throughput was studied in the context of number of queries and response throughput, overall throughput performance of PACT is not directly comparable to existing passive systems. It depends on the length of each Question and the minimum number of queries required, which are application-specific. A more rigorous analysis to calculate the network throughput and data rate will help in identifying more applications. The data rate of PACT link is expected to be lower than most comparable technologies.

ASIC implementation: The Tag design presented in this work is based on general-purpose COTS hardware. The range, energy efficiency, and the form factor of our prototype built using general-purpose hardware can be improved significantly if all the components were built into an ASIC. We notice the increase in harvesting range and decrease in Tag energy even with the use of low-power active radio. The power consumption and the form-factor of the ASIC Tag would decrease, improving the harvesting range further.

Large scale deployments: Our experimental evaluation was performed with less than 10 Tags, with outdoor deployments using battery operated Tags; due to the high cost of FPGA. Low-cost digital comparator implementations and real-world deployments of battery-less Tags will be useful to study PACT's longevity and reliability.

Wake up receiver: Improvements can be made in the design of the wake-up receiver and the matching circuit. Alternatives to a shift register such as buffered flops can reduce power consumption. A passive amplifier may be used to enhance the communication range within the energy budget.

Tag Response: The choice of the Tag response is hardware dependent. A rigorous analysis of various factors that have an impact on the response design such as the modulation type and bandwidth will further improve range.

Optimal query design Our current design assumes one query per session. Formal methods for identifying an optimum set of queries required to extract useful information are needed. Theoretical bounds on protocols for asymmetric communication have been studied in [97–99].

Integrating Energy Harvesting Sources: It is possible to harvest energy from other sources to charge the storage capacitor faster [100], often leveraging the applications. For example, solar cells or piezoelectric crystals could be incorporated to the RF energy harvesting unit on the Tag. Most on-body applications could take advantage of piezoelectric crystals to harvest usable energy [101], and outdoor applications could use solar cells similar to pLoRa [30], or polymer triboelectric nanogenerators that convert mechanical to electrical energy.

PACT Source design choice: Although any OTS radio connected to a power supply that can transmit an amplitude modulated signal can be used as a PACT Source, further study is needed for practical deployments. The harvesting range of the Tag is limited by the Source transmit power, antenna used, and its orientation. Periodically powering up the Tags to check their inventory would be needed to ensure all the Tags are functional. Similarly, further protocol design to handle Tags farther away from harvesting range is needed.

10 CONCLUSION

In this work, we proposed, designed, and prototyped PACT, a scalable communication algorithm that improves the communication range of battery less Tags. Our Tag design using active radio avoids the range limitation due to dual path loss in existing passive backscatter systems. Our energy harvesting circuit design along with ultra low power wake up receiver and demodulator reduces the energy consumption of the Tag. Our Q&A based communication paradigm where the Source queries the Tag with specific Question further simplifies the Tag design and hence its energy consumption. Our hybrid MAC protocol allows more than 500 Tags to communicate concurrently with the Reader. We identify three key applications in food safety, transportation, and storage where

PACT can be integrated. It can offer low-cost or no-cost monitoring and tracking options for these large-scale deployments over a long time, making PACT scalable and sustainable.

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