

Capturing and recording cold chain temperature violations through parametric alarm-sensor tags

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ABSTRACT

While the Internet-of-Things has already fueled a plethora of different possibilities, we are still in need of means to mitigate the inefficiencies of the cold chain generating every year massive food and drug waste, even causing serious illnesses. This is caused by the lack of remote sensing technologies suitable for a widespread deployment able to timely mark any cooled items exposed to inadequate temperatures. This work introduces a class of printable, battery-less, and chip-less passive tags, namely, the Parametric Alarm Sensor Tags (PASTs), allowing detection of any violations in the storage temperature of refrigerated items with extraordinary reading ranges. In order to do so, PASTs leverage a three-way sensing scheme and nonlinear dynamics never explored in any tag technologies to trigger the passive generation of a radio frequency signal only when the temperature exceeds a remotely configurable threshold (T_{th}). Furthermore, PASTs exhibit a dynamically enabled temperature-controlled hysteresis loop. As a result, the signal generated at the occurrence of a temperature violation remains active even if the temperature returns within a tolerable range. This allows us to flag any items previously or currently exposed to inadequate temperatures, allowing their prompt identification. We report a 870 MHz PAST and show that, thanks to its unique characteristics, it is finally possible to identify any items along the cold chain whose temperature has exceeded a remotely configurable T_{th} value as low as -47°C , even if operating in uncontrolled electromagnetic environments and up to 46 m away from the corresponding PAST outside a line-of-sight.

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In the last decades, the Internet-of-Things (IoT) has generated a variety of opportunities to overcome some of the most impactful technological challenges of our time. In particular, driven by the Radio Frequency Identification (RFID) revolution,^{1–5} a large number of electromagnetic (EM) wireless tags are now commercially available to meet the sensing needs of a broad range of applications, such as structural health monitoring⁶ and environmental surveying.⁷ Nevertheless, due to the limits of the currently available technologies, especially under harsh environmental conditions,⁸ there is a void of wireless sensing components providing the necessary means to tackle other fast-growing challenges with a tremendous societal impact. Among these challenges is finding effective ways to boost the efficiency of the cold chain responsible for the preservation and transportation of foods and drugs. In this regard, previous studies^{9–11} have shown that any failures in keeping perishable foods within highly specific tolerable temperature ranges severely threaten the safety of individuals due to the resulting accelerated growth of pathogens and of other spoilage micro-organisms. It is estimated that every year the inability to identify food products exposed to temperature irregularities costs more than \$50 billion just in the United States, even causing more than 120 000

hospitalizations and 3000 deaths.¹² Also, due to the lack of components able to quickly identify any items undergoing a temperature violation, it is appraised that almost 40% of the food produced for human consumption in the world has to be disposed.^{9,13}

Several EM-based wireless temperature monitoring technologies based on active, semi-passive, or passive tags have been previously reported.^{14–18} The active ones are equipped with an on-board battery used to supply energy to both a temperature sensor and an on-chip memory. This latter component allows us to record the outcomes of the executed temperature measurements, thus providing the means to assess whether any temperature violations have occurred. While offering a wide range of functionalities, battery-powered tags are not suitable for a widespread deployment due to their significant manufacturing costs and, because of the unbearable environmental challenges, they inevitably create when disposing their dead batteries in landfills.¹⁹ In addition, since the capacity of any available battery technology dramatically reduces as the operational temperature is decreased,¹ using active tags under frozen ($\leq -10^{\circ}\text{C}$ but higher than -20°C) or deep-frozen ($\leq -20^{\circ}\text{C}$) temperatures⁹ does not represent a technically viable option.

Many semi-passive tags for remote temperature monitoring have also been reported. When targeting the highest possible reading range without any on-chip resonant components built on expensive substrates,^{18,20–22} these include an antenna, a temperature-sensitive element or a sensor, and an energy harvesting circuit.²³ This circuit scavenges energy from the environment and uses it to modulate the backscattered portion of the interrogating signal coming from their complementary reader in manners that strongly depend on the measured temperature. Nevertheless, the capability of any interrogating nodes to reliably extract useful information from a backscattered signal significantly drops as the distance from the tag to ping is increased, limiting the sensing ranges to just few meters. Furthermore, the detection rate achievable by the existing passive tags is severely affected by the inability of the currently available harvesting circuits to exhibit acceptable efficiencies when receiving power levels significantly lower than 1 mW.²⁴ Ultimately, most semi-passive tags for temperature monitoring require on-chip nonvolatile memories (NVMs),^{25–27} such as electrically erasable programmable read-only memory (EEPROMs)²⁸ in order to record any temperature violations. Unfortunately, chip-scale NVMs require programming voltages that are too high, leading to unsustainable power levels²⁹ causing large reductions in the reading range of any tags using them. Consequently, significant attention has been recently paid to passive tags, embodying specific low-cost devices or materials^{15,30–35} to permanently change the strength of the

backscattered signal when a fixed temperature threshold (T_{th}) is exceeded. Yet, due to the limited sensitivity exhibited by such explored devices and materials, none of these tags has allowed to achieve a reading range exceeding 3 m. Furthermore, all these tags exhibit fixed and nonresettable T_{th} values barely lower than 0 °C, thus being able to monitor just a subset of items along the cold chain.

Just recently, a unique class passive tags was developed, namely, the Subharmonic Tags (SubHTs³⁶). SubHTs exploit the unique dynamical features of parametric circuits to enable the remote sensing of any parameters-of-interest (PoI) with an extraordinarily high sensitivity. Also, when interrogated by complementary readers, they allow to transmit the sensed information through a passively generated output signal whose frequency is half of the interrogating one. This operational characteristic permits to achieve exceptional sensing ranges by allowing to strongly attenuate any high-power disturbing signals originating from the interrogator, which would otherwise severely limit the maximum reading range as for the conventional semi-passive and passive tags.

In this article, by leveraging parametric nonlinearities as in SubHTs, we introduce a Parametric Alarm Sensor Tag (PAST) for temperature-monitoring, allowing to detect any specific violations of the storage temperature affecting perishable foods or drugs in the cold chain with exceptionally long reading ranges [Fig. 1(a)]. This can be done while relying on off-the-shelf lumped components assembled on

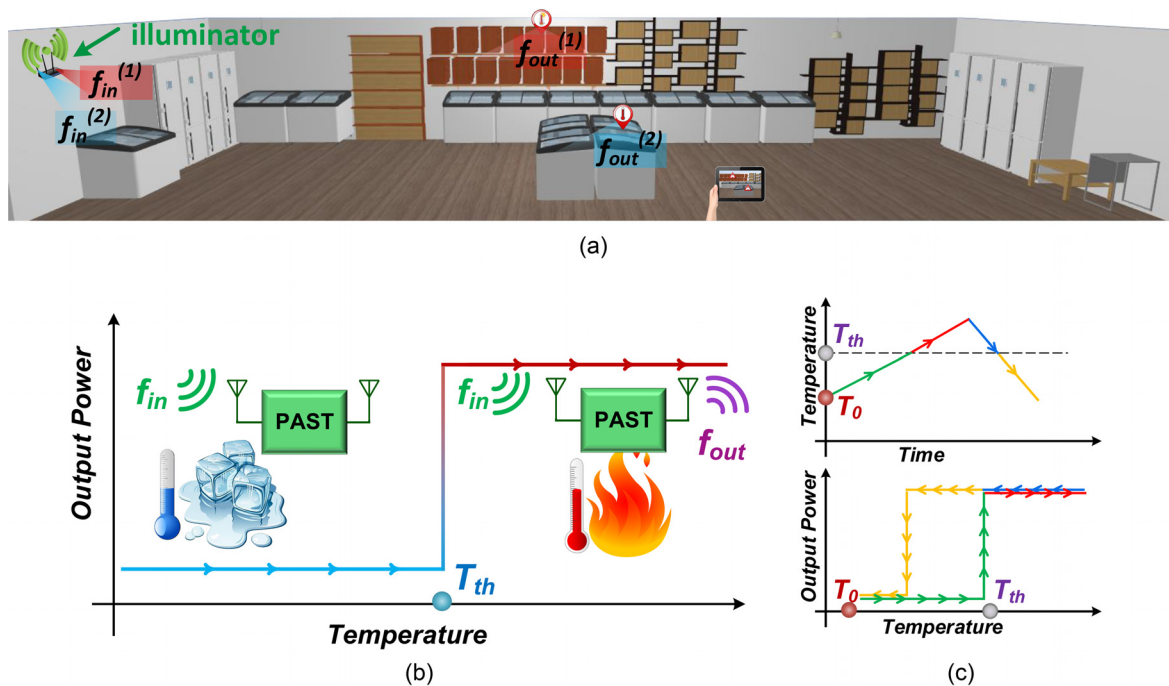


FIG. 1. The envisioned use of PASTs in a cold chain facility. (a) A tethered co-site electromagnetic node (the illuminator) radiates a pool of continuous-wave (CW) signals with dedicated frequencies ($f_{in}^{(1)}$, $f_{in}^{(2)}$, etc.) for each monitored stored item or group of items. All the monitored elements are envisioned to be carrying dedicated PASTs. (b) When the temperature of an individually monitored item exceeds its specific maximum allowed value, T_{th} , the corresponding PAST starts radiating output power at a subharmonic (f_{out}) of its received signal, acting as an alarm for any readers. (c) Example trend of the PAST's output power when exposed to an arbitrarily chosen time-variant temperature profile, showing a dynamically triggered temperature-controlled hysteresis loop that is leveraged by PASTs to implement a memory functionality. Evidently, as the temperature increases from a generic initial value (T_0), PASTs do not radiate any output power at f_{out} until the temperature reaches T_{th} and a subcritical bifurcation triggers the generation of the subharmonic signal. After the activation of such frequency generation process, further temperature increases do not impact the presence of the divided output signal. Also, PASTs remain able to sustain the generation of their frequency divided output signal even when the temperature reduces by several degrees after reaching T_{th} .

printed substrates and on a three-way sensing architecture. In particular, by leveraging some nonlinear dynamics never explored in any tag technologies, the reported PAST relies on the nonrectified energy of a received ultralow power RF signal with frequency (f_{in}), generated by a tethered co-site omnidirectional radiator used and labeled as illuminator [Fig. 1(a)], to trigger a strong output signal at a frequency (f_{out}) equal to $f_{in}/2$ only when the temperature at the tag's location exceeds a threshold value (T_{th}) that can be significantly lower than 0°C [Fig. 1(b)]. This feature allows any portable low power readers to be able to assess whether or not a temperature violation has occurred by simply monitoring the power received at f_{out} , if any. Also, since such readers do not need to transmit any interrogating signals and they can remain in stand-by until awakened by the output signal of a reachable PAST, they can exhibit much longer battery lifetimes, not affected by the high power they typically consume when transmitting any interrogating signals. Furthermore, as PAST leverages an operation in the proximity of a subcritical bifurcation, we show that its dynamics inherently show ranges of bi-stability, where the fixed operating points relative to both the trivial and the period-doubling solutions are simultaneously stable. This causes the existence of a temperature-controlled hysteresis loop in the presence of any temperature gradients around T_{th} [Fig. 1(c)]. Due to such a dynamical signature and despite the fact that only conventional passive components are utilized without memory devices, the output signal generated in the occurrence of a temperature violation event remains active even if the temperature returns to a tolerable value. This permits to flag any items in the cold chain exposed to inadequate temperatures, allowing their prompt identification and, when strictly needed, their disposal. Excitingly, we also show that by strategically selecting different f_{in} values, any PAST can exhibit remotely reconfigurable T_{th} values ranging from -47°C to 19°C , thus providing fundamental means to reliably monitor any items in the cold chain at chilled, frozen, and deep-frozen temperatures. It is important to emphasize that the ability to tune T_{th} by varying f_{in} is granted by the fact that the stability of large signal periodic regimes³⁷ in varactor-based circuits depends on the impedances seen by the adopted varactor at f_{in} (Z_{in}). Due to the presence of a thermistor in its network, the Z_{in} value of any PASTs becomes the function of temperature, activating all the PASTs' temperature-driven dynamics reported here.

A PAST device for temperature monitoring (Fig. 2) can be described as a passive two-port electrical network built on a printable substrate, formed by an un-biased diode and a set of lumped electrical passive components, including an analog temperature sensor. The two ports are connected to properly sized antennas, which can have arbitrarily selected technology (wired, planar, etc.) based on specific system-level requirements, and whose bandwidths are centered around f_{in} and f_{out} , respectively. For fixed values of f_{in} and of the power (P_{in}) received from the illuminator and depending on the temperature (T_a) varying the electrical impedance of the sensor, PASTs can exhibit operational regions where an internal 2:1 subharmonic oscillation is active,^{38–40} initiating a passive conversion process of P_{in} into radiated power (P_{out}) at f_{out} . This period-doubling mechanism occurs following a bifurcative change in the PASTs' electrical behavior, marking a transition from nondividing to dividing operational regions. However, differently from SubHTs, which exploit the unique dynamical characteristics exhibited in the proximity of a super-critical bifurcation to achieve a boosted temperature sensitivity and an intensity-level

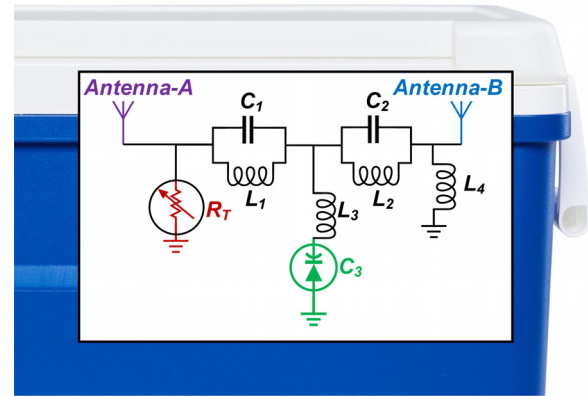


FIG. 2. Circuit schematic of the realized PAST, including a thermistor, a solid-state varactor used as the parametric element, and a set of lumped components.

sensing functionality, the parametric frequency generation in any PASTs is triggered following a subcritical bifurcation.⁴¹ Therefore, as the PASTs' temperature exceeds a certain threshold (i.e., T_{th}) that can be remotely selected by varying f_{in} , they instinctually switch from a non-dividing operational regime to a dividing one, characterized by a large P_{out} value. These features provide the means to correlate the occurrence of any events in which T_a has exceeded T_{th} with the existence of a wireless signal at f_{out} , effectively acting as an alarm for any dedicated readers [see Fig. 1(b)]. Furthermore, due to the large parametrically enabled conversion efficiency from f_{in} to f_{out} ,³⁶ PASTs can produce large P_{out} values even from low P_{in} ones (<-10 dBm), allowing any readers to reliably assess from a record-high distance whether or not a temperature violation has occurred, even when operating in uncontrolled electromagnetic environments. Ultimately, by leveraging a temperature-controlled hysteresis behavior originated from the operation at an f_{in} value corresponding to a subcritical bifurcation, the period-doubling mechanism responsible for the generation of P_{out} in PASTs remains active even if the sensed temperature returns to the tolerable range [see Fig. 1(c)]. As a result, even though no NVMs or other advanced materials and devices are used, PASTs can address the key functionality of a temperature-controlled nonvolatile memory, permitting to identify any items in the cold chain exposed to inadequate temperatures even when such temperature violations occurred while no reader was operative. Yet, the operation of PASTs can be reset to their original nondividing state at any time by temporarily interrupting the transmission of power from the illuminator. All these unique characteristics allow us to indefinitely re-use any fabricated PASTs to monitor heterogeneous items kept at extremely different storage temperatures, covering the vast majority of the products processed and distributed along the cold chain. In order to experimentally demonstrate the unique performance features of PASTs, we built a prototype (see Fig. 2) on a printed circuit board (PCB) made of FR-4, operating at $f_{in} \sim 870$ MHz and relying on two commercial antennas with bandwidths, respectively, centered around 870 MHz (i.e., "Antenna-A") and 435 MHz (i.e., "Antenna-B"), a set of off-the-shelf lumped components [four inductors (L_1 , L_2 , L_3 , and L_4), two capacitors (C_1 and C_2)], and a commercial off-the-shelf thermistor (see [supplementary material](#) Table 1 for the model numbers of all components). The lumped components were selected *ad hoc*, following the

design methodology discussed in our recent theoretical investigation on the stability of diode-based parametric circuits,³⁷ in order to minimize the minimum received power level (P_{th}) at which a frequency division can be triggered. By doing so, in fact, the reading range at f_{out} can be greatly extended and the longest distance (d) between the illuminator and any one of its illuminated tags can be used. This allows us to increase the number of PASTs and consequently the number of items that an illuminator can simultaneously reach in practical operational scenarios. First, we characterized the P_{out} vs the T_a characteristic of the built PAST placed in a digitally controlled temperature chamber. The characterization was performed through a wired experiment after connecting the PAST's input and output ports to two synchronized network analyzers, respectively, acting as a generator at f_{in} and as a power meter at f_{out} . We report in Fig. 3(a) the measured P_{out} vs T_a for a fixed P_{in} (−11 dBm) and for a set of f_{in} values giving radically different T_{th} values, ranging from −47 °C to 19 °C. From Fig. 3(a), it is evident how the built PAST undergoes sudden changes in its output power as the temperature surpasses specific T_{th} values set by f_{in} . In particular, the measured trend of T_{th} vs f_{in} is reported in Fig. 3(b) for a P_{in} value of −11 dBm, further proving that the frequency division mechanism encoding the occurrence of a temperature violation event can be triggered over a wide range of T_{th} values by remotely controlling the value of f_{in} . In order to demonstrate the existence of a parametrically induced temperature-controlled hysteresis behavior across the same range of T_{th} values found in Fig. 3(b), we studied P_{out} while sequentially selecting f_{in} to set T_{th} to three different values (−45 °C, −25 °C, and 4 °C), representative of the majority of the storage temperatures at which any perishables foods or drugs are preserved along the cold chain. For each driving condition, we applied a temperature sweep from −70 °C to 25 °C, followed by a backward sweep bringing the temperature back to −70 °C. As evident from Fig. 3(c), a hysteresis loop was found for each explored f_{in} value, proving that the unique system dynamics explored by PASTs can serve as a powerful tool to reconstruct the equivalent functionality of a one-bit temperature-controlled nonvolatile memory, even though the PAST's circuit only includes conventional and printable components without memory devices. Furthermore, for each targeted T_{th} , we found an achievable hysteresis width higher than 20 °C, ensuring that the signal generated

at the occurrence of a temperature violation event is sustained even if the temperature returns to the tolerable range or if the PAST is affected by small temperature fluctuations, such as the ones typically occurring during the transportation or the delivery of refrigerated items. It is worth emphasizing that the achievement of such significant hysteresis widths reduces the chances of missing any temperature violations even when readers relying on extremely low duty-cycles⁴² are used. It is important to point out that, due to its nonlinear behavior, the built PAST also shows a hysteresis loop vs P_{in} with a width equal to 1 dB and set by its PAST's lumped components (Fig. S5). Then, we proceeded with the PAST's wireless characterization after connecting its input and output ports to Antenna-A and to Antenna-B. We used a signal generator configured to transmit a total power of 26 dBm as illuminator. Also, we used a spectrum analyzer as a wireless power meter to verify that a long-distance detection of any temperature violations was indeed possible, even when operating in an uncontrolled electromagnetic environment. In order to do so, the spectrum analyzer was moved across the fourth floor of the Interdisciplinary Science & Engineering Complex (ISEC) at Northeastern University [Fig. 4(a)]. Meanwhile, we tuned f_{in} to set T_{th} to −25 °C by properly configuring the output frequency of the signal generator [see Fig. 3(b)]. During this wireless characterization, the dynamical changes triggered by the PAST's temperature exceeding T_{th} were detected at many locations [see the floor-map shown in Fig. 4(b)]. This permitted to demonstrate the capability enabled by PASTs of achieving extraordinarily high detection ranges, approaching 46 m not in a line-of-sight. Also, after placing the reader at one of the investigated locations and after running the same temperature cycle executed during our wired characterization [Fig. 3(c)] multiple times, the PAST responded very similarly to the occurrence of all the scheduled temperature violations, showing T_{th} values in close agreement with the targeted value [i.e., −25 °C, see Fig. 4(c)] for all the executed runs, and not significantly affected by the random changes that inevitably occur in any uncontrolled electromagnetic environments.

We have introduced the Parametric Alarm Sensor Tag (PAST), a printable, battery-less, and chip-less tag for temperature monitoring of refrigerated items. Through the reported PAST, we were able to remotely detect temperature violations triggered at −25 °C from a record-high distance of 46 m, not in a line-of-sight.

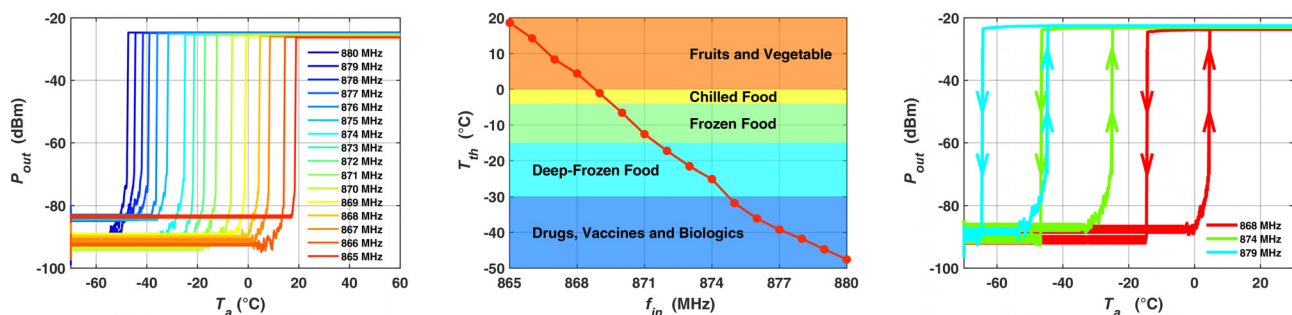


FIG. 3. Temperature threshold characterization of the built PAST. (a) Measured trend of P_{out} vs T_a of the built PAST for different f_{in} values, ranging from 865 to 880 MHz with steps of 1 MHz and the same P_{in} (−11 dBm). (b) Measured trend of T_{th} vs f_{in} for the same P_{in} considered in (a), showing that by simply tuning the output frequency of the illuminator the same PAST can be configured to exhibit T_{th} values included in the ranges of storage temperatures for the majority of the foods and medical products currently transported along the cold chain. (c) Measured P_{out} vs T_a for the same P_{in} value considered in (a) and when using the specific f_{in} values allowing to achieve T_{th} s of −45 °C (in blue), −25 °C (in green), and 4 °C (in red). During this experiment, the built PAST was subject to a temperature forward sweep from −70 °C to 25 °C, followed by a backward sweep from 25 °C to −70 °C. Evidently, the PAST's parametric dynamics allow the generation of temperature-controlled hysteresis loops that the PAST can leverage to capture and memorize the occurrence of temperature violation events.

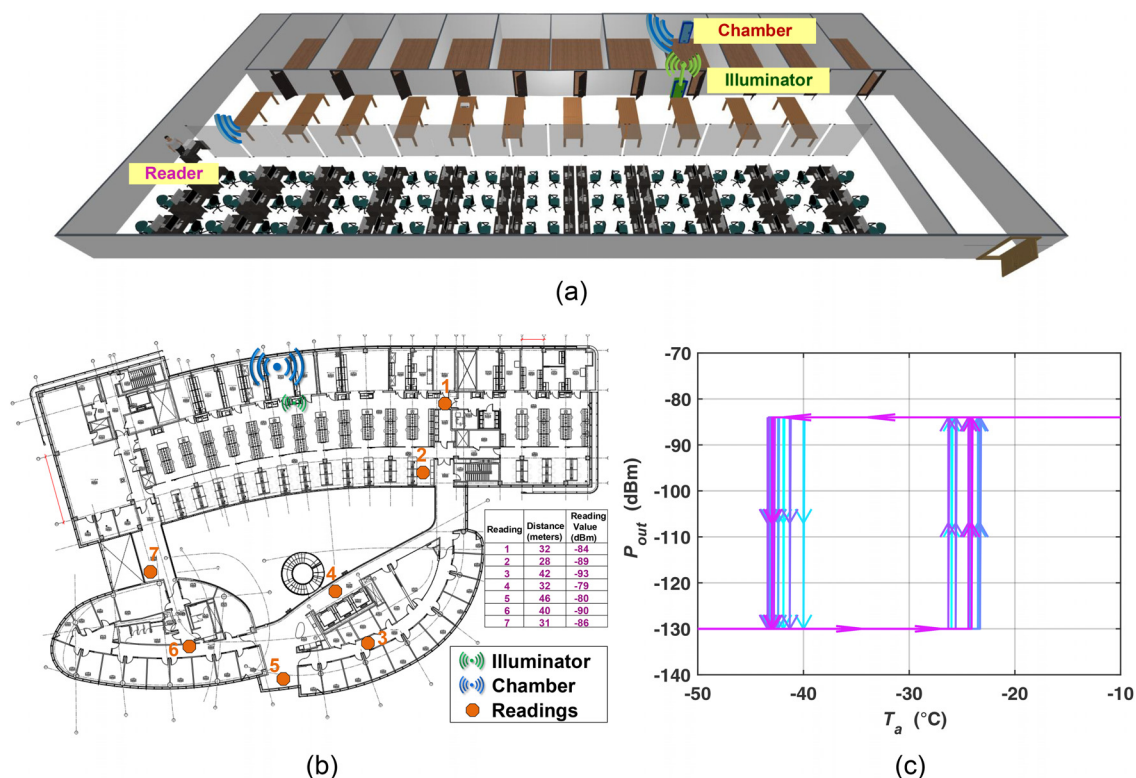


FIG. 4. Wireless characterization of the built PAST. (a) Schematic view of the setup used during the wireless characterization of the PAST. The illuminator was placed in a laboratory space housing a digitally controlled temperature chamber. The illuminator was placed at a distance from the chamber of 4 m, limited by the area of the laboratory space housing the chamber. Simultaneously, a spectrum analyzer used as a reader was moved at multiple distant locations. (b) Map of the ISEC floor where our PAST's wireless characterization took place, showing the positions of the chamber and of the illuminator, along with all the locations (orange dots) of our reader's measurements. A table summarizing the distance between the chamber and all the considered testing locations is also shown, along with the corresponding measured P_{out} values for T_a right above T_{th} . (c) Measured P_{out} vs T_a at the location marked as "1" in (b), when exposing the PAST to nine consecutive temperature cycles (each lasting 50 min) to verify that a reliable and repeatable wireless response is always attained, despite the operation in an uncontrolled electromagnetic environment.

The findings discussed in this article and the future identification of the most effective illuminators' and readers' architectures, based on the specific items to monitor and in lines with any rules and practices to be followed, pave a unique way to mitigate the inefficiencies of the cold chain.

See the [supplementary material](#) for figures of the fabricated circuit, the experimental setup and device characterization, and the details about the design flow of the circuit.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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