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Cost-Effective Wireless Sensors for Detection of Package Opening and Tampering

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ABSTRACT There is a need to develop a simple cost-effective approach for wireless detection of whether package is or was open en route during transportation. Existing approaches rely on electronic devices that need sensors with on-board and continuous power source for sensing and data logging. This paper presents three different battery-free, cost-effective, Radio-Frequency Identification (RFID)-based solutions for the detection of tampering or package opening. The first solution is for real-time opening detection. Opening or closing the package leads to unfolding or folding of the flexible -based antenna, which activates or deactivates the RFID tag. The second solution is for recording and memorizing package opening using a printed switch that shunts the antenna of the RFID tag. Opening causes a permanent disconnection of this switch activating the RFID. This change is irreversible; thus, the sensor memorizes the specific opening event without any additional electronic memory device. The third solution is for all-around package security using an RFID-based thread. Opening the package from any side allows changes in the radiation profile so the package condition can be wirelessly sensed. The approaches have been simulated and validated experimentally.

INDEX TERMS Battery-free, blockchain, flexible antenna, flexible electronics, intelligent package, package monitoring, RFID, security, smart package, smart threads, zero power sensors.

I. INTRODUCTION

With the rise of electronic commerce, there is a need to wirelessly monitor the package status along the entire supply chain from production, distribution, storage to point of use. Opening the packages improperly could have a detrimental effect on goods with fragile, perishable, and sensitive properties. The opened packages need to be quickly identified and processed. In these cases, sensors that can monitor the condition of the packages without any manual presence are essential. A simple and economical device that can be affixed directly to the package to wirelessly detect and record the package condition will enable supply chain visibility to many security-sensitive products.

Existing approaches depend on the complex hardware to realize package condition monitoring, which needs custom sensors connected to a continuous power source to detect the condition of packages in real-time. For example, a conductive pattern as a sensing resistor is printed through the seam line of the package [1]. The resistance across this sensing resistor changes when the package is open. An analog-to-digital converter (ADC) detects the voltage drop across this resistor, and this information is processed by Radio-Frequency Identification (RFID) tag. An RFID reader can remotely read the package condition. Although the RFID tag of the package condition monitoring sensor itself is battery-free, it requires additional circuitry to read the impedance information which necessitates a dedicated battery. Piezoelectric polyvinylidene fluoride (PVDF) film has the property of generating an electric charge in response to applied mechanical stress. It has been embedded into a tear-off patch type sensor placed on the opening edge of the package [2]. Opening the package leads to the mechanical stress on the film to generate a voltage pulse, which is sensed and converted to a radio frequency signal by a readout circuit module. The PVDF film, readout circuit, and battery are cost-prohibitive for securing a larger number of packages. Another common solution to detect if the package has been opened is to sense the lighting condition inside the package [3]. The platform consists of an infrared LED and a photodiode detector sensor inside the package.

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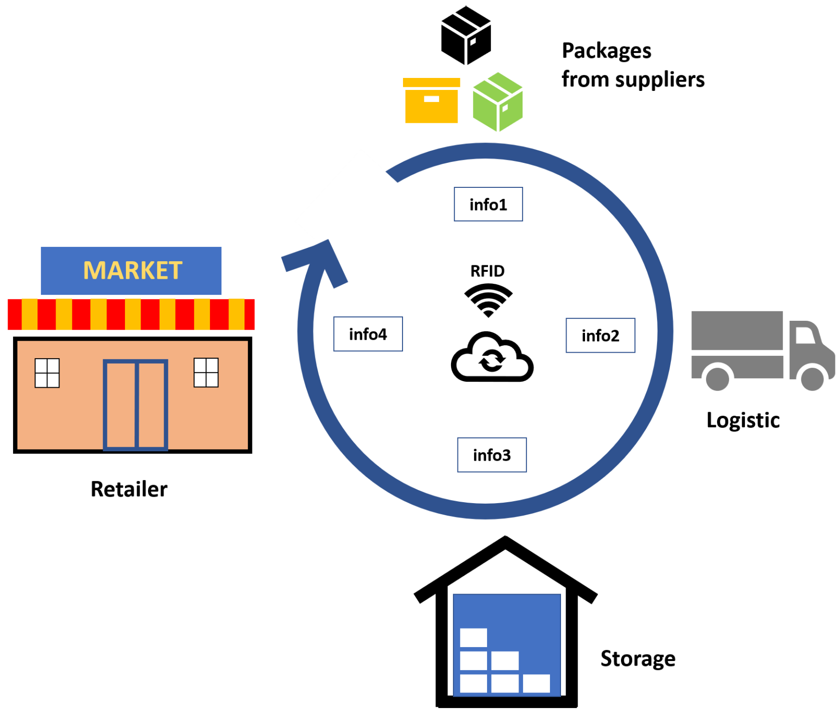


FIGURE 1. RFID tag in blockchain applications.

The photodiode detects the intensity of light reflected from the LED. If the cover is removed, the light intensity received by the photodiode would drop below a certain threshold, which would indicate the package is open. The use of photodetector and the infrared LED makes the sensor platform more expensive. Another solution for monitoring the condition of the package is to extract the unique features from the backscatter signals penetrating the internal space of the package and comparing them to the previously collected features during the check-in phase; this requires complex data analysis and machine learning to extract the information [4]. These solutions are also cost-prohibitive. The cost-effectiveness and simplicity of our solution leveraging existing RFID tags, which are already used in product tracking make our solutions more attractive for large scale package condition monitoring [5].

RFID tag is widely used for tracking and identification of packages. A passive RFID tag, consisting of a small low-profile antenna and an RFID chip, receives energy from the nearby RFID reader and it responds by sending its unique ID information back to the reader. There has been a growing trend to leverage the low-cost, lightweight of RFID tags for various sensing applications in addition to its conventional role of identification and tracking, for example, temperature sensing [6]–[9], light sensing [10]–[12], tilt sensing [9], [13], [14], strain sensing [15]–[17], humid sensing [18], [19], chemical sensing [20]–[22], screw relaxing detection [23], flooding warning [24], current sensing [25], crack monitoring [26], biophysical sensing [27]–[31], aerial vehicles application [32], drowsy driving detection [33] and RF pen [34]. To guarantee the low-cost of the whole sensor platform that bulit on the RFID tag, that sensor should be compact, and the whole circuitry should operate without a battery.

In this paper, we present three different battery-free, cost-effective, Radio-Frequency Identification (RFID)-based solutions for the detection of tampering or package opening. The first solution is for real-time opening detection. Opening or closing the package leads to unfolding or folding of the flexible thread-based antenna, which activates or deactivates the RFID tag. The second solution is for recording and memorizing package opening using a printed switch that shunts the antenna of the RFID tag. Opening causes a permanent disconnection of this switch activating the RFID. This change is irreversible; thus, the sensor memorizes the specific opening event without any additional electronic memory device. The third solution is for all-around package security using an RFID-based thread. Opening the package from any side allows changes the radiation profile and so the package condition can be wirelessly sensed. The approaches have been simulated and validated experimentally. For all the three solutions, the package status can be detected remotely by sensing the radiation changes of the RFID tag affixed on the package. Integration of the RFID technology with flexible electronics, such as smart threads, and paper-based switch, it provides a low-cost and compact solution for package

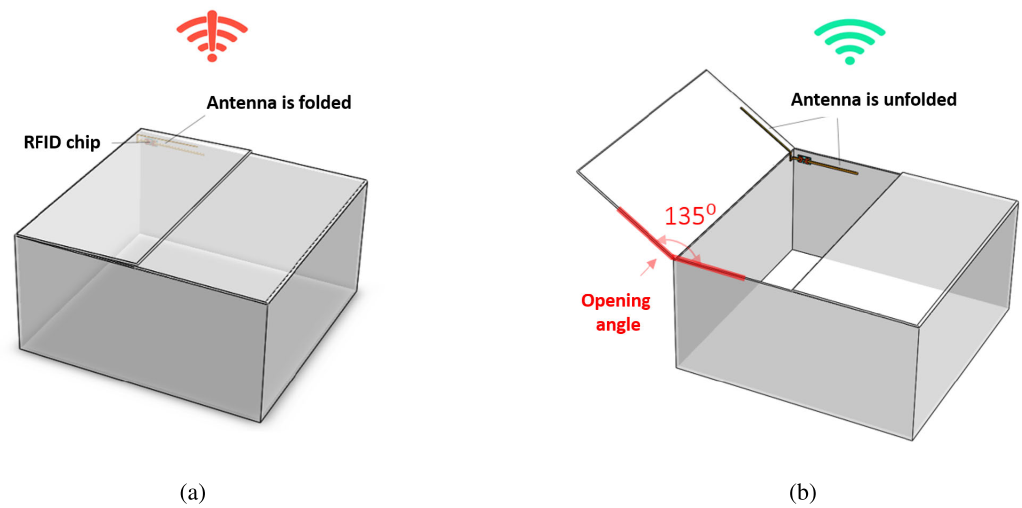


FIGURE 2. Real-time opening detection sensor using a foldable antenna: (a) The two arms of the antenna are folded into parallel line shape when the package is closed. (b) The two arms of the antenna are unfolded when the package is open.

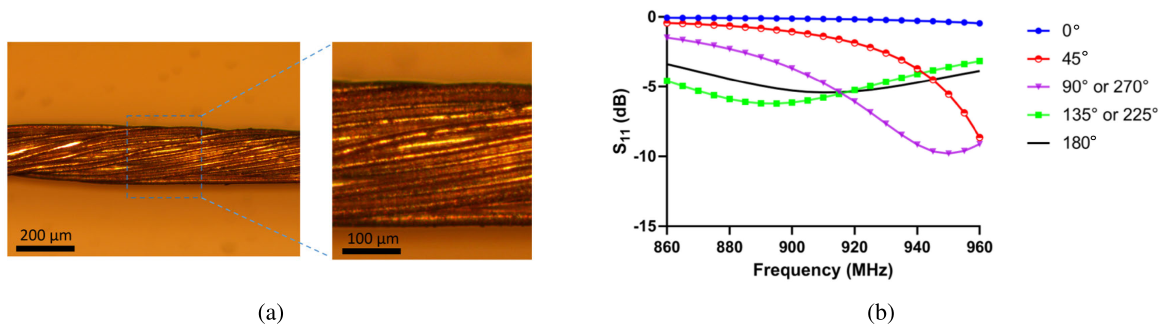


FIGURE 3. (a) The conductive tread used as the antenna. (b) S_{11} parameter of the antenna on different opening angles.

security monitory. These applications can be combined with the blockchain technology to enhance the supply chain transparency as in Figure 1.

II. REAL-TIME OPENING DETECTION BASED ON FOLDABLE RFID TAG

A. WORKING PRINCIPLE

The real-time opening detection sensor is the RFID tag itself, which composes of an RFID chip and a flexible foldable dipole antenna. Instead of using a specific sensor for sensing the opening event, the antenna of the RFID tag is used as the opening detection sensor. The two arms of the dipole antenna are affixed at the inner side of the top left surface and the back surface of the package, respectively, as shown in Figure 2 (a). The RFID chip is placed between the two arms. When the package is closed, the two arms of the antenna are placed in a parallel configuration, which counteracts the radiation. When the package is open as shown in Figure 2 (b), this unfolds the two arms of the antenna to enable far-field radiation. An RFID reader can remotely sense the presence of the tag only when the package is opened, while it fails to communicate with the closed package. The opening detection function and wireless communication capability are integrated into the antenna. There is no other electronic component required, nor is there a need for a dedicated battery inside the package to support the opening detection function. This results in a very low-cost solution for real-time monitoring of the status of the packages.

B. FOLDABLE ANTENNA DESIGN

Thread has been recently used as strain sensors [35], [36], colorimetric gas sensor [37] and antenna [38]–[42] for wearable applications due to its pliability. In this application, the dipole antenna is built with a conductive pliable thread [42], which is made of a polymer inner layer surrounded by a metal outer layer. The inner polymer yarn has a high tension, which makes it flexible. The resistance of the thread is around 0.3 Ω/cm and the diameter of the thread is around 200 μm as shown in Figure 3 (a). The length of each arm is 8 cm. The pliable property of the thread is suitable to realize

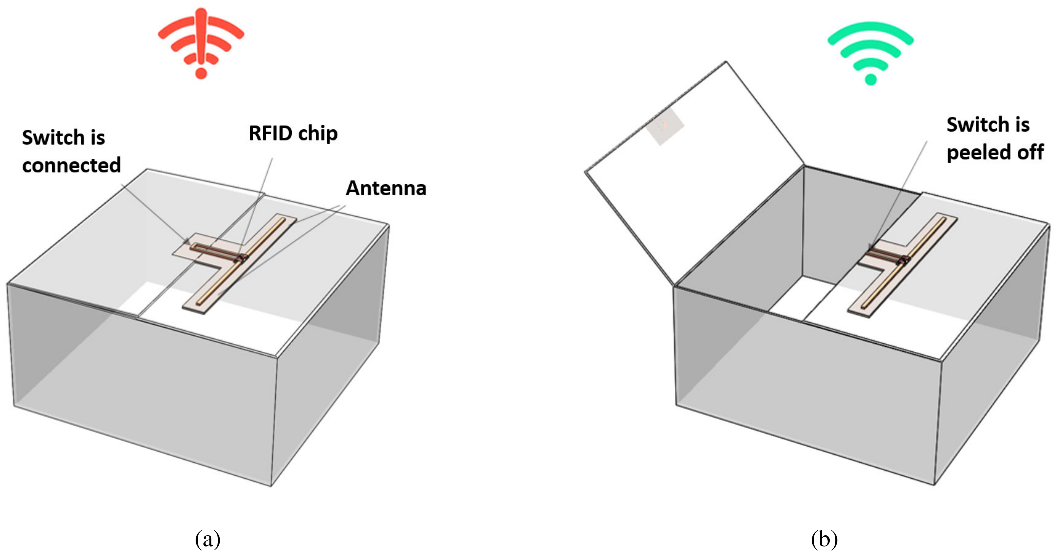


FIGURE 4. The RFID is in inactive mode by shorting the two arms of the antenna. (b) The RFID tag is active by peeled off the connection.

a foldable antenna. The half-wavelength dipole antenna has the input impedance of the 73 + j·47. RFID chip Murata MAGICSTRAP was chosen with the input impedance of 25−j·45 at 915MHz which matched the imaginary part of the dipole antenna.

The two arms of the dipole antenna are positioned 180° horizontally to maximize the radiation in conventional use. For package opening detection, however, the opening angles may be different with each opening. The opening angle is the angle formed by the top flap with respect to the horizontal level as in Figure 2 (b), which presents a 135° opening angle. This is the same as the angle formed by the two arms of the antenna. This requires the dipole antenna to work under different opening angles. Figure 3 (b) shows the simulated radiation coefficient S_{11} of the antenna opening with the angle at 45°, 90°, 135°, 180°, 225°, and 270° within the UHF band, respectively. Although the resonant frequency varies slightly from different angles, the RFID reader and tag have enough sensitivity in the UHF RFID band 860MHz-960MHz. It also indicates that the RFID tag can detect openings as small as 45° till 270°. When the package is closed, the two arms of the antenna are folded in parallel with the opening angle of 0°. The simulated S_{11} is close to 0 crossing the whole UHF band so that the antenna does not radiate. In essence, the opening condition of the package is known by whether the RFID reader can successfully communicate with the RFID tag or not. The flexible antenna couples with the RFID chip provide both the opening detection sensing and the wireless communication capability While this platform provides real-time monitoring of opening. There is no memory of the associated opening event within the package. If the package is opened and then closed in the absence of the RFID reader, there is no way of knowing this activity. Other approaches discussed below provide an inherent memory of the event.

III. OPENING RECORDING SENSOR BASED ON PAPER-BASED RFID TAG

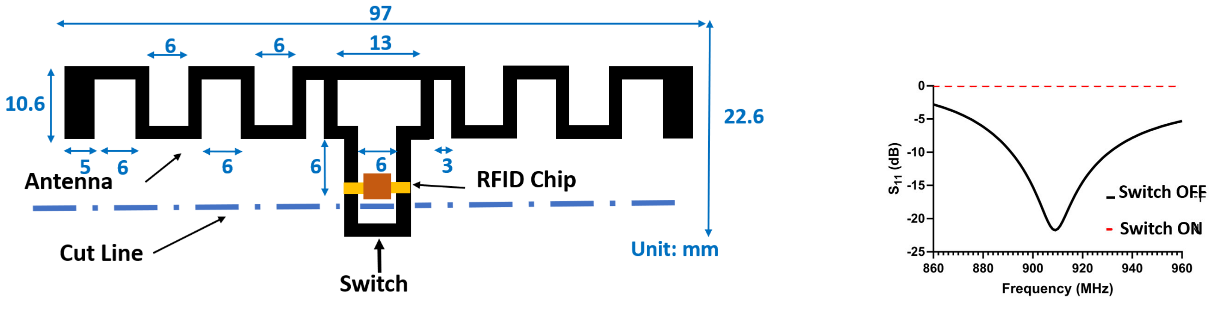
A. WORKING PRINCIPLE

Conventional sensors will need a memory device to record any history event. This will require memory and controller powered by a battery to assist its operation. Alternatively, rather than using electronic memory, using physical and chemical sources for memory can offer a battery-free solution. For example, liquid metal [9], RFID threads [42], shape memory polymer [43], and MEMS photoswitch [44] have been used to record past interest events as a permanent change in their physiochemical property. In this paper, an opening recording sensor is built by an RFID tag and a printed switch on a paper substrate as in Figure 4. The switch initially connects the two input nodes of the RFID chip and shorts the two terminals of the antenna, making the RFID tag unable to communicate since the switch shunts the antenna.

A cut line is made between the RFID tag and the printed switch. The sensor is placed on the inside lining of the package surface in a position where the cut line of the sensor is aligned with the edges of the two top flaps of the package as in Figure 4 (a). The opening event leads to the tearing of the paper and results in a disconnection between the printed switch and the RFID tag in Figure 4 (b). This will activate the RFID tag making it visible so it can be read by the external reader. This disconnection is irreversible, and reclosing of the package does not reconnect the switch and thus the event is memorized. An RFID reader at the destination can detect whether the package was opened en route by sensing the presence of the RFID tag.

B. ANTENNA DESIGN

Different materials, such as copper [45], silver [46], [47], graphene [48], and aluminum [49], [50] can be used for



(a) (b)

FIGURE 5. The dimensions of the opening event recording sensor. (b) Reflection coefficient of the antenna with the package being opened or not.

antenna fabrication. The antenna for this sensor is made using screen printing of silver ink on a regular low-cost paper substrate [9]. The antenna pattern is designed with ANSYS HFSS and the dimensions are shown in Figure 5 (a). The simulated reflection parameter S_{11} is shown in Figure 5 (b). When the package is intact and the printed switch shorts the two input nodes of the RFID chip, S_{11} is close to 0dB. The RFID reader does not absorb any incoming radiation, nor can it reflect back and thus it cannot sense the presence of the RFID tag. When the switch is peeled off so that it does not shunt the antenna structure, then the antenna of the RFID tag resonates at 910 MHz making it visible to the RFID reader.

IV. OPENING RECORDING SENSOR BASED ON THREAD-BASED RFID TAG

A. WORKING PRINCIPLE

The paper-based RFID tag opening sensor discussed earlier is suitable for sensing the opening of the package only along the edge where the sensor is placed. However, tampering or opening along other seams or edges of the packages will go undetected. An all wrap-around RFID thread presented earlier by our group in a conference brief [42] can provide all-around package security using only one RFID tag.

RFID chip and the antenna are directly connected in the typical RFID tag. In this design, the conductive thread serves as both the antenna and the long feed lines. The long feed lines not only function as the interconnection between the RFID chip and the antenna but also serve as the opening detection sensor. By wrapping the feed lines around the edges of the package, the RFID tag can provide tamper detection capability. The tampering caused by the opening of the package will lead to the breaking of the conductive thread, which results in either a change in the electromagnetic radiation profile of this thread-based antenna or the elimination of radiation. By sensing this change in radiation, an RFID reader can detect whether the package is opened or not. Breaking is an irreversible process due to the inherent elasticity of the threads. Closing the package again does not reconnect the broken conductive threads between the RFID chip and the antenna. All the RFID information of each package has been saved before shipping the packages. If the package has not been opened, then the signal strength quality (SSQ) is high as shown in Figure 6 (a), but if it has been opened then there is no signal received as shown in Figure 6 (b). Due to the long length of the thread antenna, it can be wrapped all-around to cover all edges or surfaces as needed. Note that one can use Class 3 RFID chips, where opening could have been sensed by sensing the resistance of the threads connected across two dedicated pins provided for resistive sensing. However, that approach needs to be powered either using a battery or through sufficient energy coupling to the antenna from the external reader to power up its built-in sensing circuitry. In our paper, we can use a Class 0-2 passive RFID chip such as Higgs TM 4 Strap (Alien Technology, San Jose, CA, USA) with a single port for antenna and does not provide additional ports for sensing resistance. Moreover, the price difference between the Class 3 RFID with multiples sensing abilities and Class 0-2 RFID is over orders of magnitude making use of Class 3 RFID tag for tamper detection cost-prohibitive for widespread use. We present two models for opening detection based on our approach using passive Class 1 RFID tags that provide coverage either along eight edges or along four edges based on different packaging types.

B. ANTENNA DESIGN

While the approach seems simple in principle, there is an inherent challenge in using feed lines as sensing element, since we need very long feed lines to cover all the possible opening edges of the package to secure it. First, the impedance matching between the RFID chip and antenna will be affected when the length of the feed lines is of the order of RF signal wavelength. This reduces the power transfer efficiency. Second, long feed lines may lead to false detection. For example, even if the feed lines were cut off, the rest of the feed lines connected to the RFID chip may still serve as an antenna to radiate the RFID signal to the reader failing to recognize the fact that lines were cut-off. Therefore, any solution in using RFID threads for tamper-evident packaging

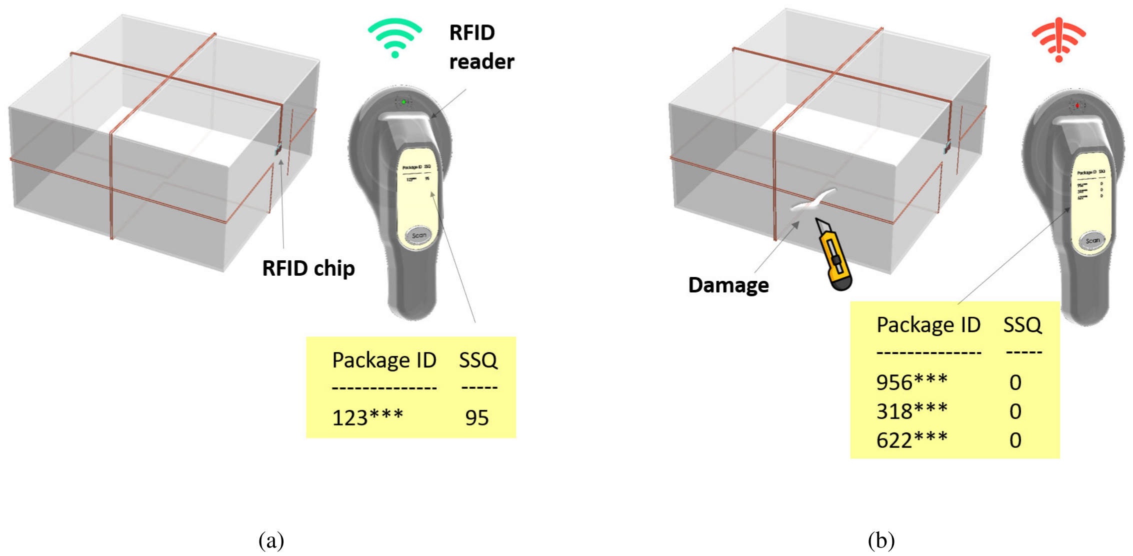


FIGURE 6. Conceptual rendering of tamper-evident packaging. (a) RFID reader receives an RFID backscatter from the package indicating it is not tampered with. (b) RFID reader does not receive the RFID backscatter indicating the package is opened. Once opened-reclosing the package will still provide detection of prior tampering.

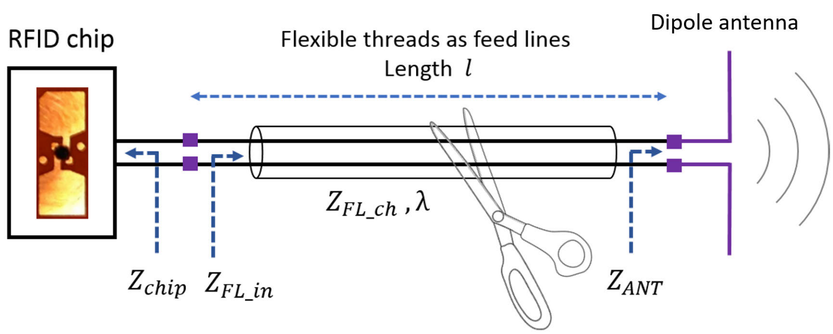
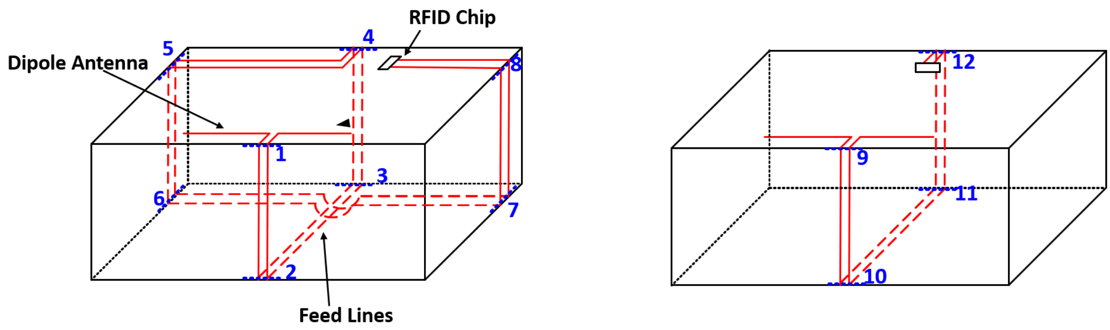


FIGURE 7. Electrical parameter of RFID tag.

will have to address these two challenges. This manuscript provides one such solution.

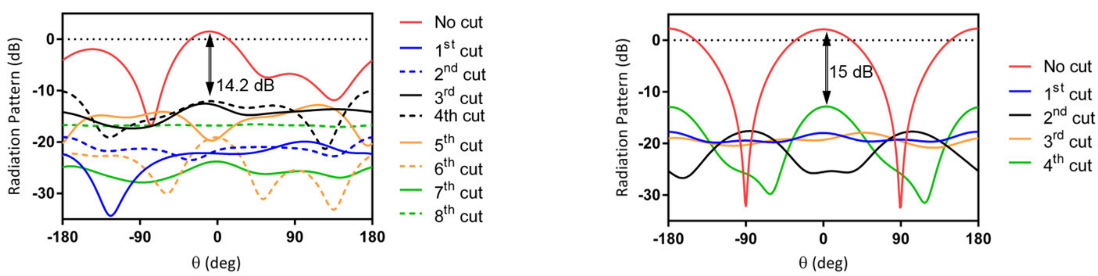
Figure 7 shows the electrical parameters of the RFID tag. It is built with RFID chip, the feed lines, and the antenna. According to the transmission theory, the input impedance of the feed lines Z_{FL_in} is determined by the characteristic impedance of the feed lines Z_{FL_ch}, the antenna impedance Z_{ANT}, the feed lines length l, and the wavelength λ in (1). By ensuring the length of the feed line as multiples of the $\lambda/2$, (1) is reduced to (2) that the input impedance of the feed lines Z_{FL_in} is equal to the antenna impedance Z_{ANT}. This means that one can use long feed lines as long as one can ensure that its length is multiples of $\lambda/2$, the input antenna input impedance can be directly matched to the RFID chip output impedance Z_{chip}. We can simply adjust the dipole antenna length to do the impedance match long feed lines that are not properly laid out may cause leaky radiation when the package is closed (secure). We address this problem by ensuring that the two differential feed lines are placed in close parallel along the entire length from the RFID chip to the far-end dipole antenna. This eliminates radiation from the feed lines themselves.

We show two different model schemes for tamper-evident packaging using the notion of RFID threads just explained earlier [42]. Figure 8 (a) shows the first model where a dipole antenna is placed on the top surface of the package. The parallel feed lines connected to the antenna surround the front, bottom, back, top, left, bottom, right, and top surface respectively, and are then connected with the RFID chip. The recovered edges are marked from 1 to 8 sequentially. Any surface of the package will break the feed lines irreversibly due to inherent elasticity in these threads. Figure 8 (b) presents the second model where the parallel feed lines are wrapped from the front, bottom, back, and top surface respectively,



(a) (b)

FIGURE 8. RFID tag with feed lines (a) The first model with eight edges covered. (b) The second model with four edges covered.



(a) (b)

FIGURE 9. 2D radiation pattern comparison between the uncut and cut package for the two models. (a) The first model. (2) The second model.

and then connected to the RFID chip. The covered edges are labeled from 9 to 12 in order. The second model is suitable for applications where the package may have fewer possible opening edges. As explained earlier, when packages are opened, the breakage cuts-off the connection between the RFID chip and the dipole antenna, and the RFID reader cannot read the presence of the RFID chip on the package – a proof that the package has been opened (tampered with) earlier. The key observation here is that closing the package again will not reconnect these feed lines and the RFID signal strength will not recover. Figure 9 (a) and Figure 9 (b) present the radiation simulation of the uncut and cut package for the first mode and second model, respectively.

V. MEASUREMENT RESULTS

The measurement setup includes an RFID reader AMS AS3992-DKMICRO, a laptop and the tested package affixed with the opening sensor.

$$Z_{FL\_in} = Z_{FL\_ch} \frac{Z_{ANT} + jZ_{FL\_ch} tan \frac{2\pi l}{\lambda}}{Z_{FL\_ch} + jZ_{ANT} tan \frac{2\pi l}{\lambda}} \quad (1)$$

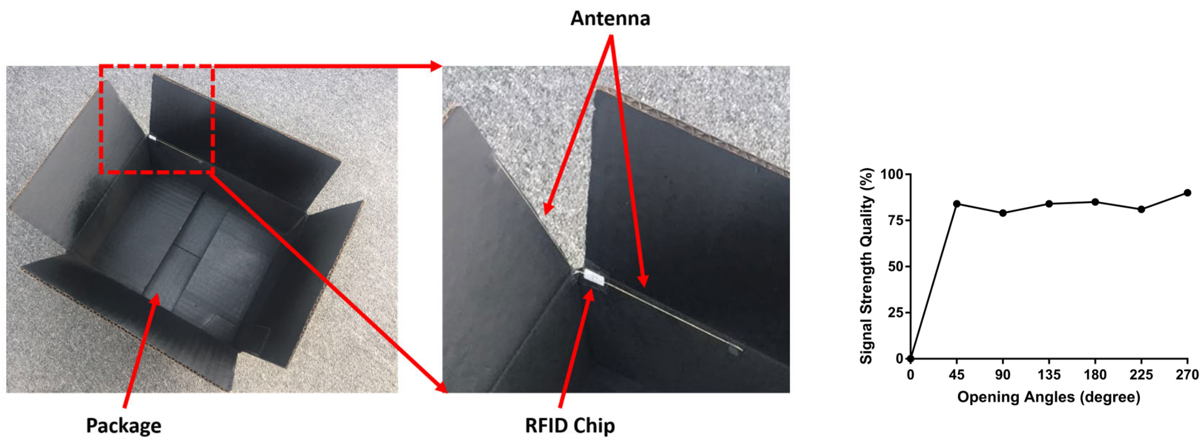
$$Z_{FL\_in} = Z_{ANT}, \quad for\ l = \frac{n\lambda}{2}, n = integer \quad (2)$$

A. VALIDATION OF FOLDABLE ANTENNA BASED REAL-TIME OPENING SENSOR

In Figure 10 (a), the two arms of the antenna are affixed at two inner surfaces. The inside of the package has been painted with a dark color for a better view of the opening detection sensor. The package is tested under 7 conditions: closed (0°), open with 45°, 90°, 135°, 180°, 225°, and 270° angles, respectively. The RFID reader reading result, signal strength quality (SSQ) is shown in Figure 10 (b). When the package is closed, SSQ is 0, and SSQ is strong when the package is open. With a higher powered and sensitive reader, the minimum detected angle of opening can be much less than 45°.

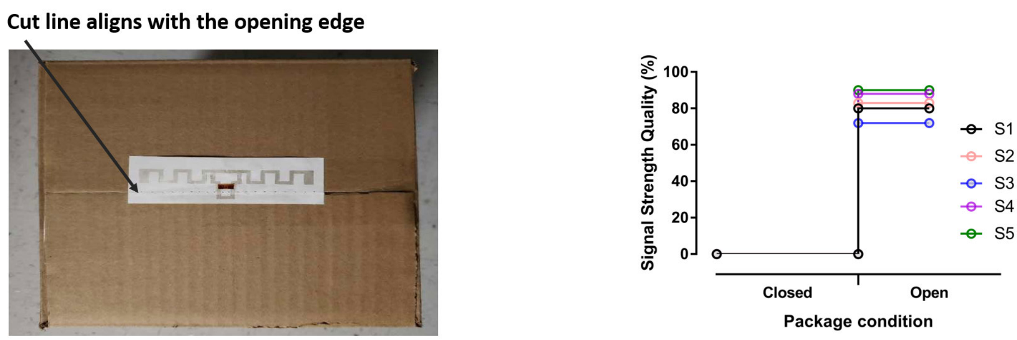
B. VALIDATION OF OPENING RECORDING SENSOR BASED ON PAPER-BASED RFID TAG

Figure 11 (a) shows the paper-based opening detection sensor attached to the package. The cut line on the sensor is aligned with the opening edge of the package. The sensor could also be placed at the inner side of the flaps by the proper assembly. Figure 11 (b) is the measurement of the SSQ of 5 opening recording sensors. Before opening, there is no signal received by the RFID reader. Once the packages have been opened, the RFID reader detects radiation from the RFID tag on



(a) (b)

FIGURE 10. (a) Real-time package opening senor is attached to the package. (b) Signal strength quality measurement with different package conditions.



(a) (b)

FIGURE 11. (a) Opening recording sensor is attached to the package. (b)Signal strength quality measurement of the opening recording sensor.

the packages. This recording solution provides 100% opening event detection and recording with the built-in physical (non-electronic) memory.

C. VALIDATION OF OPENING RECORDING SENSOR BASED ON THREAD-BASED RFID

For visual clarity, threads are integrated on the outer surface of the package as shown in Figure 12. In actual implementation, they would be hidden along the inner surface of the package. Mechanical flexibility and high electrical conductivity make the thread ideal for this tampering-evident application. Tape is used to isolate the intersection of vertical and horizontal feed lines as shown in Figure 12 (b) schematically separated by tape. Twelve packages with different cut locations as in Figure 8 have been cut for the experiment. When the package is intact, the RFID reader can receive the signal from all the packages. When each cut has been made, no signal received from the RFID reader as in Figure 12 (c).

D. DISCUSSION

The three approaches presented in this manuscript all leverage any existing passive RIFD tag and any RFID reader and does not require any specialized sensors or electronics for detection of package condition. Table 1 lists the comparison of the presented approaches with the most relevant and competitive technologies that require specialized sensors, such as impedance sensor [1], piezoelectricsensor [2], and light sensor [3]. This makes these other approaches slightly more bulky and expensive. Another advantage of using RFID is the ability of industry-standard RFID readers to sense thousands of packages simultaneously. Our approach relies on the low-cost thread or paper substrate to integrate with RFID tags without the need for any dedicated facilities to make them.

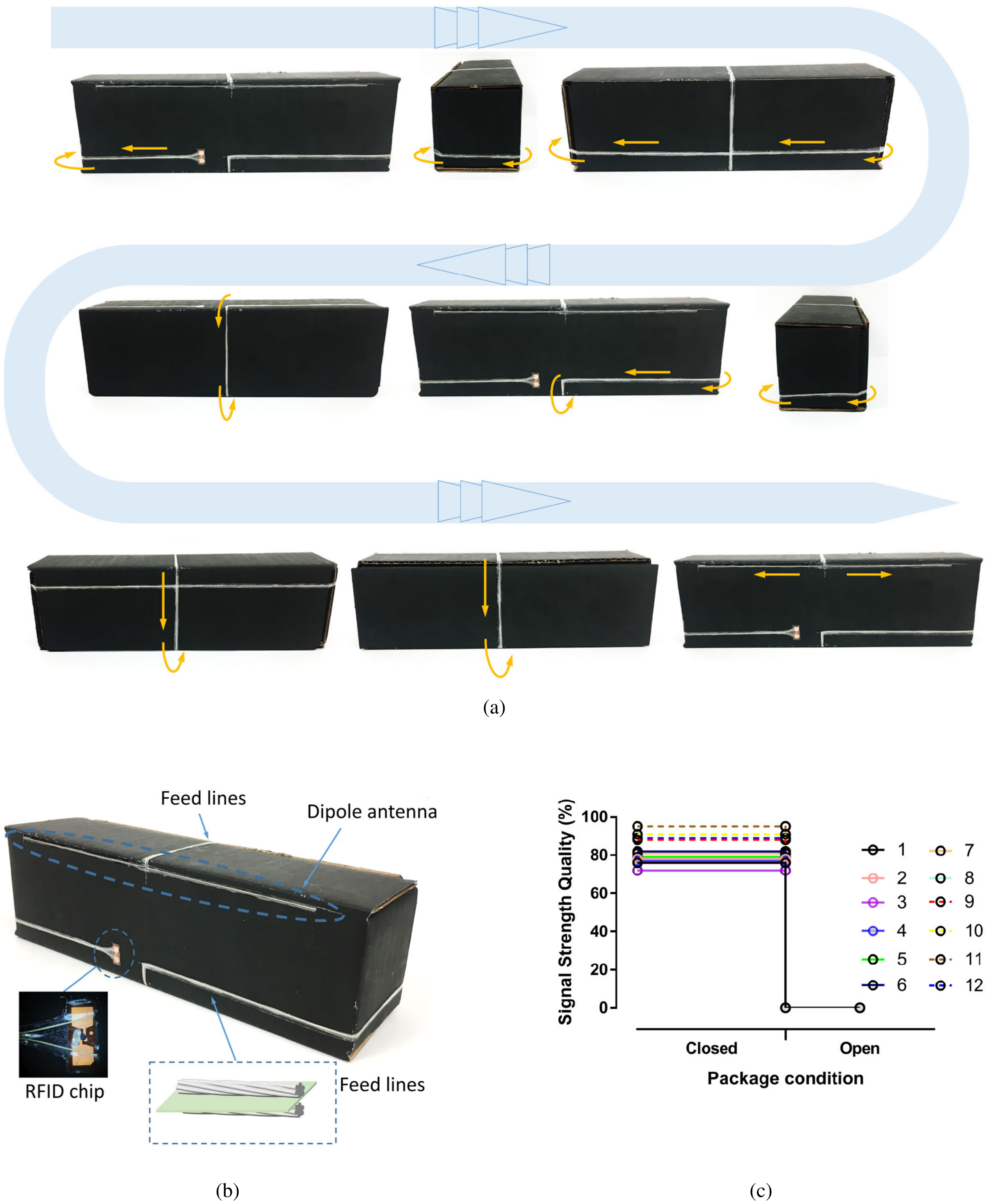


FIGURE 12. **(a) Antenna wrapping steps. (b) The box with sensor assembled, showing RFID chip, feed lines and dipole antenna. (c) Signal strength quality measurement of the opening recording sensor.**

TABLE 1. **Comparison table.**

	[1]	[2]	[3]	Real-time detection	Paper-based	RFID thread
Working Principle	impedance sense	stress sense	light sense	radiation control	radiation control	radiation control
Weight (g)	∼50	∼50	∼100	<5	<5	<5
Cost($)	∼10	∼3	∼100	∼0.2	∼0.2	∼0.2
Power(mW)	∼0.2	∼1	∼10	0	0	0

This solution is more scalable in terms of green manufacturing. In fact, this was one of the high priorities listed for intelligent packaging [51]. It should be mentioned that technology inherits all the advantages or disadvantages of the RFID. RFID based methods are more suitable for monitoring packages with limited metal content inside the package, and with metallic items, placement of the tag and the antenna structure becomes critical; this can be easily addressed with careful packaging.

VI. CONCLUSION

This paper presents three different package opening detection solutions based on RFID technology integrated on low-cost paper or thread substrates. The significance of this work is that the opening detection and recording relies on any passive RFID tag, there is no need for a specialized sensor, electronics or battery. Solutions range from the foldable antenna for real-time detection, paper-based switch across RFID tag to an all-around thread-based RFID tag for all-around package security. All solutions are flexible, lightweight and compatible with most packaging formats. This zero-power and low-cost approach can be used in the supply chain (transportation and storage) to quickly detect any opened, tampered or act of opening events. While a specific RFID frequency band was chosen, the approaches can be easily applied to transponders or tags using other wireless standards, which broaden the possible usages and application of the proposed sensor platforms.

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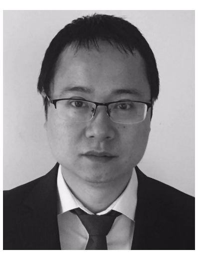

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