ID-Clicker: A Battery-Free In-Class Response System Using RFID Tags

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***Abstract*—In the last decade, there has been significant deployment of wireless in-class response systems that allow students to interactively answer instructors' questions. For example, more than 5000 instructors and 7 million students use such a system developed by iClicker Inc. Existing systems have three limitations which prevent them from achieving their full potential: (i) the cost of remotes, (ii) their need for batteries that often need changing, and (iii) misuse of the system by cheating students, who operate multiple remotes on behalf of absentees. We introduce an alternative, ID-Clicker, that addresses all three limitations. We modify commodity Radio-Frequency IDentification (RFID) tags to create battery-free and low-cost remotes. We further present an inference algorithm that analyzes students' responses and remotes' signal power similarity to detect students who cheat by responding on behalf of others. We evaluate ID-Clicker empirically and demonstrate its effectiveness in a classroom environment. We find that with a single RFID reader and four reader antennas, responses of remote pads generated from a whole classroom with a size of 7 m $\times$ 9 m area (covering 8 rows and 64 seats) are received with 100% response accuracy. Further, our system can detect cheating with high accuracy.**

***Keywords*-In-class response; RFID; Cheater detection**

I. Introduction

Studies show that asking questions during class can engage students and create an effective learning environment [1], [2]. In-class response systems (such as the typical ones available from iClicker Inc. [3]) have received significant adoption, because they provide a convenient way for an instructor to pose multiple-choice questions whose responses come from the *entire* class. In these systems, students respond to questions by using remote controllers. Then, an in-classroom access point wirelessly collects responses and a graphical user interface lets the instructor view these responses. However, such systems have three limitations:

- Remote controllers can be expensive. For example, an iClicker Gen 2 remote costs \$52.99 to purchase, or \$49.99 per year to rent [3], putting them beyond the reach of cost-conscious students and educational institutions.
- Remote controllers use battery-operated active radios, which limits their lifetime to about 200 hours [3]. Batteries can fail during a class, frustrating students.
- Existing in-class response systems cannot detect *cheating*, where a student carries more than one remote and answers questions on behalf of absentees.

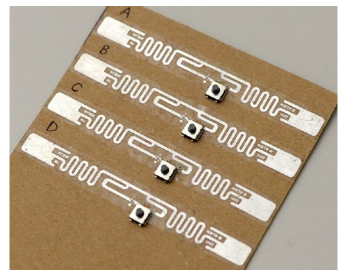

Fig. 1: An ID-Clicker remote pad, which is battery-free and low-cost. The RFID tags are modified by cutting off a small part of their antenna (silver ribbon) and replacing the cut-off parts by push-button switches.

To mitigate these issues, recently some smartphone-based question-answering apps have been developed [3], [4]. These systems are cost-effective and rely on the fact that students are motivated to charge their smartphones daily. However, studies have shown that using smartphone apps can have negative impacts on a classroom environment. One study finds that students are 20% more distracted in a classroom where cellphones are used [5], [6], resulting in lower test scores [7], [8]. Furthermore, using smartphones make it easier for students to use internet to find the answer to questions [7], [8]. Therefore, it would be beneficial to avoid using smartphone-based in-class response apps. In this paper, we describe such an alternative.

We present ID-Clicker, the first RFID-based in-class response system. Due to the use of RFID tags, our remote controllers are battery-free and cost less than a dollar. ID-Clicker has three components: a set of remote controller pads. (Fig. 1), an RFID reader, and a back-end server. A pad consists of several low-cost commodity RFID tags that have been modified: we cut away a small portion of the tag's antenna and replace it with a passive switch. When the switch is open, the tag is rendered inoperable but when the switch is depressed, the reader can 'hear' the tag and identify its ID. Thus, a tag's unique ID represents both a student's ID and a specific answer option, such as 'A' or 'B'.

Although past work has proposed using RFIDs for user interface (UI) systems [9]–[13], they are not robust enough to be used in an in-class response system. This is because these systems exploit analog features, such as the phase and received signal strength (RSS) features, to detect user interactions.

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Unfortunately, these analog features are not robust to even minor variations in the environment or tag geometry [14]. Moreover, most existing RFID-based UI systems rely on the machine learning to identify a user's interaction [10], [11], which suffers from not only a high computational cost, but also an extensive training process. In contrast, our system uses digital features, i.e., tag IDs, as the signal feature, which is not only robust to the environment changes but also computationally inexpensive.

Besides being battery-free and low cost, another advantage of ID-Clicker is its ability to detect cheaters. ID-Clicker does this by analyzing student responses and the similarities between pad signals. In section IV, we explain in more detail how ID-Clicker detects cheaters.

We built a prototype of ID-Clicker system using commodity components and evaluated the system performance in a realistic classroom with a size of 7.0 m $\times$ 9.0 m. We find that with a single reader and four antennas, remote pad responses are collected with 100% response accuracy in the whole classroom (covering 8 rows and 64 seats), where each reader antenna can cover a 4.0 m $\times$ 4.5 m area. We can also detect cheating students with 100% accuracy and a zero false alarm rate when more than three questions are posed during a class.

Our main contributions are:

1) We present the first RFID-based UI system for in-class wireless response gathering. Our system is not only low-cost and battery-free, but also robust to changes in the environment, and to a tag's rotation and location.
2) We present a cheater detection algorithm that has 100% accuracy and a zero false alarm rate when more than three questions are posed during a class.
3) Our system has been implemented using commodity RFID hardware and comprehensively evaluated in a realistic classroom setting.

II. Background and Related Work

A. In-class Response Systems

1) iClicker system: iClicker [3] is a wireless in-class response system that allows students to respond to instructor's questions in near real-time. An iClicker system consists of two main components: many 'clicker' remotes, held by students (as shown in Fig. 2), and an instructor base that is installed in the classroom. At a high level, the system works as follows: The instructor presents a question, which is either a multiple-choice question or a true/false question. Within a given time period, students choose their answers by clicking an appropriate button on their clicker remotes. The base collects all responses and then the results are shown to the instructor.

Existing iClicker's remotes require batteries because they use active radios to communicate with the instructor base, which significantly increases their power consumption. In a typical deployment, an iClicker Gen 2 remote costs $52.99 to purchase, or $49.99 per year to rent [3].

2) Other clicker systems: There are some other clicker systems, such as Qwizdow [15] and TurningPoint [16], etc.

Fig. 2: A generation 2 iClicker remote [3].

Unfortunately, the remotes of these systems are costly and require batteries. Several commercially available systems allow students to respond to in-class questions using a smartphone or laptop through Internet connection [17]–[22]. However, the Internet may become a potent source of distraction. In image-based approaches [23]–[25], students hold up a large printed card with a camera-identified unique ID. However, the camera use in a classroom is arguably an intrusion into student privacy, and the system works poorly when lighting conditions are sub-optimal or cards can be occluded.

Compared to these response systems, ID-Clicker has the following advantages:

1) Although the RFID reader can be expensive (USD 100-1000), this cost is paid only once per classroom, and each pad costs less than 1 USD.
2) Our system work with 100% precision and recall over a whole classroom area.
3) Our system does not violate student privacy.
4) In addition to collecting responses, our system also detects cheating.
5) Our system does not require students to use distracting devices such as laptops and smartphones.

B. Passive RFID Systems

A Passive RFID system has two components: an RFID reader and a set of battery-free RFID tags. Each tag has a unique ID. The reader can read multiple tags at almost the same time, and a tag can be queried up to 200 times per second [10]. Therefore, hundred of tags can be read in a few seconds. The tags are low-cost (5–10 cents USD per tag), flexible, and small. Further, they have a relatively long communication range (7-10 m), and work in both line-of-sight and non-line-of-sight scenarios.

Some researchers have proposed using RFID-based systems in classrooms for automatic person identification [26] and attendance management [27]. However, they do not address question answering. In addition, several prior systems have used RFID devices to detect touch related events [9], [10], [13]. For example, the RIO system [10] can sense the finger touch activity and the PaperID system [9] can get the touch, cover, overlap or movement by proposing a 'paper-like' interface built on RFID tags. However, all these systems use RSS and phase changes to measure touch events, which is not robust to environment changes [14].

In contrast to past studies, ID-Clicker uses a digital ID as the signal feature, which is robust to environmental change. We note our work is motivated by Wang *et al.* [28], which presents an RFID 'hacking' technique to modify RFID tags. Our system

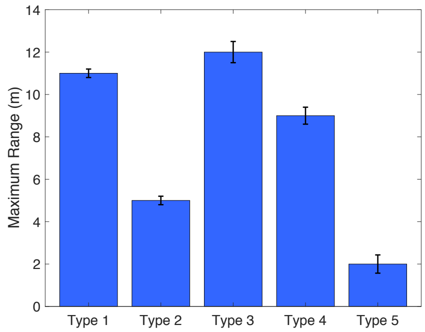

Fig. 3: The maximum working range of five different types of tags.

extends this approach to detect responses from students in realistic settings and also performs cheating detection.

III. ID-Clicker's Pad Design

We use multiple RFID tags to construct a pad as shown in Fig. 1. To answer a question, a student selects the corresponding tag. Since each tag has a unique ID, ID-Clicker can identify the student's response. In the next few sections, we first discuss some considerations in choosing the right tag type and detail how to build a pad by modifying RFID tags.

A. Selecting the Tag Type

Commercially available passive RFID tags vary in antenna structure, substrate material, and chip type, and consequently have different working ranges. For our application, we need to select a tag type which has a relatively long working range and also is easy to modify.

We use five types of RFID tags that are commonly used in RFID-based systems [29]–[35]. Type 1 is a Alien Squiggle ALN-9740 tag [36], Type 2 is a Avery Dennison AD-160u7 tag [37], Type 3 is a SMARTRAC Frog 3D tag [38], Type 4 is a Avery Dennison AD-383u7 tag [39], and Type 5 is a Avery Dennison AD-172u7 tag [40]. We first compare the maximum working range of these tags in a classroom environment by fixing the location of the reader's antenna and then increasing the distance between the reader's antenna and the tag until the tag stops responding. For each tag, we also measure its maximum working range for ten different deployment angles of a tag *w.r.t.* the reader's antenna.

Fig. 3 shows the maximum working range of the five types of RFID tags. The results show that the tag 'Type 1' and the tag 'Type 3' have a working range of 11 m and 12 m, respectively. Although 'Type 1' and 'Type 3' have similar working ranges, we choose 'Type 1' since it is smaller and has a structure which is easier to modify. In particular, since we need to disconnect the tag's chip from its antenna, it is easier to use tag 'Type 1,' which has a simpler antenna structure (shown in Fig. 4).

B. Modifying RFID Tags

We now describe how to build an RFID-based remote pad, i.e., ID-Clicker pad. An ID-Clicker pad supporting k answer

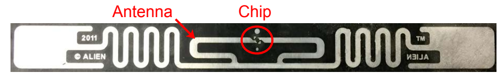

Fig. 4: A passive RFID tag (Type 1).

options requires modifying k RFID tags. For each tag, we first remove its plastic cover, as shown in Fig. 5(a)-(b). Then, we cut away a small part of the antenna, which is close to the chip, as shown in Fig. 5(c). By doing so, we disconnect the tag's chip from its antenna with a minimum impact on the antenna's structure and impedance. Next, we place a switch on the tag's antenna to replace the cut part, as shown in Fig. 5(d). The switch is secured to the tag by using conductive glue [41]. We place k of these modified tags next to each other to build a remote pad, as shown in Fig. 5(e). Finally, we add a non-modified battery-free RFID tag with an LED (i.e., EVAL01-Stella-R RFID tag [42]), as shown in Fig. 5(f). This tag has an LED that can be flashed to confirm that the reader has received the student's response.

When none of the switches are pressed, all RFID chips are disconnected from the antennas and the reader does not receive any response. When a switch is pressed, the switch connects the tag's antenna to its chip and the reader receives the tag's ID. The tag's ID represents both a student's ID and her/his answer to the question. Once the system detects the student's response, it sends a message to the RFID tag with an LED causing it to blink, which provides a visual confirmation of receipt.

C. Encoding a student's ID

We store a student's ID on a tag's Electronic Product Code (EPC) memory [43]. For example, the Alien Squiggle ALN-9740 tag has 128 bits of EPC memory [36]. We divide the EPC memory into two parts: the student's ID and the answer. We use the first 125 bits for the student's ID and the last 3 bits for the answer (i.e. supporting up to 8 answer options). Therefore, once a key is pressed, the reader can easily detect students who are present in the class as well as their responses to the instructor's questions.

IV. Cheater Detection

In order to detect cheating students, who hold two or more pads in class and answer questions on behalf of absent students, one potential approach is to estimate locations of ID-Clicker pads, and see if two or more pads are very close, e.g., within one seat area. However, this approach requires a sub-meter localization accuracy which cannot be guaranteed by existing localization techniques in the real world [14].

To solve this challenge, ID-Clicker introduces a cheater detection algorithm that does not require the locations of ID-Clicker pads. Our cheater detection algorithm is based on the following intuitions:

- Although RSS measurements of cheating pads are not robust enough to be used for localization, they have some similarities since the locations of those cheating pads are close.

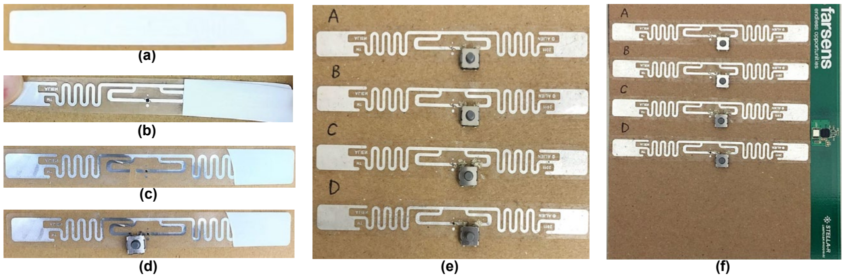

Fig. 5: How we build the ID-Clicker remote pad: we (a)-(b) remove the plastic cover, (c) cut away a small part of its antenna, (d) replace the cut-off part with a push-button switch and secure it by using the conductive glue, (e) put multiple modified RFID tags together to form our ID-Clicker remote pad. Moreover, by adding a battery-free LED tag in (f), we can enable the feedback function.

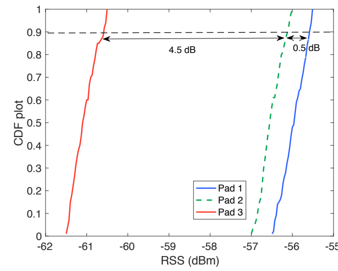

Fig. 6: The CDF plot of RSS measurements of three pads.

- A cheating student selects the same answers for all remote pads that he/she holds.
- The answers from cheating pads are received within a similar period of time.

We validate our first intuition through real-world experiments. We deploy three ID-Clicker pads on a desk, where the distance between 'Pad 1' and 'Pad 2' is close (i.e., 20 cm), and the distance between 'Pad 1' and 'Pad 3' is far (i.e., 150 cm). Then, we collect RSS measurements of each pad. Fig. 6 shows the Cumulative Distribution Function (CDF) plot of RSS measurements of the three pads. It is clear that when the two pads are close, the RSS distributions of two pads are similar. For example, at the 90th-percentile, the RSS difference of 'Pad 1' and 'Pad 2' is only 0.5 dB. On the other hand, when the two pads are far away from each other, their RSS distributions are quite different. For example, the RSS of 'Pad 1' and 'Pad 3' is more than 4.5 dB different in most measurements. This experiment suggests that there is a similarity between RSS of pads that are close to each other.

It is challenging to validate the two other intuitions experimentally since the ground truth on cheating is hard to establish in a real class setting. Instead, we try to validate these intuitions through a questionnaire that we gave to 67 university students. We asked each student— "If you hold your own clicker and other clickers on behalf of your classmates in the class, (i) will you choose the same answers for the instructor's question, (ii) and will you press the two clickers at the almost same time?" 100% of students said they would definitely select the same answers for all clickers. For the second question, ~95% of students said they would operate the clickers almost simultaneously. These results add credibility to our second and third assumptions.

Using these three intuitions, we design an algorithm to detect cheating students. Furthermore, to reduce false positive errors, our algorithm considers the results from multiple questions to make a decision. Assuming that the instructor poses N questions in a classroom with M pads, we first collect RSS readings, response answers and the time of response from M pads for N questions. Let $\mathbf{R}_{M\times N}$ denote the *RSS reading matrix*, $\mathbf{A}_{M\times N}$ denote the *answer matrix*, and $\mathbf{T}_{M\times N}$ denote the *response time matrix*, where $\mathbf{R}(i,n)$, $\mathbf{A}(i,n)$ and

Algorithm 1 Cheater Detection Algorithm

Input: M: the number of ID-Clicker pads, N: the number of questions, $\mathbf{R}$: the RSS reading matrix, $\mathbf{A}$: the answer matrix, $\mathbf{T}$: the answer response time matrix, R_{th}: the RSS difference threshold, T_{th}: the pre-defined time interval threshold, P_{th}: the probability threshold.

Output: $\mathbf{C}$: a matrix which shows the index of the cheating ID-Clicker remote pads.

$q = 1$;
for $i = 1 : M-1$ **do**
  for $j = i+1 : M$ **do**
    $p = 0$;
    for $n = 1 : N$ **do**
      if $|\mathbf{R}(i,:) - \mathbf{R}(j,:)| \leq R_{th}$ && $\mathbf{A}(i,:) == \mathbf{A}(j,:)$ && $|\mathbf{T}(i,:) - \mathbf{T}(j,:)| \leq T_{th}$ **then**
        $p = p + 1$;
      end if
    end for
    if $p/N \geq P_{th}$ **then**
      $\mathbf{C}(q,:) = [i,j]$;
      $q = q + 1$;
    end if
  end for
end for
return $\mathbf{C}$;

$\mathbf{T}(i,n)$ are the RSS measurement, response selected by, and the response time of the i-th pad ($i \in [1,M]$) and the n-th question ($n \in [1,N]$). We term the i-th and j-th pads as suspecting cheaters if: (i) the differential RSS values of the i-th pad and the j-th pad ($i \neq j$) is within a threshold R_{th}, (ii) the answers of two pads are the same, and (iii) the difference between the response time of two pads is smaller than a pre-defined threshold T_{th}. If, over the duration of a class, two pads are deemed suspicious for a fraction of questions exceeding a threshold P_{th}, we mark the student who holds these two cheater pads as a cheating student. The pseudo-code of cheater detection algorithm is shown in Algorithm 1, which outputs the index of the detected cheating pads. Based on the ID information of the cheating pads, we can quickly

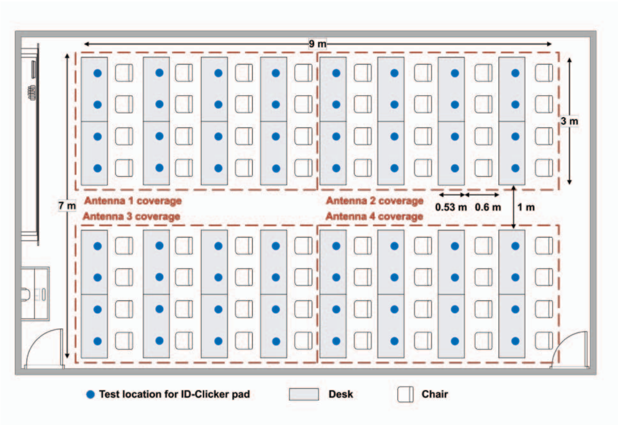

Fig. 7: The experimental deployment layout in a classroom.

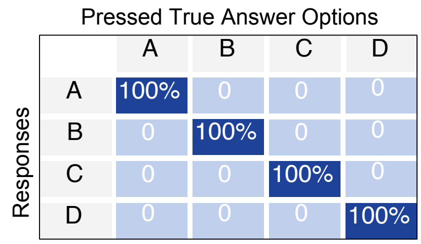

Fig. 8: Confusion matrix: The identification results of an ID-Clicker pad on four answer options over 1200 tests.

identify cheating students. Note, we assume that students do not know the principle of cheater detection method. Therefore, if the cheating students move the clickers around, or answer in different times, our system will not able to detect them. Designing a more accurate cheating algorithm is an interesting direction for future research.

V. Evaluation

A. Experimental Setup and Environment

We deployed our system in a classroom with dimensions 7.0 m $\times$ 9.0 m. The classroom has 8 rows and 64 seats, as shown in Fig. 7. Each row spans 3.0 m and the distance between two rows is 0.6 m. The height of the desk is 1.0 m. We use an Impinj Speedway R420 reader [44], which operates in the 902.75–927.25 MHz band. Four RFMax directional reader antennas [45] are connected to the reader. The reader antenna has a 9.5 dBi gain, 70° elevation beamwidth, and 65° azimuth beamwidth. We deployed the 4 antennas on top of the test area that face down. The distance between the reader's antenna and the ground is 3.0 m. Each antenna can cover an area with a size of 4.0 m $\times$ 4.5 m. Thus, one antenna covers 4 rows and 16 seats, and four antennas can cover the whole classroom. The cost of the RFID reader used in this paper is around $1k. However, one can use a cheaper reader. For example, the XC-003 UHF RFID Reader costs only $70 [46]. We build 15 pads using 60 Alien Squiggle ALN-9740 RFID tags [36] and 15 EVAL01-Stella-R RFID tags [42], as shown in Fig. 5(f).

B. Performance Metrics

1) Response accuracy: The *confusion matrix* [47] measures the response accuracy for each of the four answer options of a remote pad. We use this metric in Section V-C. The *average response accuracy*, denoted $\overline{Acc}$, shows the average response accuracy of all answer options of a pad, and is defined as:

$$\overline{Acc} = \frac{1}{J}\sum_{j=1}^{J}\frac{n_j}{N_j}, \qquad (1)$$

where, N_j is the total number of times that a j-th answer option is selected and n_j ($n_j \leq N_j$) is the number of times that the reader correctly identifies the response. Our pad provides four options, thus, J=4. This measures performance in the experimental setups presented in Section V-D.

2) Cheater detection accuracy: We use two well-known performance metrics to evaluate the accuracy of our cheater detection algorithm: *precision* and *recall* [47]. 'Precision' is the ratio of the number of true positives–correctly identified cheating pads–to the total number of pads said to be cheating. If this value is 100%, the systems raises no false alarms, i.e. marking a non-cheater as a cheater. 'Recall' is defined as the ratio of the number of correctly detected cheating pads to the number of the pads actually cheating. A value of 100% means that all cheating (i.e., duplicated) pads were detected. Thus, when both values are 100%, all cheaters are correctly detected without any false alarms.

C. Overall Response Accuracy

To measure the overall response accuracy, we ask 15 test subjects to randomly sit at 15 seats in the classroom. Each subject holds one pad and presses each of the four answer options (i.e., 'A', 'B', 'C' and 'D') 20 times. Thus, we have a total number of 300 tests for each answer option and 1200 tests for all four answer options. To obtain ground truth, we test the four options one by one and the subjects record the answer options they pressed. Fig. 8 shows the resulting confusion matrix for the four answer options over 1200 tests. Our system identifies *every* pressed answer option correctly, that is, the overall response accuracy is 100%.

D. Response Coverage

We evaluate the response coverage when a single reader antenna is used. We let a user to place a pad on the desk or hold it in her hand and then move to different seats in the classroom, as shown in Fig. 7. For each location, the user presses each answer option 50 times. We define the response coverage as the area where the system detects 100% of responses. With a single reader antenna, an effective and reliable coverage area is 4.0 m $\times$ 4.5 m. This coverage is limited by antenna's pattern. Hence, when a pad is out of the antenna's coverage area, the signal gets weaker and the pad doesn't have enough energy to reply to the reader's query.

To extend the coverage area to the whole classroom, we deploy four antennas as shown in Fig. 7. Hence, our system can cover 8 rows (64 seats). Note that RFID reader antenna are

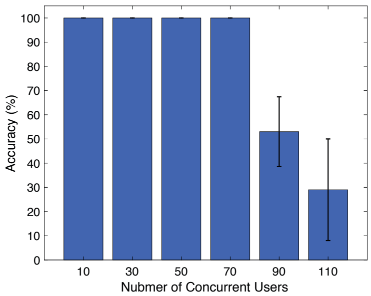

Fig. 9: The impact of the number of concurrent users.

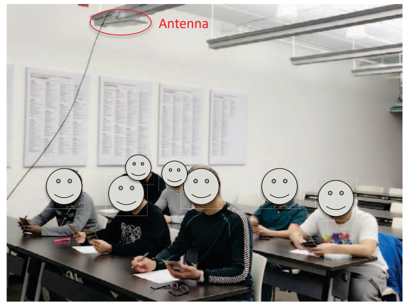

Fig. 10: The experimental scene for the cheater detection.

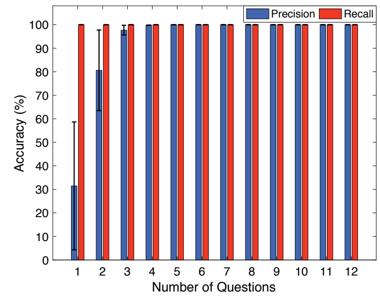

Fig. 11: The cheater detection accuracy versus the number of questions asked.

inexpensive and most commodity RFID readers can support multiple antennas. For example, the Impinj Speedway R420 RFID reader can support up to 32 antennas when their antenna hubs are used [44]. Thus, we believe that our system is suitable for use in a practical settings.

E. Impact of Concurrent Responses for One Antenna

Usually, there are multiple students in a classroom. Thus, we expect over-the-air response collisions when many students simultaneously use their pads [48], the common case. This could reduce the response accuracy since an RFID reader cannot decode overlapping responses. Therefore, we evaluate the impact of the number of concurrent users at one reader antenna on the systems average response accuracy.

We deploy a N (N=10, 30, 50, 70, and 110) unmodified Alien Squiggle ALN-9740 tags on the desk to simulate N concurrent users. Additionally, one user holds a pad and sits near the N tags. In this experiment, each of the four switches is pressed 50 times, and then we calculate the accuracy based on Eqn. (1). Fig. 9 shows the average response accuracy for different number of concurrent users. We note that the average response accuracy is always 100% with fewer than 70 concurrent users. The accuracy decreases significantly when the number of concurrent users exceeds 90 because of an increase in the number of collisions. Note that a simultaneous response by N tags is much worse than what would happen in practice, since students in a classroom can be expected to respond over a minute or two, rather than all at once.

F. Accuracy of Cheating Detection

We note that evaluating our cheater-detection algorithm 'in the wild' is challenging because cheating students are averse to detection. We are therefore forced to emulate cheating behaviour by asking one of our test subjects to cheat. Specifically, we simulate a teaching task with seven students and one teacher. The seven students sit in two rows, as shown in Fig. 10. We deploy eight pads for this evaluation: One of the seven students holds two pads and acts as the cheater. The remainder are normal users and each of them holds only one pad. A teacher sits near the reader side and asks 12 questions. Each question has four answer options, i.e., 'A', 'B', 'C' and 'D'. All the questions are asked and answered one by one. For each question, a student has one minute to select his/her answer option on the pad. Different students answer a question at different time points during the one minute. The cheating student answers a question by selecting the same answer options on both pads at almost the same time. To get the ground truth of each student's answer selections, we ask every student to record his/her answers on a paper.

Fig. 11 shows the precision and the recall versus the number of questions asked. We empirically set the time interval threshold T_{th} as 5 seconds and the RSS difference threshold R_{th} as 3 dB. We see that the recall is always 100% no matter how many questions are asked, which means that our cheater detection algorithm has detects all the cheating pads even with only one question asked. In addition, when the number of questions increases, the precision increases to 100%. For example, when 4 questions are asked, all cheating pads are correctly detected without any false alarm. Thus, in this experiment, we set a threshold vale P_{th} that is bigger than $1/3$. In a typical class, an instructor is likely to ask at least 5-10 questions, so we expect both precision and recall to be 100% in realistic settings. Finally, note when the number of students in a classroom is large, our algorithm may suffer from false alarm. In this case, we can reduce the false alarm rate by separating the students' responses by exploiting the different coverage areas of reader's antennas as shown in Section V-D.

VI. Conclusion

We demonstrate the practical application of 'RFID hacking' [28] of commercial RFID devices to build a battery-free, low-cost, and wireless in-class interaction system. With simple modifications to a handful of cheap RFID tags, ID-Clicker provides students with a very affordable alternative to existing 'clicker' systems. ID-Clicker also can accurately detect cheating students with a simple and effective algorithm.

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