Activating Wireless Voice for E-Toll Collection Systems with Zero Start-up Cost

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Abstract—This work enhances the machine-to-human communication between electronic toll collection (ETC) systems and drivers by providing an AM broadcast service to deployed ETC systems. This study is the first to show that ultra-high radio frequency identification signals can be received by an AM radio receiver due to the presence of the nonlinearity effect in the AM receiver. Such a phenomenon allows the development of a previously infeasible cross-technology and cross-frequency communication, called Tagcaster, which converts an ETC reader to an AM station for broadcasting short messages (e.g., charged-fees and traffic forecast) to drivers at tollbooths. The key innovation in this work is the engineering of Tagcaster over off-the-shelf ETC systems using shadow carrier and baseband whitening without the need for hardware nor firmware changes. This feature allows zero-cost rapid deployment in existing ETC infrastructure. Two prototypes of Tagcaster are designed, implemented and evaluated over four general and five vehicle-mounted AM receivers (e.g., Toyota, Audi, and Jetta). Experiments reveal that Tagcaster can provide good-quality (PESQ > 2) and stable AM broadcasting service with a 30 m coverage range. Tagcaster remarkably improves user experience at ETC stations and two-thirds volunteer drivers rate it with a score of 4+ out of 5.

1. INTRODUCTION

Electronic toll collection (ETC) is a system enabling electronic collection of toll payments, thus allowing for near-nonstop toll collection and traffic monitoring. ETC (e.g., Z-Pass and I-PASS) has become the most successful and widespread application of Radio Frequency IDentification (RFID). Approximately, 70% to 89% of cars are equipped with ETC transponders (or tags) in the US. In particular, over 80% of Illinois’ 1.4 million daily drivers currently use I-PASS [1]. ETC can eliminate delay on toll roads, HOV lanes, and toll bridge by collecting tolls without requiring cars to stop. Owing to this wide adoption, the industry and academia are looking into delivering new services via the currently deployed ETC infrastructure. Examples include paying for food at drive-through restaurants or parking lots with an e-toll transponder, tracking the number of cars at every road intersection for traffic control, and detecting and ticketing over-speeding cars without the need for car-mounted radars and hidden police officers. ETC offers an opportunity for using ETC systems to enable smart cities in the future [2].

As a typical technology of the Internet of Things, ETC systems are designed for machine-to-machine communication only (e.g., identifying cars or monitoring traffic). Drivers cannot directly obtain related information (e.g., charge amount, credit balance, real-time traffic and road condition). Achieving direct machine-to-human (M2H) communication between drivers and ETC systems requires extra peripherals and efforts. For example, drivers must slow down their cars to view an LED screen installed at the tollbooth for charge details. The information acquired by drivers is usually quite limited due to the small screen size. Slowing down also worsens the congestion during rush hours. Facing this practical issue, we ask “Is there any convenient and user-friendly M2H communication way to provide informative interaction fast?”

In this study, we introduce a novel ETC service, called Tagcaster, which supplements the function of an AM radio to the existing ETC infrastructure with zero start-up cost. Tagcaster can activate a deployed ETC tollbooth to provide the wireless voice service for direct M2H communication. Fig. 1 illustrates our service scenario. When a driver passes through a tollbooth, the ETC reader automatically identifies the vehicle’s ID and retrieves its related data from backend servers. Then, the reader broadcasts the data in the form of an AM radio. The driver can listen to the AM radio through the vehicle-mounted radio receiver.

“Wireless voice” is more user-friendly and spontaneous than current interactive medias (e.g., LED screens or external speakers). It provides a new means to deal with the issue of poor visibility in bad weather conditions, such as stormy, foggy or smoggy, when viewing feedback from ETC screens is difficult for drivers. Such functionality is also useful in a wide range of application scenarios. Apart from charging
information, Tagcaster can also broadcast greetings, real-time traffic conditions, account balance, and advertisements. Moreover, drivers do not need to slow down to acquire information from an ETC system as they are pushed actively. Additional scenarios that motivate our design and the reason why not choose other technologies are displayed in section II.

The fundamental challenge in Tagcaster is in the seemingly impossible cross-technology communication between ETC RFID and AM radio due to the large frequency gap. ETC RFID systems operate at ultra-high frequency (UHF) (e.g., 800-900 MHz), whereas an AM radio works at radio frequency (e.g., 500-1700 kHz). A real AM station is usually equipped with a 60 m long antenna because the length of transmitting antenna must be close to half of the carrier wavelength. Clearly, a 16 cm long directional antenna for ETC reader fails to propagate AM radio signals into the air. Our insight is that non-linearity effect in the circuits of radio receivers can receive and pull the UHF signal down to the low-frequency band if the signals are transmitted via two UHF carriers. Specifically, on the transmitter side, the RFID reader broadcasts two signals at $f_1$ and $f_2$ (e.g., $f_1 = 820.5$ MHz and $f_2 = 820$ MHz) simultaneously. Given that both signals are at UHF, they can be propagated successfully by the existing UHF antenna. On the radio receiver side, a new signal is created at $|f_1 - f_2|$ (e.g., 500 kHz) due to the nonlinearity effect of the pre-amplifier at the radio receiver. The process is equivalent to performing an additional downconversion called the zeroth downconversion before the radio signal is further downconverted and decoded to an audio signal. Unlike traditional wisdom that regards non-linearity as detrimental, we use it as a natural downconverter.

Engineering a Tagcaster must address two practical issues that stem from the pursuit of zero start-up cost (i.e., without requiring modification in the hardware of the ETC system).

- **How to generate two carriers?** The zeroth downconversion requires two signals from an ETC reader to operate at $f_e$ and $f_e + f_r$, so that their difference of $|f_e + f_r - f_e|$ is exactly equal to the $f_r$ that the radio receiver can process. Here, $f_e$ and $f_r$ are operating frequencies of the ETC reader and the AM radio, respectively. Therefore, we must enable the ETC reader to modulate signals at two carriers ($f_e$ and $f_e + f_r$).

Although total 52 frequency channels are available for an RFID reader, only a single channel can be used at any moment for the reading. Our transparent design views the reader as a “black box”, whose input is limited to predefined reader commands. Finally, Tagcaster whitens the baseband to a square signal by inputting a long sequence of RFID commands. Given that the reader uses pulse interval encoding (PIE) for modulation, multiple harmonics can be observed on the receiving side. Inspired by this physical-layer characteristic, we set the parameter of length of bit tactically to “frame” the first-order (i.e., fundamental) and fifth-order harmonics to appear at frequencies of $f_e$ and $f_e + f_r$, respectively.

- **How to modulate audio signals?** An ETC reader is a typical digital communication system whose baseband signal contains two different level voltages (i.e., high and low) only. The envelop of its modulated signals changes at two levels (i.e., OOK). On the contrary, AM stations and receivers are analog systems in which the quantized analog audio data are represented using multiple level voltages. Therefore, analog radio receivers cannot decode the digital binary signals transmitted from the reader. To deal with this issue, Tagcaster leverages the controllability of RF power to adjust the transmitting power dynamically for the required amplitude modulation.

Specifically, Tagcaster initially quantizes the analog audio data into four-bit discrete values, then manipulates the transmitting power among 16 levels correspondingly. In such a way, the audio data can be carried onto the desired frequencies.

We implement two prototypes of Tagcaster using an R2000 chip from ImpinJ [3] and USRP N210 respectively. Nine off-the-shelf radio receivers including five vehicle-mounted and five general-purpose radio receivers are tested. Our results demonstrate that Tagcaster can fully provide AM radio service and enhance the ETC user experience on these devices. The perceptual evaluation of speech quality (PESQ) of the received voice is around 2, which is equal to that of the current telephone communication system. The coverage range is 30 m with two-way antennas. Demo audios are uploaded in [4].

**Contributions:** This work presents Tagcaster, the first system utilizing the non-linearization phenomenon in radio receivers to provide high-quality radio service for ETC readers. The design of Tagcaster provides three key contributions. First, it proves the engineering possibility of down-converting communication with hardware non-linearity. Second, it introduces a new amplitude modulation scheme by controlling RF power. Finally, Tagcaster presents a practical prototype and a comprehensive evaluation.

II. BACKGROUND AND MOTIVATION

In this section, we introduce system background, typical application scenarios and potential alternative solutions.

A. System Background and Scope

ETC systems are a combination of techniques and technologies that allow vehicles to pass through a toll facility without requiring any action from drivers. The core of ETC is a typical RFID system where an active or passive e-toll transponder (RFID tag) responds to a query command transmitted by the reader. The readers are installed in tollbooths, whereas transponders are attached to vehicle’s windshields. ETC systems are typical closed-loop systems that only work within particular regions. Therefore, no agreement on the ETC standard has been achieved so far. For example, dozens of ETC networks exist in the US [5] and these include E-ZPass, I-Pass, SunPass, TxTag and Fastrack. Even so, these ETC networks have three common factors as follows:

- Readers work at the UHF band (i.e., 860-960 MHz) to achieve good penetration because transponders are located inside vehicles. For example, E-ZPass works at 915 MHz.

- The simplicity of the transponders results in a cheap and low-power device. The forward link from readers to transponders uses PIE-like encoding to facilitate the decoding at powerless transponders.

- The zeroth downconversion requires two signals from an ETC reader to operate at $f_e$ and $f_e + f_r$, so that their difference of $|f_e + f_r - f_e|$ is exactly equal to the $f_r$ that the radio receiver can process. Here, $f_e$ and $f_r$ are operating frequencies of the ETC reader and the AM radio, respectively. Therefore, we must enable the ETC reader to modulate signals at two carriers ($f_e$ and $f_e + f_r$).

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- The simplicity of the transponders results in a cheap and low-power device. The forward link from readers to transponders uses PIE-like encoding to facilitate the decoding at powerless transponders.
• Readers maintain continuous wave (CW) to supply energy to passive transponders or to awaken active transponders. In view of diversity, our design concentrates on two mainstream standards, namely ISO18000-6 and EPCglobal Gen2, which have been widely adopted in the world. ISO18000-6 defines one model (i.e., Interrogator-Talks-First) with four types: A, B, C, and D. EPCglobal Gen2 is considered the de facto standard instance of ISO18000-6 at 860-960 MHz for types B and C. We use type C as an example to introduce our design and implementation. Nevertheless, extending the design to other types is similar.

B. Application Scenarios

Tagcaster enables a spontaneous setup of a radio broadcast service for vehicle-mounted radio receivers. Such a service is useful in a wide range of application scenarios. We provide a few examples. (1) Charging notification. This scenario is a fundamental service of ETC systems for drivers, who should be precisely informed of how they are charged when passing through an ETC tollbooth. The traditional means is to watch an LED indicator installed at the tollbooth. With Tagcaster, drivers are informed by tuning to the radio. (2) Overspeed warning. An increasing number of states or regions have begun adopting an average speed (i.e., total distance traveled divided by the time interval) for overspeeding surveillance. ETC systems deployed at adjacent critical junctions can now warn drivers of potential violations of local traffic regulations. (3) Road traffic broadcast. Drivers can listen to special traffic news and the latest traffic conditions around the ETC station.

C. Comparison against Alternatives

• Why not install an AM station at the tollbooth? ETC service is private for each driver but AM station is designed for large-scale public radio service. The radio signal can be received kilometres away. Installing an AM station at each tollbooth for ETC broadcasting will leak user’s privacy and disturb the surrounding radio. Instead, RFID is a short-range communication and many existing RFID systems with beamforming technology [6]–[8] or directional antenna can provide desired directional communication. Therefore, an RFID system can only cover the desired area (ETC lane) so that to protect user’s privacy. • Why not use Bluetooth or Wi-Fi? Cars equipped with Bluetooth chip have their Bluetooth antennas inside to communicate with smart devices or wearables [9]. An antenna inside a car can be shielded from signals from an ETC station by the car’s metal body. By contrast, radio antennas are already outside the car where FM or AM signals are the strongest. Finally, we stress that the primary merit of Tagcaster is that it does not require the firmware or physical layer of ETC transceivers to be modified. Therefore, Tagcaster can fully co-exist with the given alternatives for complementarity even when they are already deployed in several stations.

III. TAGCASTER DESIGN

In this section, we first exploit the nonlinearity effect and zeroth downconversion in radio receivers and describe how Tagcaster can utilize the zeroth downconversion for its design.

A. Exploiting the Nonlinearity Effect

Primer on AM Radio. All AM radio systems work from 520 to 1700 kHz without a license from FCC. Radio receivers usually adopt the superheterodyne design, as displayed in Fig. 2. The RF signal (@ f_r) is amplified by the pre-amplifier to improve the signal-to-noise ratio (SNR). Then, the amplified RF signal enters a superheterodyne mixer along with the output of the local oscillator, which is tuned to a frequency (@ f_l) that is higher or lower than the intended reception frequency. As a result, the mixer output includes two signals, that operate at f_r + f_l and f_r - f_l. The sum signal at f_r + f_l is immediately filtered out by the following IF filter. This difference can always be at a fixed value of the frequency offset and is called the intermediate frequency (IF). This stage is called the first downconversion or superheterodyning. Superheterodyning exhibits good performance because radio components can be optimized to work at a single intermediate frequency. The desired baseband signal is then extracted by the detector (e.g., an envelope detector of Foster-Seeley discriminator), which performs the second downconversion by tuning the center frequency to the expected. The downconverted audio are transmitted to the speaker.

Nonlinearity Effect. In RF system, circuits are designed to work linearly. If an RF amplifier receives an input signal S, then output signal, denoted by S_{out}, is given as

$$S_{out} = AS$$

(1)

where A is the amplification factor. The amplifier is supposed to scale the signal magnitude and introduce a constant phase distortion. Unfortunately, the non-linearity effect of the amplifier can generate many harmonics. Consequently, the practical output signal is given by:

$$S_{out} = \sum_{k=1}^{\infty} A_k S^k = A_1 S + A_2 S^2 + A_3 S^3 + \cdots$$

(2)

where A_k are the gains of the various harmonics introduced by the circuit. These components are called fundamental, second-order, third-order and so on. The third-order and higher-order harmonics attenuate fast and become undetectable. Therefore, our focus is on the first- and second-order terms only. If the input signal S is a superimposition of two sine waves with different frequencies f_1 and f_2, that is, $$S(t) = \sin(2\pi f_1 t) + \sin(2\pi f_2 t)$$, where t is time, then the equation can be expanded.
MHz, the amplified signals appear at 2f1 + f2. Four new frequencies (i.e., using a trigonometric formula as follows:

\[ S_{out} = S(t) + S^2(t) \]

\[ = \sin(2\pi f_1 t) + \sin(2\pi f_2 t) + \sin(2\pi f_1 t) + \sin(2\pi f_2 t))^2 \]

\[ = \sin(2\pi f_1 t) + \sin(2\pi f_2 t) + \frac{1}{2}((2 - \cos(2\pi f_1 t) - \cos(2\pi f_2 t)) + \cos(2\pi f_1 t) - \cos(2\pi f_2 t)) \]

Four new frequencies (i.e., 2f1, 2f2, f1 + f2 and f1 − f2) are created after the first-stage magnification. Translating into actual numbers, when f1 = 920 MHz and f2 = 920.7 MHz, the amplified signals appear at 920 MHz, 920.7 MHz, 2 × 920 = 1840.7 MHz, 2 × 920.7 = 1841.4 MHz, 920 + 920.7 = 1840.7 MHz, and (920 − 920) MHz = 700 kHz. The first five frequencies are filtered out by the IF filter. However, 700 kHz remains. The net effect is that the UHF signal appears at a low frequency of 700 kHz, which radio receivers can process. The nonlinearity effect was considered a type of “pollution” in previous work. Nevertheless, we explore this underlying physical property as an opportunity to achieve cross-technology communication between ETC system and AM radio receivers. Since difference frequency is our interest, this item is extracted from Eqn. 3 and expressed as follows:

\[ S_i(t) = \frac{1}{2} \cos(2\pi(f_1 - f_2)t) \] (4)

where \( S_i(t) \) is the downconverted signal due to the nonlinearity effect.

B. Activating the Zeroth Downconversion

The previous discussion inspires us to leverage nonlinearity to pull down UHF signals to the radio band. Specifically, Tagcaster enables an ETC reader to transmit to two carriers, whose frequencies are denoted by f1 and f2. When the two signals pass through the pre-amplifier simultaneously, a low-frequency signal appears at |f1 − f2| in the amplifier. This process is equivalent to conducting an additional downconversion before the first and the second downconversions at the mixer and detector. To distinguish them, we refer to the downconversion caused by the nonlinearity effect at the pre-amplifier as the zeroth downconversion. Fig. 2 shows their stages and process order. The next discussion is about the leveraging of the zeroth downconversion for Tagcaster’s radio service.

Upconversion at the reader side. Suppose that an ETC reader and a radio receiver work at frequencies of \( f_r \) and \( f_r + f_e \), respectively. To activate the zeroth downconversion, our ETC reader modulates the audio data onto two carriers at \( f_r \) and \( f_r + f_e \) simultaneously. For clarity, we call the new carrier at \( f_r + f_e \) the shadow carrier. The left part of Fig. 3 illustrates an example where \( f_r = 550 \) kHz and \( f_e = 920 \) MHz. The audio data are modulated onto the 920 MHz original carrier and 920.55 MHz shadow carrier. Formally, \( v(t) \) denotes the audio signal, which is a low-frequency signal below 20 kHz. Then, the output upconverted RF signal from the reader is given as

\[ S_i(t) = v(t)(\cos(2\pi f_e t) + \cos(2\pi(f_r + f_e)t)) \] (5)

One might wonder why a single-tone signal is not generated at the shadow carrier for the downconversion only. The hardware limits the current commercial ETC reader to work at a single channel for each reading. Further details are discussed in §V.

Downconversion at the receiver. After receiving the mixed signal transmitted from the ETC reader, the pre-amplifier in the radio receiver automatically performs the zeroth downconversion. Substituting the given signal into Eqn. 4, a new signal is produced as follows.

\[ S_i(t) = \frac{1}{2} v^2(t) \cos(2\pi(f_r + f_e)t) \] (6)

\[ S_i(t) \] is the result of the zeroth downconversion. It operates at the radio frequency \( f_r \), which the receiver can process. That is, the zeroth downconversion can pull the mixed signal at \( f_r \) and \( f_r + f_e \) down to radio frequency \( f_r \). The right side of Fig. 3 presents the entire workflow at the receiver. \( S_i(t) \) can be further downconverted twice by the mixer and the decoder to extract \( v^2(t) \), which is finally played by the speaker. Notably, the side effect of our design is that the audio signal is distorted due to the squaring, i.e., \( v^2(t) \). We can eliminate this distortion by taking a square root of the raw audio signal (i.e., \( \sqrt{v(t)} \)) before it is modulated onto the carriers, such that the downconverted signal \( S_i(t) = \frac{1}{2}(\sqrt{v(t)})^2 \cos(2\pi f_r t) = \frac{1}{2} v(t) \cos(2\pi f_r t) \).

IV. ENGINEERING TAGCASTER

The core of Tagcaster is the engineering of dual-carrier upconversion at the ETC reader (i.e., modulating the audio data onto two carriers) because only such an upconversion can activate the zeroth downconversion at the radio receiver. However, achieving this task is challenging because Tagcaster is required to be a transparent service. The only way to change the behaviors of ETC readers is to feed data in the application layer in accordance with corresponding standards. Given such a strict constraint, two engineering challenges are discussed in this section.
Modulating the Audio Signal. The shadow carrier is used to pull RF signals from UHF down to the radio frequency at radio receivers. The first challenge is how to generate an undefined shadow carrier by complying with ETC regulations.

- Modulating the Audio Signal. An AM radio conveys the analog audio data by changing the amplitude of the carrier, whereas the reader baseband only accepts the digital bitstream from the upper layer. The second challenge is how to carry the analog data through a digital wireless system.

A. Primer on RFID Transmission

To explain Tagcaster, how an ETC reader works must first be introduced. Readers are required to generate high-power CW, which persistently supplies energy to passive transponders in the field. Two data links are involved. The first link is data transmission from readers to tags, called downlink transmission. The second link is the opposite, which is called uplink transmission. Given that Tagcaster broadcasts audio in a single way, we only introduce the downlink here. Fig. 4(a) illustrates a schematic of a reader transmitter that contains four main components: PIE encoder, local oscillator, mixer, and antenna. The entire workflow is sketched.

Baseband Encoding. A reader encodes the data (e.g., commands) coming from the host using PIE in baseband. Fig. 4(b) illustrates the coding scheme. PIE coding uses different durations to represent bit zero and bit one. Bit zero has the duration of a single Tari, whereas that of bit one equals to Tari + X. Tari is the unit duration for the signaling reference. It can be set as from 6.25 to 25 μs. The duration of bit one is always X-μs longer than that of bit zero and must be between 1.5 and 2 Tari. Both bits start with a high voltage and end with a low voltage. The durations of low voltage for the two bits are the same and equal to the pulse width (PW). Tari, PW and X can be set by users to suit their scenarios.

Modulation. The PIE-coded baseband signal is then multiplied by the UHF carrier generated from a local oscillator to produce the output RF signal. Fig. 4(c) shows this procedure. Given that the multiplication only changes the amplitude of the carrier to carry the baseband signal, it is called as AM. In terms of carrier frequency, the ISO/IEC 18000-6 standard only specifies a broad spectrum (i.e., 820-920 MHz) and allows local agencies to regulate the channel division. For example,
By changing the value of $Tari$, the fundamental frequency of the square signal at the baseband can be varied within $40 \sim 160$ kHz (i.e., $f_b \in [40, 160]$ kHz). However, we desire a frequency shift of $f_e \in 500 \sim 1700$ kHz (i.e., AM radio frequency). Even the upper limit of $f_b$ (i.e., 160 kHz) cannot reach the lower limit of $f_e$ (i.e., 500 kHz) because FCC regulation only allocates 500 kHz bandwidth to RFID reader for each channel (see Fig. 5).

The fundamental of signal processing indicates that the square wave is composed of infinite sinusoidal harmonics. Thus, $S_b(t)$ can be expanded as follows by using the Fourier series.

\[
S_b(t) = A_b + \frac{4}{\pi} \sum_{n=1,3,5,\ldots} \frac{1}{n} \sin(2\pi nf_b t)
= A_b + \frac{4}{\pi} \left(\sin(2\pi f_b t) + \frac{1}{3} \sin(2\pi 3f_b t) + \frac{1}{5} \sin(2\pi 5f_b t) + \cdots\right) \tag{8}
\]

Instead of a single-tone signal, $S_b$ is composed of infinite odd sinusoidal signals at frequencies of $3f_b, 5f_b, 7f_b, \ldots$, which are called first-order, third-order, fifth-order harmonics, and so on, respectively. By substituting Enq. 8 into Enq. 7, the modulated signal in the air is updated as follows:

\[
S_{w} = \left( A_b + \frac{4}{\pi} \sum_{n=1,3,5,\ldots} \frac{1}{n} \sin(2\pi nf_b t) \right) \cos(2\pi f_e t)
= A_b \cos(2\pi f_e t)
+ \frac{2}{\pi} \sum_{n=1,3,5,\ldots} \frac{1}{n} \left(\sin(2\pi (f_e + nf_b) t) + \sin(2\pi (f_e - nf_b) t)\right) \tag{9}
\]

Enq. 9 indicates that the output RF signal actually appears at $f_e, f_e \pm f_b, f_e \pm 3f_b, f_e \pm 5f_b, \ldots$. Given that $f_b \in 40 \sim 160$ kHz, the fifth-order harmonic $5f_b$ falls into the range of 200 $\sim$ 800 kHz. It has 300 kHz overlapping (i.e., from 500 $\sim$ 800 kHz) with the allowable AM radio spectrum. To visually understand the spectrum, we illustrate various bands and their relation in Fig. 5. Therefore, the frequency of Tagcaster’s radio service can be fixed at any frequency between 500 and 800 kHz (highlighted in red). Conversely, if radio frequency $f_r \in [500, 800]$ kHz, then we should set the duration of the bit zero at the baseband to.

\[
Tari = 1/f_b = 5/f_r \tag{10}
\]

where $f_r = 5f_b$. For example, if we choose $f_r = 500$ kHz, then $Tari = 1/f_b = 1/100$ kHz $= 10 \mu s$.

2) Whitening the Baseband with Zeros: Our basic idea of generating a shadow carrier is to force the reader to transmit a long sequence of bit zeros. This procedure is called as baseband whitening. However, commercial ETC readers only accept the predefined commands from hosts. A long sequence of zeros is unacceptable. About 30 commands defined in the ISO18000-6 or EPCglobal Gen2, among which we select the NAK command to whiten the baseband. Fig. 6 shows the structure of this command, which starts with a three-bit unmodified preamble and contains eight-bit command code.

The time consumed for one NAK transmission is given as

\[
(3 + 2 \times 1.5 + 6) \times Tari = 12 \times Tari \tag{11}
\]

where 3 $Taris$ are for the preamble, 1.5 $Taris$ are for the two ones (i.e., $X = 0.5 \times Tari$), and 6 $Taris$ are for the six zeros. NAK command is selected for us in two reasons. First, the payload of the command is fixed to the bitstream of $11000000$ where 75% of the bits are zeros. Second, NAK is a mandatory command that all commercial readers must support. In practice, we can command the reader to keep transmitting NAKs to achieve long-sequences of bit zeros approximately. The transmission of the remaining 25% bit ones almost does not affect the broadcast because their presence lasts for a short time (a few microseconds) in each cycle. Therefore, the instant pause in voice is hardly noticed by humans.

To verify this idea, we uses an ETC reader (refer to §V for details) to transmit a sequence of NAKs by setting $f_r = 500$ kHz. Then, we set the parameter of $Tari$ to $10 \mu s$ (see Enq. 10). We also employ USRP to receive the RF signal. Fig. 7 illustrates the baseband signal of the received signal in time and frequency domains. As desired, the signal spikes exactly at 100 kHz (i.e., first order), 300 kHz (third order), 500 kHz (fifth-order), and so on. This results verify that we can whiten the reader’s baseband using the NAKs.

\[
\begin{array}{c}
\text{(a) Time domain} \\
\text{(b) Frequency domain}
\end{array}
\]

C. Modulating Audio Signal

Both AM radio and ETC reader adopt amplitude modulation to carry baseband signals. At first glance, Tagcaster can directly use the modulation component in an RFID reader for the AM modulation. Unfortunately, this naive approach fails to work in practice for two reasons. First, AM radios stations and receivers are designed for processing analog audio signals, but readers can only process digital signals. Specifically, the envelope of the reader’s carrier only has two levels (Fig. 7(a)), whereas an AM radio uses different amplitude levels to represent quantized analog audio data (Fig. 8). Second, this
approach requires the modification of reader hardware and firmware, which violates our design principle of transparency.

The essence of amplitude modulation is to carry data by changing the amplitude of the output RF signal. Commercial RFID readers can dynamically set the transmitting power in a real-time. For example, Impinj R2000 [10] has 31 power levels that the user can set. This functionality inspires us to modulate audio signal by adjusting the power of the output RF signal directly instead of modulating the multiplication. In doing so, we can skip the baseband processing to achieve amplitude modulation equivalently. The whole procedure is sketched as follows:

- **[Step 1] Sampling:** First, Tagcaster resamples audio data every 12 Tari. The sampling period is exactly equal to the duration of a NAK command (see Eqn. 11) because NAK is the minimum unit before which the transmitting power can be updated. Correspondingly, the sample rate is equal to $1/(12 \times Tari) = f_r/60$ Hz (see Eqn. 10). Given that $f_c = 500 \sim 800$ kHz, the sampling rate is equal to $8.33 \sim 13.33$ kHz. An 8 kHz sampling rate is regarded as adequate for human speech. For example, the telephone system usually uses 8 kHz ADC [11]. Thus, our sampling rate can fully address the common quality demand of radio broadcasting. Fig. 8 provides an example where each box represents one sampling.

- **[Step 2] Quantization:** Second, Tagcaster quantifies the amplitude of audio data into 16 levels, namely, four-bit quantization. Each quantified result corresponds to an output RF power level. A normal audio ADC adopts 8-bit or 16-bit quantization. However, we can only set the RF power to one of the 32 predefined levels in the reader. Moreover, we must ensure that the signal can propagate into air with sufficient energy. Only 16 levels (from 15th to 31st) are available for us (four-bit quantization). In Fig. 8, the audio signal is quantized to 16 levels indicated by horizontal gray lines. Our evaluation reveals that four-bit quantization is acceptable.

- **[Step 3] Broadcasting:** Finally, Tagcaster broadcasts the audio samples in such way: for each sample, it initiates a power adjustment and a subsequent NAK transmission. In Fig. 8, the green and red boxes indicate the RF power and NAK commands, respectively. The time cost for power adjustment is almost negligible because it does not require signal processing and is executed quickly (i.e., $< 1$ $\mu$s).

In summary, NAK transmission holds the shadow carrier, whereas the power adjustment modulates audio data. The adjustment affects all RF signals coming out from the reader, so the audio signal is actually modulated onto both carriers ($f_e$ and $f_e + f_r$). This reason explains why we move $v(t)$ outside the sum of the two carriers in Eqn. 5. To validate the effectiveness of Tagcaster, Fig. 9 illustrates a comparison of the raw and received audio signals, both of which represent the sentence “Good morning, Mr. Bob!”.

### V. IMPLEMENTATION

**Tagcaster Reader.** We implement the prototype of the ETC reader for Tagcaster with an USRP-N210 SDR. It is equipped with an SBX daughterboard. An RF power amplifier [12] is used to magnify the max transmitting power to 31 dBm. The prototype fully supports Gen2 PHY [13]. Notably, the USRP emulated reader is used for evaluation purposes to measure low-level PHY information, such as harmonics and signal strength, which are inaccessible by commodity devices.

**Radio Receiver.** We test nine commercial radio receivers, including (1) five vehicle-mounted receivers (VMRs) at Toyota Sienna, Audi Q7, Audi Q5, Jetta Avant, and Jetta Sedan; and (2) four general-purpose receivers (GPRs), which are TECSUN ICR-110, Sony ICF-P36 [14], PANDA T-16, and AMHA 010. The main difference among them is sensitivity. VMRs are sensitive to work with low SNR.

**AM Radio Channels.** Seven radio channels (e.g., $f_r$) are listed in Table I. These channels are not uniformly distributed within $500 \sim 800$ kHz because the sampling rate is 2 MS/s in the reader so the adjustable step of $Tari$ is 0.5 $\mu$s. Moreover, an AM radio receiver allows users to tune the frequency with a step of 5 kHz. However, only five channels are tested in our experiments because C5 and C7 are in conflict with commercial AM stations in our city.

**TABLE I: Radio Channel in Tagcaster**

<table>
<thead>
<tr>
<th>Channel(#)</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Tari(\mu$s)</td>
<td>9.5</td>
<td>9</td>
<td>8.5</td>
<td>8</td>
<td>7.5</td>
<td>7</td>
<td>6.5</td>
</tr>
<tr>
<td>$f_r$(kHz)</td>
<td>530</td>
<td>555</td>
<td>590</td>
<td>625</td>
<td>665</td>
<td>715</td>
<td>770</td>
</tr>
</tbody>
</table>

### VI. EVALUATION

In this section, we evaluate the Tagcaster through series of outdoor experiments.

#### A. Communication Performance

We begin with a group of benchmark experiments to present the performance of the communication from the ETC reader to the AM radio receiver in terms of different parameter settings. The zeroth downconversion only occurs in radio receivers,
which are composed of highly integrated circuits. We have no direct means to acquire downconverted low-level radio signals from these receivers. Recalling that our ultimate goal is to provide audio service, we use the audio data played from receivers to evaluate the link performance indirectly. The audio is recorded by a microphone in the format of WAV with a sampling rate of 48 kHz.

Moreover, the broadcasting should only be received by the target for privacy protection. Thus, a long-range broadcasting is unprofitable for Tagcaster. Given these considerations, we only present the audio strength in the range of 12 m. The results are shown in Fig. 11. When the distance increases to 10 m, the strength is approximately 20 dB which is sufficient to provide a good quality for the audio decoding. In addition, current ETC stations are usually equipped with two independent antennas in the heading and leaving directions. Thus, the real coverage range for good-quality broadcasting is up to about 30 m in practice.

B. Audio Performance

In this section, we evaluate the quality of the resulting audio signals in terms of PESQ. PESQ is a common metric used to measure the quality of telephony systems [15]. It outputs a perception score between 0 and 5, where a high score indicates good quality. Generally, the audio is good enough to be understood when the score is over 1.2. We manipulate the Tagcaster reader to broadcast the PESQ benchmark dataset [16] and use the official PESQ tool [16] to score the recorded audio data. Given that the PESQ tool only works for the audio data sampled with 16 or 8 kHz, we need to reduce the 48 kHz-recorded audio to 16 kHz. All experiments are conducted in our campus and in nearby noisy and busy streets (10 m away) where many vehicles run at every moment.

2) Characterizing the Broadcasting Range: We also evaluate audio strength as a function of the distance between the radio receiver and ETC reader. We notice that the reading range of an ETC reader for transponders is controlled under 10 m to ensure that a single vehicle closest to the station is identified. Tagcaster aims to broadcast related information about the vehicle. Thus, the broadcasting should be initiated exactly after when the vehicle is identified by the ETC system (i.e., when its distance to the reader is less than 10 m). Moreover, the broadcasting should only be received by the target for privacy protection. Thus, a long-range broadcasting is unprofitable for Tagcaster. Given these considerations, we only present the audio strength in the range of 12 m. The results are shown in Fig. 11. When the distance increases to 10 m, the strength is approximately 20 dB which is sufficient to provide a good quality for the audio decoding. In addition, current ETC stations are usually equipped with two independent antennas in the heading and leaving directions. Thus, the real coverage range for good-quality broadcasting is up to about 30 m in practice.

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AM radio operates at 665 kHz in our city, and its leakage may interfere with these two channels. However, we can still understand the audio marked with a score of 1.4 even in a noisy situation.

3) Audio Quality at Different Driving Speeds: We also evaluate audio quality by considering the impact of driving speed. The Doppler effect can be an issue for UHF carriers, as indicated in §III. Fig. 14 illustrates audio quality as a function of driving speed. In the figure, the positive and negative speeds indicate that the vehicle is heading to and leaving from the ETC station, respectively. The audio quality fluctuates only within the score of ±0.2 compared with the stationary case where the speed is zero. When the vehicle is driving at 50 km/h, the 920 MHz carrier shifts to 42.6 Hz, but the radio receiver only detects a 0.01 Hz shift.

C. Human Experience

We finally investigate the user experience of Tagcaster. We invite 20 drivers to experience Tagcaster service and ask them to rate the service. The rating score is from 0 to 5, where 5 is excellent. Fig. 15 illustrates a comparison of AM radio and ETC service. The subjective opinions of the 20 drivers are strongly positive. They appreciate the in-time wireless voice notification of charging fee using the AM radio, which is described as “extremely convenient and interesting”. Specifically, approximately 60% of the volunteers have rated our service with a score of 4+ whereas only 30% have given scores to existing ETCs.

VII. RELATED WORK

We review related work in three fields.

1) Nonlinearity effect. Although the study and exploitation of the utilization of nonlinearity in diode based devices are not new, the harmonics in the RFID system have only elicited attention in recent years. The harmonic phenomenon in RFID was reported in [17]–[23], which focused on eliminating the negative impact of RF amplifier nonlinearity [24]. The work of [25] characterized the harmonic signals in UHF RFID via extensive experiments. The study of [26] used harmonics to achieve multi-frequency continuous wave ranging and further localize tags in 3D space. The work also explored harmonics as a secondary communication channel [18]. Deepak et al. [27] introduced a new backscatter device for deep issue detection through the nonlinearity effect. However, unlike previous work that focused on tag’s uplink communication, our work is the first to bridge the communication from ETC readers to AM radio receivers.

2) Cross-technology communication (CTC). Many recent studies on CTC introduced deep cooperation between heterogeneous wireless devices. Most of them focused on the technologies in the same ISM band, such as Wi-Fi and Zigbee [28]–[32]. Specifically, WeBee [32] introduced a physical-level emulation technique to provide a high-throughput connection. The work of [33] utilized the harmonic backscatter technique to connect the UHF RFID and Wi-Fi. This work suggested a new type of CTC, that has never been used before.

3) Backscatter and RFID. Similar to RFID tags, backscatterers are battery-free devices that modulate data by reflecting the source signals. Dozens of backscatterers have been proposed in the past years [9], [34]–[39]. Our work is inspired by the FM backscatter [9], which reflects FM radio signals for broadcasting. Previous studies embedded the RFID reader into a bulb to make it easily deployable indoors [40]. ETC transponders have been used to localize and count vehicles for building smart cities [2]. By contrast, our work aims to enhance RFID application in outdoor ETC service with powerful human to machine interaction.

VIII. CONCLUSION

This work presents Tagcaster, a system that enables commercial UHF ETC systems to provide additional broadcasting service with only a software update. Tagcaster is the first system to offer down-converting cross-technology communication. Our extensive experiments indicate that Tagcaster can provide good-quality radio service with only a software updated ETC reader.

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