Caraoke: An E-Toll Transponder Network for Smart Cities

Abari et al., ACM SIGCOMM '15

Motivation/Introduction

- **Background:** RFID is pervasive, everyone has an EZPass, e.g., transponder (mandatory in PA?)
- Deploy RFID readers on street lamps, intersections, everywhere in city (at some cost), as shown in **Figure 3**.
- Interact with e-toll (EZPass) transponders anywhere in an urban environment
- Enables some new **use cases:**

    1. Vehicle flow at traffic intersections
    2. Red light enforcement via localization
    3. Street parking management and billing

Transponder Background

- *Reader* (high powered multi-Watt radio + directional antenna) sends message to tags, tag replies
- But **no MAC protocol** so common practice is to place readers in non-overlapping locations (spatial reuse)
- **Figure 2:** Shows the reader transmitting the 915 MHz sinewave *Query* signal and the transponder's *Response* data packet

    - Simple radio so carrier frequency offset up to 1.2 MHz (that's one part per thousand – typical Wi-Fi radio CFOs are 10-30 parts per million)
    - Transponder response is **On-Off Keyed (OOK):** Each symbol period, transmit carrier for a one, or be silent for a zero.
    - Receive picture – peaks at the CFO value Delta-f (on board)

Contribution/Key Idea

- Let tags collide when they are read simultaenously but view collision in the **frequency domain** – use **carrier frequency offset (CFO)** to separate the tags

Design

- LTE backhaul, solar-powered lamppost-mounted reader

§5: CFO-Based Sharing

- **Goal:** Estimate the number of vehicles crossing a busy intersection
- Take the FFT of collision (sum of many received tags replying at the same time)
    - **Figure 4:** Most likely, # peaks = # transponders responding

1. Need to look at the **distribution** of the transponder CFOs
2. Need to consider **frequency resolution** of the FFT
    - Inversely proportional to FFT **time window T*
    - Tag response 512 us so frequency resolution = 1.95 KHz
    - That's 615 "bins" over a range of 1.2 MHz
    - Eq. 7 gives prob of an accurate transponder count if we just count peaks in the frequency domain

- **Insight:** Time shifting property of DFT – time shift in in the time domain transforms with a phase shift linear with frequency, in the frequency domain.
- Receive two signals R(f) and R(f'), then looking at that with a time shift you get R(f)exp{j2pi*f*tau} + R(f')exp{j2pi*f'*tau}
    - Paper claim: Then magnitude of that bin changes b/c the two frequencies rotate by different amounts and then sum…
- Now a miscount happens when three transponders end up in same FFT bin
    - Very unlikely (math in Eq. 9)

§6: Localizing Transponders

- **Goal:** Localize the transponders, to enable smart parking, red-light violations
- Calculate the AoA at a two-antenna reader via the same math as spatial signatures (**Figure 5** and Eq. 10)
- Do this on a per-frequency basis to separate the AoA estimates for each tag (unnumbered equation on p. 302, lower right column)
- Issue: Sensitivity to small perturbations of Delta-phi at the ends of the two antenna array
    - Fix: Use three antennas in a triangle, switch to the pair that doesn't end-face the tag
    - But need a story for either adding a radio OR switching and then re-querying to get more readings

(only partially discussed in paper)

- Result (**Figure 7**): A *cone* locus, which intersects the road at a *hyperbola*
    - Two readings from two readers results in two hyperbolas, intersect them for location fix.

§7: Measuring Speed

- Localize car at two different locations, NTP timesync, compute average speed

§8: Decoding IDs

- Spectrum is sinc-squared power versus frequency, not white noise
- Nice trick to separate closely-spaced replies in frequency:
    - Estimate channel to one tag
    - Receive another batch of collisions, estimate channel to the same tag and equalize
    - Add the results: the one tag adds coherently, the others are random and average to zero
    - Repeat with even more readings for better results (**Figure 8**)

§9: Coordinating Multiple Readers

- Preceding was interference between tag replies; now consider two readers initiating queries at the same time
    - This is usually OK: sum of two sinuoids is a sinusoid
- Collision of query with tag reply:
    - Listen for duration of query + reply (this is the slot time), then use CSMA/CA like Ethernet/ALOHA

§11: Evaluation

- Implemented in hardware, experimented on quiet urban environment streets
- EZPass transponders in real cars, on real street

Counting Accuracy

- **Figure 11:** Vary the number of transponders responding, accuracy maintains high
    - Collect traces by measuring each transponder in isolation, using highly directional antenna
    - Then sum up varying numbers of transponders (so know ground truth) to obtain another trace instance

Localization Accuracy

- Two readers, 175 localization instances
- Measure **bearing estimation accuracy**, not localization accuracy
    - Accurate to within 4 degrees on average – low intensity multipath reflections outside, line-of-sight path from car to elevated reader.
    - Measured the MUSIC AoA profile (**Figure 14**) to support this.