Time-Resolved Designs for Narrowband Radio Localization and Vehicular Visual Sensing Compromise

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Abstract

The Internet of Things relies heavily on accurate and reliable sensing for applications. *Time-resolved sensing* is a paradigm that leverages fine-grained temporal analysis of sensor signals, and the intrinsic relationship between space and time, to extract rich spatial and contextual information. This concept expands the sensing capabilities in IoT applications, but also introduces new challenges in synchronization, processing efficiency, and security. In my research, I explore both the constructive and adversarial aspects of time-resolved designs, highlighting their dual role in improving the capabilities of IoT systems and exposing potential security vulnerabilities. Specifically, I study how time-resolved radio signals can be carefully processed to achieve indoor localization under narrow signal bandwidth constraints. I also reveal how time-resolved camera-based visual sensing can be exploited to affect vehicular perception.

CCS Concepts

• Computer systems organization → Embedded and cyber-physical systems; **• Networks → Location based services**; **• Security and privacy → Systems security**.

Keywords

Time-resolved sensing, Internet of Things, narrowband radio localization, vehicular visual sensing

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1 Time-Resolved Sensing in IoT

In Internet of Things (IoT) systems, networked devices, such as industrial sensors, actuators, intelligent cameras and mobile platforms, continuously generate and exchange data, enabling real-time, predictive, and data-driven system features. A key requirement for effective IoT systems is reliable sensing of the environment. By accurately capturing and interpreting environmental data, these systems can make informed decisions and adapt to changing conditions in real time. One methodology for achieving this reliability involves measuring data with sufficient *temporal resolution* and leveraging the *relationship between space and time*. In this paper, such an approach is refered to as *time-resolved sensing*.

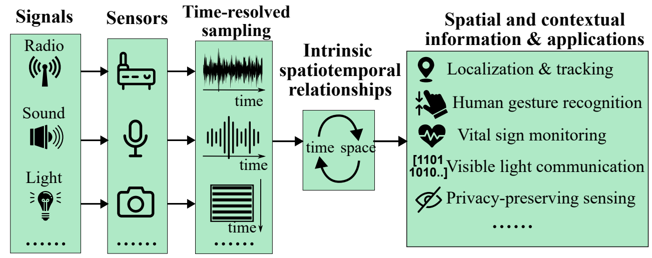

Figure 1: Time-resolved sensing in IoT.

As illustrated in Fig. 1, time-resolved sensing spans multiple domains. For example, radio or acoustic signals can be sampled at suitable time resolutions to determine their propagation times, thereby deriving the distances traveled. This methodology supports various applications, such as device localization and tracking, human gesture recognition, and vital sign monitoring. Similarly, many camera sensors capture visual light signals over time through a rolling shutter mechanism, which expose the scene line-by-line with down to sub-millisecond resolution. This design offers a balance between cost and image quality. Moreover, it inherently encodes a temporal dimension within a single image and brings richer spatiotemporal information, enabling diverse IoT applications, such as visible light communication, landmark-based localization, privacy-preserving sensing, and pose tracking. Taken together, these scenarios illustrate the essential role of temporal resolution in extracting spatial and contextual information. By exploiting time-resolved sensing, IoT systems gain a richer, more fine-grained understanding of their environments, laying the foundation for enhanced sensing capabilities, more intelligent decision-making, and more adaptive responses.

Building upon this principle, I develop *time-resolved designs* that exploit fine-grained timing signals to enhance or compromise IoT capabilities. First, I propose *ILLOC*, a time-resolved narrowband radio localization system enabling unobtrusive indoor localization of LoRaWAN devices. Second, I introduce *GhostStripe*, a physical deployable attack system exploiting time-resolved visual sensing to compromise autonomous driving perception, serving as a preliminary step toward enhancing perception robustness.

2 Narrowband Radio Localization

Low-power wide-area networking (LPWAN) is a wireless access network paradigm that provides narrowband connectivity to the Internet of Things (IoT) objects distributed in a geographic area. Among various LPWAN technologies, LoRaWAN, which is an open data

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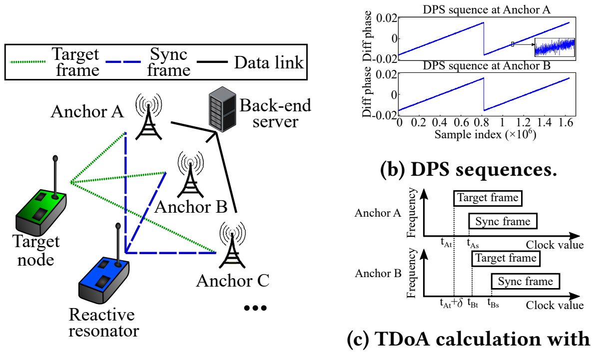

(a) System deployment. **(b) DPS sequences.** **(c) TDoA calculation with JIT synchronization.**

Figure 2: Time-resolved narrowband radio localization.

link layer specification based on the LoRa physical layer technique, has been favorably considered for IoT systems While LoRaWAN is mainly designed for establishing connectivity, being able to localize LoRaWAN devices unobtrusively using their uplink frames is desirable. The unobtrusiveness here means that no special software instrumentation is needed for the LoRaWAN end devices. As such, the localization service is free from entanglement with any other applications running on the LoRaWAN devices; the already deployed LoRaWANs can develop the localization capability seamlessly. My research [1] investigates the feasibility of unobtrusive localization for LoRaWAN devices in hall-size indoor spaces like warehouses, airport terminals, sports centers, museum halls, etc. I study the Time Difference of Arrival (TDoA)-based approach, which needs to address two challenges of poor timing performance of LoRaWAN narrowband signal and independent clock skews among anchors. I propose the *ILLOC* system (Fig. 2) featuring two LoRaWAN-specific techniques: (1) the cross-correlation among the differential phase sequences (DPS) received by two anchors to estimate TDoA and (2) the just-in-time (JIT) synchronization enabled by a specially deployed LoRaWAN end device providing time reference upon detecting a target device's transmission. In a long tunnel corridor, a $70 \times 32\,\mathrm{m}^2$ sports hall, and a $110 \times 70\,\mathrm{m}^2$ indoor plaza with extensive non-line-of-sight propagation paths, ILLOC achieves median localization errors of 6 m (with 2 anchors), 8.36 m (with 6 anchors), and 15.16 m (with 6 anchors and frame fusion), respectively. The achieved accuracy makes ILLOC useful for applications including zone-level asset tracking, misplacement detection, airport trolley management, and cybersecurity enforcement like detecting impersonation attacks launched by remote radios.

3 Vehicular Visual Sensing Compromise

Camera-based computer vision is an essential perception channel of autonomous vehicles, especially for the tasks of traffic sign recognition and lane detection. Thus, reliable camera-based perception is vital to autonomous vehicle's safety. As the rolling shutter technology provides a satisfactory balance between cost and image quality, it has been widely adopted in camera sensor products, including those deployed on vehicles. In my research [2], I studied how the rolling shutter effect (RSE), which has been widely used for time-resolved visual sensing, can be exploited to launch stealthy and stable attacks on camera-based perception systems in autonomous vehicles. I design and imeplement *GhostStripe* (Fig. 3),

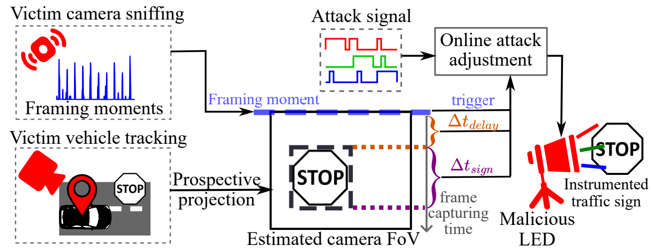

Figure 3: Time-resolved vehicular visual sensing compromise.

an attack system that uses light-emitting diodes and exploits the camera's RSE to create adversarial stripes in the captured images to mislead traffic sign recognition. The attack is stealthy because the stripes on the traffic sign are invisible to human. For the attack to be threatening, the recognition results need to be stable over consecutive image frames. I analyze the principles for achieving stable RSE-based optical adversarial example against autonomous driving perception and present techniques to satisfy the conditions obtained from the analysis. Following the principles, *GhostStripe* controls the timing of the modulated light emission to adapt to camera operations and victim vehicle movements. Evaluated on real testbeds, GhostStripe can stably spoof the traffic sign recognition results for up to 94% of frames to a wrong class when the victim vehicle passes the road section. In reality, such attack effect may fool victim vehicles into life-threatening incidents. To counteract this threat, I also propose *GhostBuster*, a software-based defense module to detect and mitigate the effects of GhostStripe, incorporating a perturbation detector and a sign restorer, effectively restoring the natural appearance of compromised traffic signs and reducing the attack's impact.

4 Future Work

Time-resolved attacks on broader visual sensing tasks. Future work will explore extending the GhostStripe principle to other visual tasks (i.e., object detection, semantic segmentation, and depth estimation). Investigating vulnerabilities introduced by RSE across these tasks and developing targeted or universal defenses will enhance the safety of visual sensing systems.

Application of new time-resolved sensors for robust vehicular perception. Integrating dynamic vision sensors (DVS) into autonomous driving systems could improve perception reliability, especially under challenging lighting and high-speed conditions. Future research can study efficient DVS data processing, DVS vulnerability to novel adversarial attacks, and multimodal sensor fusion with DVS.

Time-resolved infrastructure-free echolocation. Research will investigate infrastructure-free echolocation methods using mobile phone acoustic signals, specifically leveraging analytic approaches based on room impulse response. Addressing challenges like multipath reflections and environmental variations will pave the way for practical, scalable mobile self-localization solutions.

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