

Hybrid-Powered Internet-of-Things for Infrastructure-to-Vehicle Communication

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Abstract—While autonomous and networked vehicles are being designed to navigate under different driving conditions, there is an emerging need for the infrastructure (roadways) to communicate with the vehicles so as to reliably convey current road conditions. Wireless sensors or devices that are embedded inside the infrastructure can facilitate real-time information exchange, however, its design requires a careful trade-offs between different factors such as operational lifetime, communication distance and latency. In this paper, we discuss three particular methods for establishing a radio-frequency communication link within our previously reported framework of infrastructural Internet-of-Things (*i*-IoT). We propose a figure of merit (FOM) to compare and contrast different topologies of infrastructure-to-vehicle (I2V) communication devices which includes the traditional battery-powered approach, a passive approach that harvests RF energy for its power source and only polls a sensor when power is available, and a hybrid approach that leverages an RF harvesting mechanism to activate a battery-powered sensor. The estimated FOM suggests that a hybrid approach is the most pragmatic for the particular use case of road-condition monitoring.

I. INTRODUCTION

One of the challenging problems faced by current generation autonomous cars and also by human drivers is limited visibility during adverse weather conditions, like heavy snow and rain, which causes conventional vision-based or LIDAR-based sensing methodologies to suffer [1]. Several groups have proposed inter-vehicle communication (IVC) as a way of providing safety and position information to operating motor vehicles through the transmission of information between these vehicles [2]. Other works [3], [4] proposed alternative algorithms that can improve visual acuity for lane tracking or collision avoidance in cases of extreme weather conditions; as an extension of IVC, others have also explored infrastructure-to-vehicle communication [5]. In order to combat these issues, sensors can be integrated into the surrounding infrastructure to provide information about the status of the roadways and vehicles' surroundings. To enable communication between smart infrastructure and vehicles, the smart infrastructure needs to be able to rapidly respond to the presence of a vehicle and relay back the relevant information in order allow the vehicle to process the information and act on it accordingly. Embedding sensor systems into the physical infrastructure would afford a physical layer of protection against malicious tampering and give a level of insight not readily available in surface-level sensors. Many general purpose wireless sens-

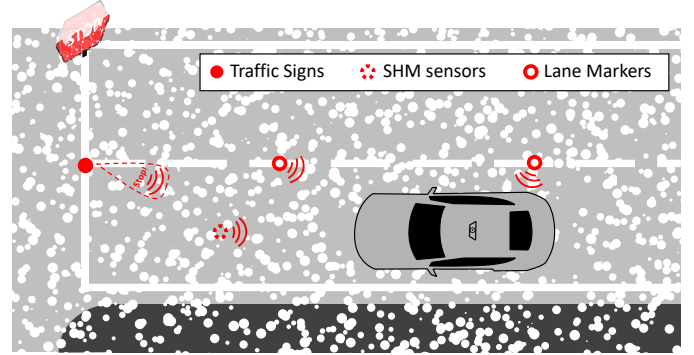


Figure 1. Example infrastructure-to-vehicle communication using *i*-IoT setup in snowy conditions. Data can be static (signs/markers) or dynamic (sensors).

ing platforms have been reported in literature, but the main challenge they face is their limited operational lifetime, which may preclude them from candidacy in long-term embedded sensing applications [6]. There is ongoing work in developing essentially zero-power sensor networks that operate only when needed [7].

In [8] we introduced the concept of infrastructural Internet-of-Things (*i*-IoT) for the purpose of structural health monitoring (SHM), enabled in part by self-powered, embedded sensors. While this specific system was designed to measure strain, the *i*-IoT framework can be extended to other types of sensors and wireless communication platforms. In this paper, we will outline a general platform for the infrastructure-to-vehicle (I2V) sensor system and demonstrate the feasibility of three prototypes that were analyzed with regards to their performance in the target application of interacting with a moving vehicle operating in typical driving conditions. The target application of collecting data from a car moving at expressway speeds (approximately 120 kph) has certain operational life, start-up latency, and transmission distance metrics that must be met. We consider these to be 20 yrs, 100 ms, and 10 m, respectively. In subsequent Sections, we will introduce: II. *i*-IoT framework, III. design examples for an active, passive, and hybrid approach, and IV. our figure of merit (FOM) before concluding in V.

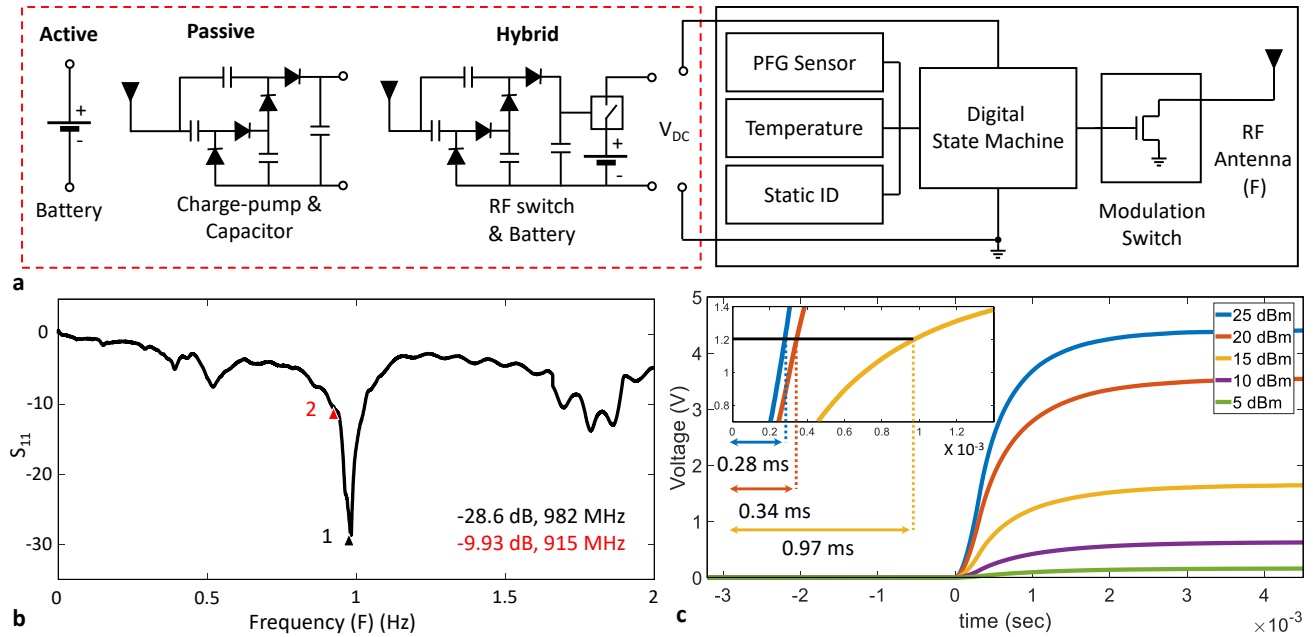


Figure 2. (a) System diagram of three powering modes (in red) for *i*-IoT. (b) Measured return loss characteristics of the PCB antenna. (c) Characterization of startup latency with change in RF transmission power for a seven stage charge pump with 10 nF load.

II. INFRASTRUCTURAL INTERNET-OF-THINGS

Localized data related to physical and structural conditions of the infrastructure could be of great help for drivers to better assess their environment. For example, Fig. 1 shows car driving in heavy snow where the driver has only limited visibility, yet the presence of sensors indicating road position, structural health and traffic signs can help overcome the visual impairment. A general architecture for the sensing system is usually built using dedicated modules for powering, sensing, computing and communication [9] as seen in Fig. 2(a). By developing a modular system, different modules with different characteristics can easily be swapped in and out depending on the desired performance or function of the overall system. Having a flexible fabric for the system architecture also enables the use of a single system for multiple applications, i.e. by using piezoelectric transducers the system could monitor strain levels or by attaching a small non-volatile memory cell it could indicate the presence of a stop sign. It should be noted that such an architecture will sacrifice pure performance to enable modularity, for an approach that can otherwise optimize the device size, power, and startup latency, see [10].

Within any sensor network the primary focus is the information from the sensor itself; for any specific application, we are limited in the applicable sensor modalities — this drastically impacts the flexibility of the rest of the system. For example, choosing a sensor with high power draw excludes the ability to use RF power harvesting and other low energy modalities, however a self-powered sensor like the Piezoelectric Floating-Gate (PFG) or other near-zero-power sensors can provide a large amount of flexibility when designing the remaining system components [11]–[14]. Once the sensing requirements

are met, the powering methodology of the system can be determined. Traditionally, active (i.e. battery) or passive, for example energy-harvesting of RF sources, methods are used to power wireless sensor nodes [15], [16]. A hybrid approach that borrows elements from active and passive to operate within the *i*-IoT framework will be introduced.

III. DESIGN OF EMBEDDED IOTs

We will now examine three prototypes and their performance parameters against a preset group of design parameters. Based on modes of powering and operation, the sensing tags were classified as: active, passive, or hybrid. Each of the systems are designed to collect data from a PFGs digital readout interface and then transmit this data back to the reader in the 915 MHz ISM band, with the systems using a variety of methodologies for RF communication and data transmission. The system level diagram for each of the three prototypes is shown in Fig. 2(a). In order to facilitate RF data transmission, a helical antenna was constructed on a custom printed circuit board (PCB), following the procedure in [18] with the same design shared across all three systems. The efficiency of the antenna was expected to be 40% and it operates with a gain of approximately -9.93 dB as shown in Fig. 2 (b).

A. Active System

The main characteristic of the active system is that the system is always supplied with external power, usually from a battery. We selected a TI CC1310 RF Micro-controller (MCU) to serve as the digital state machine and transceiver for this

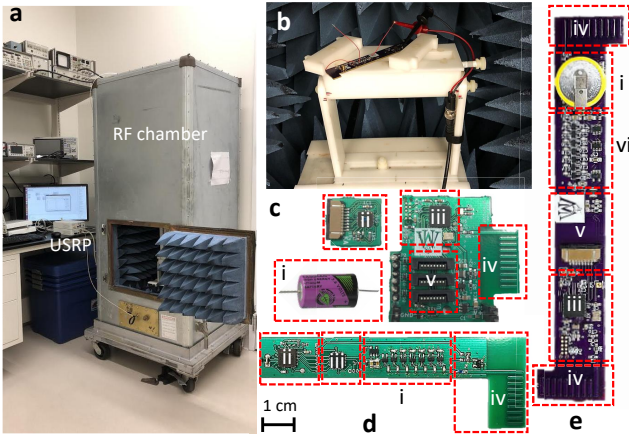


Figure 3. (a) Experimental setup with NI USRP210 as the RF transmitter (b) placement of a sensor in the RF chamber. Prototypes for (c) active, (d) passive and (e) hybrid implementations of sensor tags. (i) Power source (ii) PFG sensor (iii) State machine implemented on MCU (iv) RF antenna (v) removable sensor connection (vi) RF switch for hybrid case.

specific prototype. This system waits for a specific command from an RF interrogator, upon reception it extracts data from the PFG sensor and transmits it back to the interrogator. There are many benefits to this active system, which include a relatively long transmission range (100 m) and a very low start up latency, however the nature of the always-on system results in a very short lifetime, even when using low power modes of the MCU. If an interrogator requests data once every minute, a 1.2 ampere-hour battery might last for seven months in such a system configuration. Other performance parameters regarding the active system can be found in the Table. I, as measured in [13].

B. Passive System

The main distinction of the passive system is that it does not require an external power source. Energy is harvested through a seven stage Dickson charge-pump, which rectifies and stores RF energy provided by the presence of the interrogator, which is constantly streaming out a signal in the 915 MHz ISM band. The charge-pump was built using off-the-shelf zero threshold Schottky diodes (HMS-282x) and bridge capacitors in the pico Farad range. A 20 μF capacitance was chosen to store the rectified charge. After sufficient energy is harvested, the system activation is triggered and power is supplied to an MSP430 MCU. Once powered, the MCU reads data from the PFG sensor and will use backscatter to transmit the data back to the interrogator following industry-standard EPC UHF Gen 2 Air Interface Protocol [12]. A backscatter approach is taken instead of active transmission to minimize the power consumption by leveraging the RF carrier provided by the interrogator. Results regarding the performance of the passive system in comparison with the other systems can be seen in Table. I. Although there is no battery to limit the lifetime, we estimate the lifetime as 20 yrs, based on manufacturer specifications on components such as capacitors. In addition, the start-up latency for this particular implementation is relatively high compared

to an active method due to a slow trickle charging of the 20 μF capacitor, which is used to power the system. A image of this prototype is presented in Fig. 3(d).

C. Hybrid System

It is clear that there are major design trade-offs between the two systems discussed above. The active system trades a larger transmission range and a lower startup latency for a much shorter lifetime. The passive system has the opposite trade-off, allowing for a much longer lifetime in exchange for a shorter transmission range and longer start-up latency. We attempted to balance these trade-offs in our hybrid system. The hybrid system borrows the same seven stage Dickson charge pump from the passive system, but only uses a 10 nF source capacitor, which greatly reduces the startup latency. Once this capacitor is charged to 1.2 V, a power gate switch is activated, supplying current to a CC1310 MCU (from the active system). The CC1310 collects data from the PFG sensor and sends it back to an RF interrogator. A similar concept of using RF-triggered switching has been presented in [19], [20], our proposed method was developed independently using off-the-shelf components and is compatible with most RF standards, and offers a future path for building hybrid systems with rechargeable batteries.

Due to the presence of a battery, the transmission distance of this hybrid system can be much greater than that of the passive backscatter. However, since we utilize a passive antenna for building up a charge in the presence of an RF interrogator, and a second antenna for the active transmission, we can reduce the active transmission power to better match the target application requirements. An image of this prototype can be seen in Fig. 3(e). The strength of the RF interrogator's transmission power will affect the startup latency of the passive frontend, and measured results for the 10 nF case are presented in Fig. 2(c). Note that, although the hybrid system is able to communicate longer distances its read distance will be limited by the sensitivity of the passive frontend. Finally, assuming the system is turned on and interrogated once every 10 seconds (traffic rate), the estimated lifetime comes to around 16.85 $\approx$ 17 yrs, which is directly related to the lifetime of the components and the amount of charge that can be stored on the battery.

IV. DEFINING A FIGURE OF MERIT FOR I2V SENSORS

Application-specific target parameters, like lifetime (l_A), startup latency (t_A) and transmission distance (d_A), are graphically shown in Fig. 4 as a red triangle. Giving equal weight to these parameters we define a figure of merit (FOM) as the overlapping area between the regions confined by the triangle edges of the prototype (l_P, t_P, d_P) and the target application. More specifically,

$$\text{FOM} = \frac{\text{Area} \{ \min(l_P, l_A), \max(t_P, t_A), \min(d_P, d_A) \}}{\text{Area} \{ l_A, t_A, d_A \}}$$

and the estimated values for each prototype are summarized in Table. I and illustrated (see digital version for color) in Fig. 4. Note that latency and distance are considered on a log scale.

Table I
KEY SPECIFICATIONS AND FOM

Parameter	Active	Passive	Hybrid
PCB Area (cm ²)	17.08	10.62	22.68
Radio Band	915 MHz ISM		
Battery Capacity	1.2 Ahr	-	0.5 Ahr
Avg. Power Consumption	684 μ W	320 μ W	10.15 μ W
Lifetime	0.6 yrs	20 yrs	$\approx$ 17 years
Distance	100 m	0.5 m	8 m
Startup Latency	15 ms	200 ms	26 ms
FOM	0.2725	0.5236	0.8227

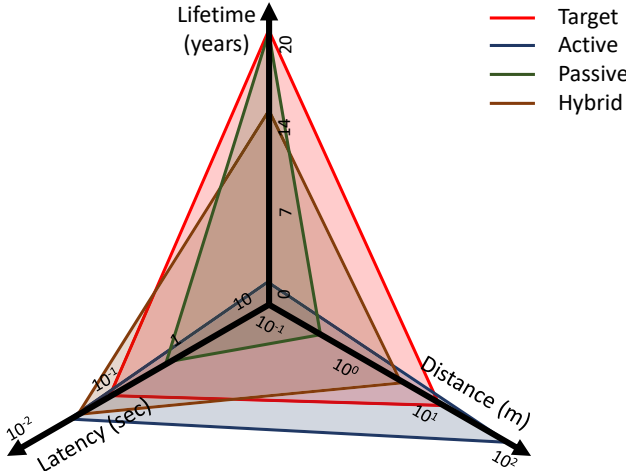


Figure 4. Comparison across the prototypes in terms of distance, latency and the device lifetime and FOM estimated based on the overlap area of triangles.

V. CONCLUSION

In a target application of infrastructure-to-vehicle communication, specifically an automobile traveling on an expressway, we roughly specify that a sensor node should have an operational lifetime of at least 20 yrs, startup latency less than 100 ms, and a communication range of at least 10 m. From the FOM introduced in Section IV, we can compare and contrast three approaches for implementing a sensor node. The results presented in Table I and Fig. 4 corroborate our claim that a hybrid approach could lead to more ideal sensor nodes; moreover, this approach is inherently adept at utilizing a rechargeable battery, which could extend the operational lifetime beyond 20 years, dependent on battery technology and other component (most notably, capacitors) lifetimes. Employing more optimized methods can also extend the read distance of the hybrid case beyond 100 m [19]–[21].

VI. ACKNOWLEDGMENT

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