Real-time Infrastructure-to-Vehicle Communication using RF-Triggered Wireless Sensors

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Abstract*—An infrastructure-to-Vehicle (I2V) communication framework enables autonomous and semi-autonomous vehicles to localize and detect the presence of infrastructure markers like lane-dividers, stop signs or infrastructure health information which can enrich the information captured by cameras and LIDAR systems and enhance driving experience. However, the key challenge in designing electronic tags for I2V platform is to make them operate in embedded conditions and while being able to retrieve wireless data with lower latencies that can support real-time I2V. In this regard, we propose hybrid RFID sensors that are battery-powered and integrated with a RF trigger element that can be selectively triggered using an appropriate RF source. In this paper, we experimentally demonstrate the functionality of a hybrid-powered prototype under a controlled operating conditions and validate the power consumption and latency using prototypes assembled using commercial-off-the-shelf components. The measurement results demonstrate triggering distances of 1m can be achieved at driving speeds of at-least $40\,\mathrm{km\,h^{-1}}$, and the operational life-span of the tag is estimated to be greater than 20 years.

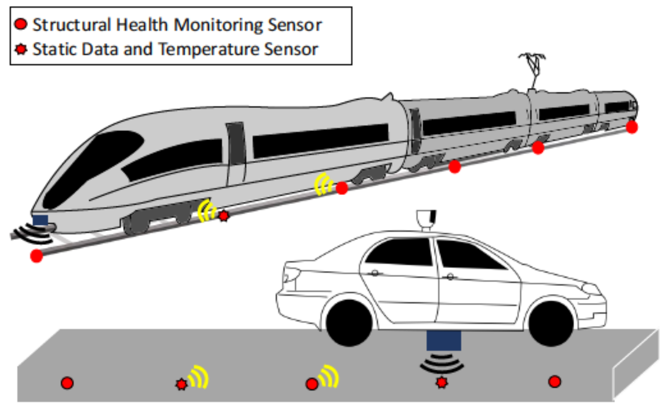

Figure 1. An illustrative example of Infrastructure to Vehicular (I2V) communication, where the infrastructure is endowed with sensor nodes that provide dynamical data and static information pertinent to real time decision making in vehicles traveling along the route.

I. Introduction

Technological advances in real-time sensing and computing modalities have enabled the development of self-driving and driver assisted vehicles [1] that can operate them autonomously or with the assistance from human drivers. However, the development of an ideal sensing platforms for vehicles remains an elusive target, one that neither human or modern artificial-intelligence (AI) systems has perfected — especially when faced with non-ideal conditions (e.g. occluded vision from fog, loss of wireless connectivity, unexpected changes in infrastructure conditions). For example, LIDAR based systems suffer especially poor performance in instances of heavy snow and rain [2]. To mitigate these problems, several algorithmic and machine learning based methodologies have been developed to increase the performance of these systems [3]–[5]. For conditions where these traditional AI approaches may encounter difficulties, a framework based on Infrastructure-to-Vehicle (I2V) communication can provide additional information about their surroundings to aid in their decision making process. Example scenarios of an I2V platform is illustrated in Fig. 1 where the sensors can be embedded inside the infrastructure, whether it be railway tracks or pavements, and can transmit information about their surroundings to the vehicles in real-time [6]. Due to its modular nature this framework could be extended to other motorized vehicles.

Previously, we evaluated three different topologies of sensors and tags that could be used to demonstrate I2V communication and compared their performance based on target application specifications. These topologies include: (a) battery-powered active sensor; (b) energy harvesting based passive sensor; and (c) a hybrid sensor built by integrating a minimally-loaded RF trigger wakeup for a battery-assisted wireless transceiver. Although hybrid topology has been investigated in literature in several other variants [7], [8], the RF trigger modality has added advantages of being low latency and longer life span which is crucial in I2V communication [9]. Although the study concluded that the hybrid approach provided the best trade-off we haven't evaluated the performance of the hybrid prototype. In this paper, we present experimental results on power consumption during different modes of operation, evaluate the start up latency and test system performance in simulated deployment conditions.

II. System Architecture and Characterization

The hybrid prototype is designed to provide static data (lane markers, speed limits, infrastructure material) and dynamic data (temperature, damage, etc.) through a wireless link, but only under RF interrogation. As shown in Fig. 2(A)-(B), the hybrid prototype primarily consists of a RF trigger load switch selectively connecting the battery to a sensing platform and a

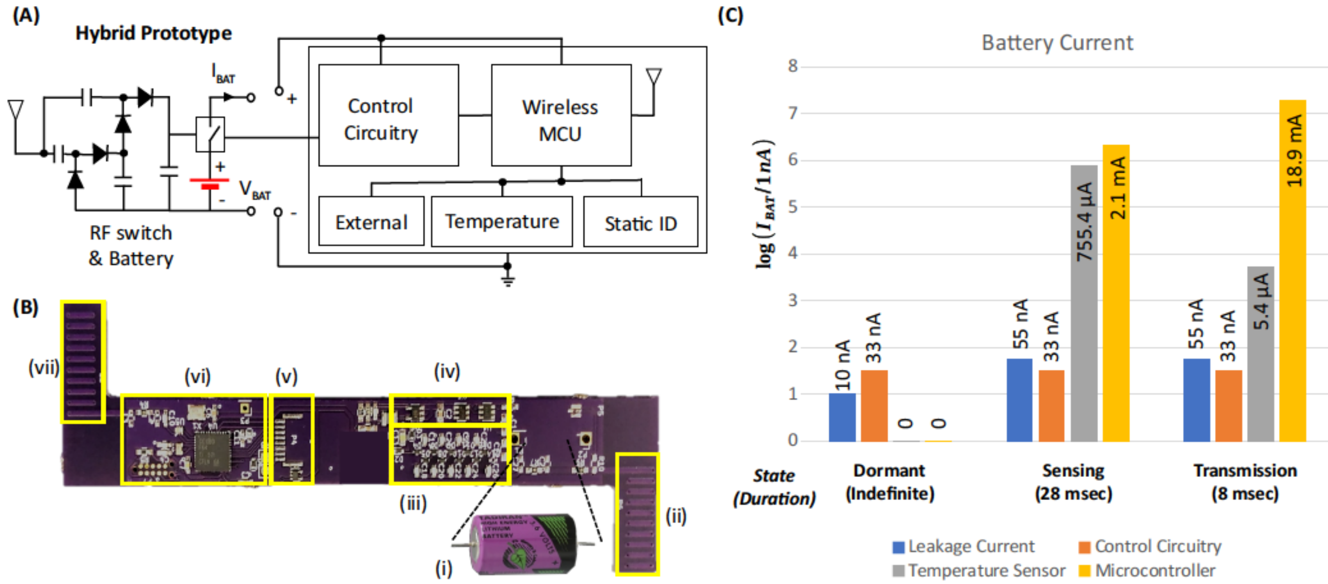

Figure 2. (A) A circuit schematic of the energy harvesting module on the left, and a block diagram of the sensing modules to the right. (B) An image of an implemented prototype containing: (i) Battery (ii) Energy Harvesting Antenna, (iii) Charge Pump,(iv) Control Circuitry, (v) Sensors, (vi) Wireless MCU, (vii) Transmitting Antenna. (C) Plot showing the estimated current supplied by the battery in different operating modes.

wireless microcontroler (MCU). By using a charge pump as the wakeup trigger, the wireless MCU is power-gated, resulting in the MCU only being operational for short time periods (ms).

A. RF-Trigger Wakeup Circuitry

Currently, our primary target is to reduce the response time while increasing the transmission distance and life time of sensor tags that can be embedded in infrastructure. We chose to use a RF-DC converter to implement the RF-trigger to power-gate a battery in order to enable low latency, long distance communication. However, batteries only contain a limited amount of energy, about 1000 mAh in our case, thus it is vital to keep the system in the lowest power state whenever possible. This is accomplished by using an RF triggering circuitry consisting of a five-stage Dickson Charge Pump built using pF capacitors and zero threshold Schottky diodes (SMS7621-079LF, from Skyworks Solutions Inc.). This charge pump operates with an efficiency of approximately 40%, while the helical PCB antenna connected to the input stage is designed for US ISM Band at 915 MHz with a measured S11 of 9.93 dB. Energy that couples onto the antenna is boosted by the charge pump and used to signal an ultra-low power latch (TPL5111, from Texas Instruments) that is connected to a load switch (TPS22860) that isolates the battery from subsequent circuitry. Unlike a traditional energy harvesting approach that attempts to provide the several mA of supply current for a sensor system using the RF to DC charge pump scheme, this method essentially only needs to charge the gate of a MOSFET. By drastically reducing the load of the charge pump, the sensitivity and responsiveness of the system is vastly improved.

At a fixed distance of 1 m, it takes 212 µs for the voltage on the 10 nF source capacitor to reach this threshold with a continuous transmission of 20 dB. Once the voltage on the enable pin of the latch exceeds the switching threshold (530 mV), it has a measured internal latency of 13 ms , which is one of the larger sources of latency in the system. For preliminary system evaluation, this latency was not a major limitation; however, if we require an faster hybrid startup it is recommended that the TPL5111 is avoided in its use as a latch, a latch built using discrete transistors. The timer enable pin is also connected to a pulldown resistor, the value of which causes the internal circuitry of the timer to manually shut of power to the MCU and sensors after a fixed amount of time proportional to this resistance. In our current implementation, this timer operates as a watchdog, preventing the system from getting stuck in an unwanted state. After triggering, the timer will enable the TPS22860 switch, which supplies power to the MCU and various sensors.

B. Data Acquisition and Transmission

The second module contains an RF MCU and multiple sensors which have the capability of delivering both static and dynamic data to a vehicle when it interrogates the tag. For this prototype, we elect to utilize the CC1310 Wireless MCU from Texas Instrument to both collect data and transmit it wirelessly back to the vehicle. After being triggered by the interrogator, the hybrid wakeup circuitry enables the power-gated MCU. Specific to the experiments in this manuscript, we included the LMT84 analog temperature sensor to generate representative dynamic data. As with most MCUs, several other types of sensors can be integrated within this platform to supply a wide variety of information that can be used to

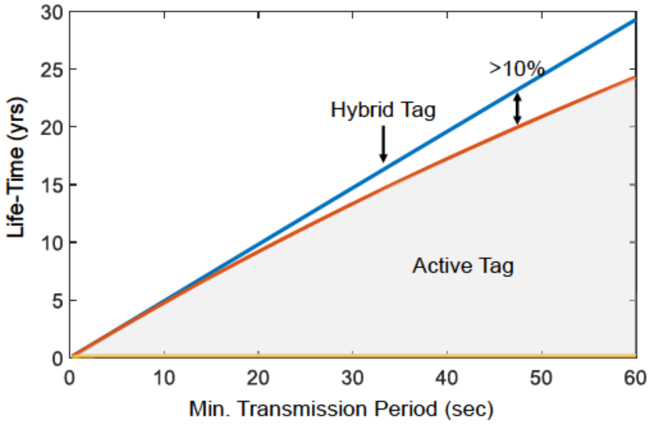

Figure 3. Comparison of hybrid and active sensor in term of lifespan (in years). The shaded region indicates the active sensor operation which can vary based on the implementation.

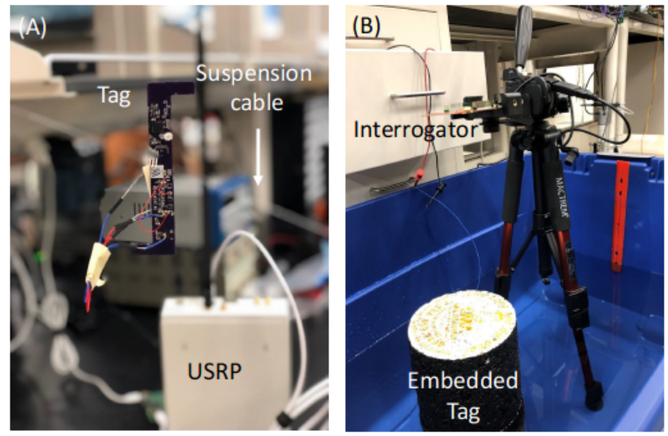

Figure 4. (A) Experimental setup used in speed test. (B) Experimental setup for verifying the functionality in embedded environment.

characterize the infrastructure, provided they operate from a standard analog or digital interface. It is also important to note that adding additional modalities and functions could potentially increase the power consumption or latency of the platform. In addition to the dynamic data, a static 16-byte array is assigned to each sensor, capable of providing a large amount of identification information, such as an infrastructure ID, lane markers, speed limits, road history, or surface material. Once all of this relevant data has been collected, it is transmitted back to the interrogator over a $915\,\mathrm{MHz}$ ISM link with a transmit power of $8\,\mathrm{dB}$. This will allow for the tag to still communicate with the vehicle even if exceeds the interrogator, which is likely to occur when the sensors are embedded under several tens of cm of pavement. We have verified transmit distances (of full information packets) in excess of $10\,\mathrm{m}$. Upon completing its transmission, the MCU will revert back into a dormant state by asserting a done signal to the switch, forcing an immediate shutdown of all subsystems.

C. Interrogator

For these specific prototypes, the interrogation system consists of one software defined radio (SDR) to provide the energy to the RF wakeup circuitry and a separate TI CC1310 connected to a PC for receiving any transmitted data from the hybrid boards. The SDR, provides a layer of flexibility to vary the frequency and power of the RF wakeup carrier which allows us to deliver a sufficient amount of power to each tag despite differences for the environmental conditions that tag could experience. The TI CC1310 reader on the interrogator continuously listens for returning data packets and is able to detect any valid transmissions and logs them back to a PC for further analysis and long-term storage.

III. Results

All prototype evaluation and system testing was conducted in a controlled laboratory environment. The hybrid operation principle shown in Fig. 2(A) reduces the system current consumption down to a few nA when the MCU is not operational. Out of this current budget, only $10\,\mathrm{nA}$ is spent on maintaining the charge on bypass capacitors and $35\,\mathrm{nA}$ for the load switch's latching logic. When under interrogation the voltage built up by the charge pump which in turn triggers the latch of the load switch. Once the wakeup circuitry is activated the wireless MCU can operate as a typical battery-based sensor. After the MCU has collected the sensor readings and transmitted the data back to the interrogator, it will disable the load switch, thereby returning to a nA sleep mode. Typical battery usage of the prototype is summarized in Fig. 2(C). Life-span is be estimated based on the capacity of the battery ($1000\,\mathrm{mAh}$) and the average current required by the prototype in each operation state [10]. Estimated life-span of a hybrid prototype with respect to different traffic rates (transmission per second) is shown in Fig. 3. Also, comparison is presented with respect to active tag, as seen in Fig. 3, indicating the advantage of hybrid prototype over the active prototype by atleast 10% in embedded applications.

A. System Performance Evaluation

In order to test the prototype in situations similar to ones that it would experience in a real world deployment, we constructed three test scenarios. The first test scenario consisted of a zipline apparatus that caused the prototype to move past the interrogator at a fixed distance, and at a repeatable speed, as depicted in Fig. 4(A). The reader component of the interrogator was located a distance of approximately $10\,\mathrm{m}$ away to demonstrate the device's ability to maintain communication with a vehicle even if the vehicle has left the immediate vicinity of the sensor node by the time that a transmission of data occurs. This setup validated that the tag functioned as expected at speeds of approximately $38.26\,\mathrm{km\,h}^{1}$ (velocity estimated from high-speed video). Beyond these levels of speed, we would need to take the prototypes outside of the lab for testing, this is a task that we are in the process of organizing now that the feasibility of this method has been demonstrated.

A second experimental configuration tested the prototype's ability to respond several times in rapid succession, very similar to what it might experience if it were placed on a busy road where many vehicles would interact with it over a short period of time. In order to test this, we developed a circular track with a movement apparatus that caused the sensor node to pass by an interrogator approximately once every five seconds. In this experiment, we were able to have the sensor node trigger and transmit data on one hundred percent of the passes (out of approximately 50 trials). During this experiment, we had zero false triggers, demonstrating that the tag's sensitivity can be precisely controlled. Consider for example, an attack where a malicious party attempts to generate many false triggers in an effort to discharge the node's battery would require the individual to physically stand right over the device, in the middle of traffic, therefore eliminating the risk of remote attacks.

Preliminary testing was also conducted to evaluate the feasibility of the RF-triggered load switch when the node was embedded in a simulated deployment environment, seen in Fig. 4(B). During this testing, the prototype was placed under 8 inches of asphalt that was partially submerged in water while the RF interrogator antenna was placed 16 inches above the surface of that asphalt. This test verified that in stationary conditions, the interrogator was able to consistently deliver enough energy to the tag to trigger the load switch in stationary conditions.

We acknowledge that this testing setup is not the most robust, however we do believe that it provides strong preliminary results for the efficacy of our proposed architecture as an I2V platform and we are currently working on finding locations and outfitting a vehicle to perform more conclusive field tests.

IV. Conclusion

Previously, we had defined a set of specifications for designing an I2V sensing network that would allow for a network to operate with a moving vehicle operating under typical driving conditions [9]. We believe that this prototype and the reported parameters, as summarized in Table. I, can be extended more generally to any set of land based vehicles, and that the an optimized hybrid prototype can be used to create an effective I2V sensor network for providing both relevant static and dynamic data. Testing results in this paper demonstrated the tag operating at interrogation speeds of $38.26\,\mathrm{km\,h}^{1}$ with a one hundred percent success rate in triggering and receiving of packets during a circuit test. Using a typical $1000\,\mathrm{mAh}$ battery, we estimated the prototype will last more than 20 years when responding as frequently as once per minute (traffic-rate), which when paired with future vehicle-to-vehicle standards could provide up-to-date infrastructure data to a fleet of vehicles. In this hybrid configuration, the bottleneck for longer-lasting sensors has been moved from the battery capacity to the operational lifespan of the electronic components (e.g. capacitors, oscillators, etc.).

Table I
Key Device Specifications

Parameter	Hybrid I2V Prototype
PCB Area (cm^2)	22.15
Transmission Power (dBm)	8
Transmission Distance (m)	>10
Lifetime (yrs)	>20
Trigger Distance (m)	1
Trigger Latency (ms)	75
Battery Usage	
Dormant (nW)	141.9
Awake and Sensing (mW)	10.86
Transmitting (mW)	57.2

We are currently moving towards conducting a field deployment and complete system test during which a sensor network will be fully embedded in pavement and interrogated by vehicles that are operating in typical driving conditions.

V. Acknowledgment

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