The Case for Intra-Vehicular Energy Harvesting Wireless Networks

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Abstract—Vehicles have mutated from mechanical systems into cyber-physical systems featuring a large number of electronic control units (ECUs), sensors and actuators. The wiring harnesses used for the transmission of data and power delivery for these components may have up to 4000 parts, weigh as much as 40 kg and contain up to 4 km of wiring. The amount of wiring is actually expected to grow as vehicles evolve with enhanced active safety features and eventually self-driving capabilities, and diversified sensing resources. Consequently, being able to eliminate wires in vehicles is a compelling value proposition: It decreases part, manufacturing and maintenance costs, improves fuel efficiency and, therefore, greenhouse gas emission. Further, it may spur innovation by providing an open architecture to accommodate new components, offering the potential for growth in automotive applications - possibly similar to the computer and phone industry over the past decade. This article presents the envisioned energy harvesting wireless network based vehicle architecture, where sensors and actuators communicate data with the corresponding ECU over a wireless channel and scavenge energy from either ECU via radio frequency harvesting or devices directly attached to them. The potential benefits of this architecture together with the research challenges are then elaborated.

Index Terms—intra-vehicular network, wireless communication, energy harvesting

INTRODUCTION

The exponential increase in the number of electronic components and corresponding wiring harnesses for both data and power transfer within vehicles over the past twenty years started to negatively affect their cost, complexity and fuel economy. This exponential increase is expected to continue over the next years, as vehicles advance further with self-driving capabilities, and communicate with each other and the Internet. Recent advances in low-power wireless networks and energy harvesting technologies together with improvements in local computing may be the key for the removal of these wires.

The envisioned in-vehicle energy harvesting wireless networking architecture contains a central control unit, a battery, ECUs, wireless sensors and wireless actuators, as shown in Fig. 1. In the architecture, sensors send their data to the corresponding ECU over a wireless channel or devices directly attached to them. Actuators receive their commands from the corresponding ECU and power from either ECU without any wiring or an energy scavenging device. ECUs communicate among themselves over a wired backbone network and are connected to the battery of the vehicle to supply power for both their own operation and the operation of the wireless sensors and actuators communicating with them. This article argues about the potential benefits and open research challenges of this architecture.

OVERVIEW OF INTRA-VEHICLE NETWORKS

Until the beginning of the 1990s, each new application within the vehicle was implemented by a stand-alone subsystem containing an ECU device, its corresponding sensors and actuators. The data were exchanged through point-to-point links among these components. As the need for functions to be distributed over several ECUs and information to be exchanged among functions arose, the ECUs were also connected to each other through point-to-point links. This large amount of information exchange has led to a significant increase in the number of wires and connectors, which required the introduction of communication networks multiplexing the communication of ECUs over a shared link.

A similar transition with even more consequences may repeat in the near future from wired to wireless networks. Currently, different requirements of automotive applications for cost, performance and dependability have led to a diversification of protocol designs, such as controller area network (CAN), local interconnect network (LIN), media oriented systems transport (MOST), FlexRay and lately Time Sensitive Networks (TSN). The increasing amount of wiring due to the increase in the number of electronic components for various electrification, safety and Internet of Things applications...
motivates the search for alternative technologies: power line communications and energy harvesting wireless communication. Power line communication reuses power wires inside the vehicle for data communication, taking into account the geometrical characteristics of the cable bundles and activation schedules of electrical functions. On the other hand, energy harvesting wireless communication removes both data and power wires, further reducing cost and complexity of wiring harnesses while providing additional flexibility for the placement of in-vehicle components.

**Benefits of In-Vehicle Wireless Architecture**

The transition to the envisioned in-vehicle wireless architecture is expected to bring benefits on several fronts, as illustrated in Fig. 2.

**Significant Cost Savings**

As in-vehicle wireless architecture is used, billions of dollars will be saved per year for about hundred million vehicles, e.g. 94 million vehicles produced in 2016 [1], in wiring harness, manufacturing and assembly. This estimate assumes that the cost of wireless transceiver eventually reaches zero per unit device considering that part vendors integrate the technology into their process flow, thereby allowing volume manufacturing. The wiring harness cost per vehicle may be as high as a few hundred dollars. Moreover, the costs of purchasing different types of wires, plant internal handling and extra assembly process are again tens of dollars per vehicle.

**Fuel Efficiency and Greenhouse Gas Emission Reduction**

Decreasing the weight of the vehicle by 40 kg would increase fuel efficiency by 2%, which is considerable by automotive engineering standards. As this wireless architecture proliferates, the greenhouse gas emission of vehicles decreases by almost the same percentage, around 140,000 tonnes per day.

**Spurring Innovation**

Eliminating wiring provides an open architecture to accommodate new sensors and actuators. Such architecture allows the integration of new components into vehicle locations where cable connection is not possible. For instance, in Intelligent Tire, a wireless subsystem, including triaxial accelerometers, energy scavenging and signal processing, is embedded in the tyres to measure the grip of a car on the road for a number of safety applications [2]. Moreover, vehicles are already becoming a platform for the development of third-party applications by the extraction of the vehicle data from the CAN bus. For instance, the company Automatic released a car adapter that plugs into the diagnostic port of the vehicle and extracts such sensor data as fuel consumption, acceleration, deceleration, speed, diagnostic information and position. The adapter connects to the smartphone over Bluetooth providing these data to a wide range of applications from check engine light diagnosis to automatic trip tagging. In-vehicle wireless architecture has the potential to extend these applications by the easy installation of new wireless sensors and actuators as needed.

**Research Challenges**

While in-vehicle energy harvesting wireless architecture provides significant gains on several fronts, there are various challenges to tackle, as shown in Fig. 3. In the following sections, these key challenges and potential solutions are discussed.

**Energy Harvesting**

Energy harvesting needs to be incorporated into the wireless networking rather than relying on a finite storage capacity in a battery to provide infinite operational lifetime for the components: The components should have enough energy as long as they are functioning properly.

Automotive applications impose the following constraints on energy harvesting:

- **Predictability**: Energy harvesting should provide predictable amount of energy within the strict delay constraints of a wide range of automotive applications.
- **Adequacy**: Energy harvesting should provide adequate amount of energy for data communication, sensing and computing operations within delay constraint.
• **Small size:** The small form factor of the in-vehicle components enables both easy deployment and low cost.

The novel characteristics of the vehicular environment that may affect energy harvesting capability include

- existence of a large number of metal reflectors,
- production of a lot of vibrations,
- operation at extreme temperatures.

Energy can be harvested from natural sources, inductive and magnetic resonant coupling, and radio frequency (RF). The limited energy transfer range of inductive coupling, on the order of centimeters, and large size of the transmitters for magnetic resonant coupling, on the order of a few meters, make them unsuitable for in-vehicle energy harvesting.

Natural sources that satisfy the predictability, adequacy and small size constraints in the vehicular environment can be used for energy harvesting. Vibration based harvesting has been demonstrated to provide predictable energy levels in a 10 − 200µW range for real-world tire scenarios, which has been proven to be adequate for the ultra-low power transceiver and sensor design in Intelligent Tire application [2]. The adequacy and predictability of vibration based harvesting need to be investigated for the components in other parts of the vehicle. On the other hand, thermal energy harvesting might be suitable for the components within the engine compartment with temperatures up to 250°C. The temperature variation in different locations within the engine compartment should be explored to judge the adequacy and predictability of this technology.

RF energy harvesting is based on carrying energy in the form of electromagnetic radiation with frequency range 3 kHz-300 GHz. RF energy harvesting provides controlled energy at a fair distance with a small form factor. The existing RF energy harvesters are designed at 900 MHz, 2.4 GHz and millimeter wave frequencies. Energy harvesters at 900 MHz have been demonstrated to achieve a peak efficiency of 60%, efficiency above 30% in [−15, 0] dBm input power range and a sensitivity of −22.5 dBm, whereas those at 2.4 GHz provide an efficiency above 20% in [−6, 5] dBm input power range and a sensitivity of −10 dBm. The best energy harvester design at millimeter wave frequency is performed at 24 GHz with demonstrated efficiency of above 20% for input power greater than −10 dBm [3]. Determining the adequacy of RF energy harvesting requires investigating in-vehicle wireless channel characteristics.

The amount of harvested energy for the wireless sensors and actuators is expected to be less than milliwatts, in contrast to tens of kilowatts harvested from other forms of energy harvesting, such as regenerative braking, shock absorbers, to charge the traction battery in electric and hybrid vehicles. The availability of limited energy in wireless components is mainly due to the small size and low cost requirement of these components, with the goal of reducing the weight and increasing space within the vehicle. Charging the traction battery, on the other hand, mainly aims to increase the driving range of electric vehicles, with more relaxed cost and size constraints.

### Wireless Channel Modeling

In-vehicle wireless channel modeling is required to test the feasibility and optimize the performance and robustness of data communication and RF energy harvesting systems at different frequencies.

Channel measurements at 900 MHz and 2.4 GHz focus on testing the feasibility of communication in a limited number of locations, a maximum of 4 transmitter-receiver location pairs, within the engine and passenger compartments [4], [5]. The path loss, delay spread and coherence time parameters have been derived. The packet loss probability has been measured to be below 1%, which can be decreased further through time, frequency and space diversity at the data access protocol. Considering the measured maximum path loss of 55 dB and maximum allowed transmit power of 4 W at these frequencies, the minimum received power is expected to be around −20 dBm. Given that the sensitivity of existing RF energy harvesters is around −20 dBm and −10 dBm at 900 MHz and 2.4 GHz, respectively, as explained in the previous section, RF energy harvesting may be feasible at these frequencies. Testing and optimizing the robustness of the data communication and energy harvesting require collecting data at a larger number of locations and deriving all channel parameters, allowing the regeneration of the wireless channel.

Channel measurements in the 3 − 10 GHz frequency range for ultra-wideband (UWB) communication focus on developing a simulation model for the wireless channel within the engine compartment, passenger compartment, and beneath the chassis [6], [7], [8], [9]. These simulation models are derived based on the wireless data collected for at least 24 transmitter-receiver pairs, different types and conditions of the vehicle. Given the maximum allowed transmit power of −11.3 dBm over 1 GHz bandwidth in this frequency range, a maximum of 58 dB measured path loss corresponds to a minimum received power of around −70 dBm. This received power level may allow data communication at this frequency. Packet loss characteristics considering transmitter design and the derived channel model need to be further investigated. However, RF energy harvesting is not feasible at this received power level.

Channel measurements at 60 GHz focus on characterizing the channel based on the data collected for at most 200 transmitter-receiver pairs within the passenger compartment [9], [10]. The comparison between 3 − 10 GHz and 60 GHz channel characteristics demonstrates that an average additional path loss of 20 dB is experienced at millimeter wave frequencies. This is mainly due to the increase in carrier frequency and higher loss in common materials. Given the maximum conducted power of 10 dBm in Europe, the usage of directional antennas with gain of 25 dBi at both ends may increase the minimum expected received power to −20 dBm. This minimum achieved received power level can be increased further by the placement of multiple ECUs. Given that the sensitivity of energy harvester at millimeter wave frequencies is −10 dBm, both energy harvesting and data transmission may be feasible at millimeter wave frequencies. Data collection with directional antennas at a larger number of locations in different vehicle compartments and different
transmission directions under various movement scenarios is required to design a robust communication and RF energy harvesting system at this frequency.

**Transceiver Design**

Automotive applications and energy harvesting impose the following requirements on transceiver design:

- **Low energy consumption:** Energy harvesting provides very limited energy to the in-vehicle components. The minimum received power is $-20$ dBm at 900 MHz, 2.4 GHz and 60 GHz and can be further increased by the placement of multiple ECUs in the same compartment. RF energy harvesters mostly provide a minimum of 20% efficiency for received power above 0 dBm, resulting in at least 200 µW available energy. Vibration based harvesting can also provide up to 200 µW, although the amount of energy harvesting for locations other than the tire in the vehicle has not been investigated yet. Assuming half of this energy is reserved for sensing and computing, the available energy for operating the radio is around 100 µW.

- **Heterogeneous data rates:** The transceiver needs to provide a fairly high transmission rate to meet the delay requirements of various vehicular applications in 1ms-1s range, as provided in Fig. 4. Since many in-vehicle components share the wireless channel, the minimum required data rate is around 1 Mbps.

- **High temperature operation:** Since the temperature within the engine compartment can go up to 250°C, the transceiver design may need to consider the operation at high temperatures depending on its location.

- **Small size:** Small size and low complexity constraint on the transceiver enables low cost deployment of in-vehicle components.

The low power receivers and transmitters at the in-vehicle wireless components should provide data rate of at least 1 Mbps and power consumption of at most 100 µW on average. The data rate and power consumption performance of the example previous designs in the literature are shown in Fig. 5. There exist a low power receiver providing 1 Mbps data rate with 50 µW power consumption at 315 MHz [11], and many low power receiver designs attaining very close to the desired performance at other frequencies [12], [13], [14], [15]. These designs may need to be revisited to meet the desired data rate and power consumption depending on the frequency of interest. On the other hand, the transmitter designs in the 3–10 GHz frequency band usually aim low power consumption at high enough data rate and small size. [16] presents the design of a UWB pulse generator with power consumption of around 500 µW at 1 Mbps data rate and size 0.54 mm². The low power transmitter designs at 60 GHz in a standard below 90 nm CMOS process mostly aim very high data rates above 4Gbps with power consumption below 200 mW at transmit power of 10 dBm [17]. Although wireless personal area networks aim low power consumption in the nodes, the achieved power levels are still not low enough for energy harvesting networks. For instance, Bluetooth Low Energy (BLE) at 2.4 GHz, such as Texas Instruments CC2541, achieve 1 Mbps data rate with power consumption below 20 mW at 0 dBm transmit power. Furthermore, the standards developed for vehicular networks, e.g. IEEE 802.11p, mostly aim vehicle-to-vehicle or vehicle-to-roadside communication without considering any energy constraint. These transmitter designs need to be investigated for the possibility of reducing power consumption to the desired level by low duty cycle operation while considering the settling time of the circuits. At some frequencies, novel transceiver designs may be required to achieve the tight power consumption requirement of wireless communication in the harsh vehicular environment.

**Electromagnetic Compatibility**

Electromagnetic compatibility is a strict requirement of vehicular electronic components enforced by standardized testing procedures to regulate both unintentional electromagnetic emissions from electronic components and susceptibility of these components to electromagnetic disturbances. Although test procedures and failure criteria have been clearly defined for in-vehicle wired networks, there exists no international test standard for wireless networks.

Spread spectrum techniques aim to transmit a signal over a bandwidth considerably larger than the frequency content of
the original information to reduce both unintentional electromagnetic emissions and provide better resistance to interference. The packet reception performance of ZigBee and Bluetooth Low Energy standards, based on spread spectrum at 2.4 GHz, however, has been demonstrated to degrade significantly in the presence of interference [18]. UWB is another form of spread spectrum technique incorporating the transmission of short duration pulses with emitted signal bandwidth exceeding the lesser of 500 MHz and 20% of the center frequency. However, UWB still exhibits significant degradation of the bit error rate performance in the presence of narrowband interference. Therefore, various interference mitigation techniques adopting adaptive and predictive methods have been proposed with different receiver complexities, but with no consideration of the strict delay and reliability requirements of in-vehicle applications.

The distinguishing propagation characteristics of millimeter wave frequencies are expected to inherently provide electromagnetic compatibility without complicating receiver design. Large attenuation of millimeter wave frequencies over distance and the feasibility of packing large number of antennas in small form factors allow beam-forming with very large gains. This directional narrow beam transmission towards the intended receiver combined with the high attenuation through the vehicle reduces interference to the electronic systems. Further measurements need to be performed within and nearby the vehicle at different frequency bands to test their electromagnetic compatibility.

Security

Security is a major barrier to the widespread deployment of in-vehicle wireless networks. Actually, the first in-vehicle wireless network, Tire Pressure Monitoring System (TPMS), currently being integrated into all new cars in both U.S.A and Europe, has been demonstrated to be susceptible to security attacks [19]. Each in-tire wireless sensor in TPMS inserts a 32-bit identifier into the packet and communicates it over wireless channel without relying on any cryptographic mechanism. This allows not only tracking of vehicles through these identifiers, raising privacy concerns, but also message spoofing injecting such forged data as low tire pressure warnings into the corresponding ECU, preventing proper operation of the overall system. Furthermore, an attacker who is able to infiltrate any ECU has been demonstrated to adversarially control a wide range of automotive functions, such as disabling brakes, stopping engine, by using CAN vulnerabilities. The requirements for providing secure in-vehicle wireless architecture are listed as follows:

- **Encryption**: Every wireless data packet should be encrypted to prevent passive attacks, where an attacker is able to interpret data gathered through snooping. The low-power processors and radios in the wireless components require sufficiently light-weight cryptographic algorithms and short cryptographic keys while providing enough resistance to cryptanalysis.

- **Authentication**: Both the authentication and integrity of every wireless packet should be provided to prevent replay attacks, where the received packet is repeatedly retransmitted to deceive the in-vehicle receiver components. This requires the inclusion of a message authentication code into transmitted packets. This code should be short enough to reduce the overhead on packet transmission.

- **Susceptibility to jamming**: The only attack that may not be resolved by encryption and authentication is jamming. Jamming involves malicious nodes transmitting signal at the frequency of in-vehicle communication to avoid error free reception.

Security protocols proposed for in-vehicle wireless networks focus on encryption and authentication mechanisms for TPMS. [19] proposes many alternatives for master key sharing, including rare event imprinting, external tool imprinting and safe environment imprinting. These different key sharing mechanisms need to be further analyzed in comparison to each other. Efficient mechanisms are also proposed for the regular update of the session key based on the lightest symmetric primitives relying on hardware or light software implementation of current standards. These methods need to be extended for general in-vehicle wireless components,
incorporating their data generation characteristics and delay requirements into the security protocol.

No previous work has focused on the resistance of in-vehicle wireless networks to jamming. Better electromagnetic compatibility characteristics of millimeter wave frequencies may inherently prevent such attacks. Wireless channel measurements need to be performed to determine the interference level from outside of the vehicle to the in-vehicle wireless communication among vehicular components at various frequencies.

**Data Access Protocol**

The data access protocol needs to ensure satisfying the heterogeneous delay requirements of wireless in-vehicle components with extremely high reliability given the small amount of energy provided by energy harvesting as follows:

- **Delay constraint:** In-vehicle components generate packets in either time-triggered or event-driven manner. Time-triggered components transmit small-sized data packets periodically at various pre-known frequencies to guarantee that the control system has the appropriate performance. The data access protocol should exploit the pre-known nature of these periodic transmissions to satisfy the jitter constraints in presence of the variability of wireless channel conditions. On the other hand, event-driven components generate small-sized data packets at random times triggered by the changes in the monitored condition. These packets should be allocated with minimum access delay in presence of the unpredictability of transmission times.

- **Ultra-high reliability:** The packets of both time-triggered and event-driven components should be transmitted with error probability on the order of $10^{-9}$. Such high level of transmission reliability can only be achieved by incorporating diversity techniques in frequency, space and time into the data access protocol.

- **Energy harvesting:** Energy harvesting from predictable natural sources, such as vibration and heat, and RF, provides very limited energy to the wireless components. Therefore, the data access protocol should put the radio of the components in sleep mode if they are not scheduled to transmit or receive any packet. If energy is harvested from natural sources, then the energy generation pattern should be estimated and used in the data access protocol. If RF energy harvesting is used, then the data access protocol should also determine the RF harvesting parameters, such as timing, duration and communication direction.

Protocol design for wireless in-vehicle networks is still in its infancy. Most of the studies for in-vehicle networks demonstrate the limitations of current protocols, e.g. IEEE 802.15.4, in meeting the low latency and high reliability requirements of vehicular applications [20]. Indeed, the protocols proposed for wireless networked control systems may be used within the vehicle due to the tight interaction of vehicular control systems with the wireless communication among sensors, actuators and ECUs. However, these protocols do not address the constraints of in-vehicle networks, disregarding wireless communication imperfections and event-driven components.

**Energy Harvesting**

- Predictability
- Adequacy
- Small size

**Transceiver Design**

- Low energy consumption
- Heterogeneous data rates
- High temperature operation
- Small size

**Electromagnetic Compatibility**

- Regulation of electromagnetic emissions
- Regulation of susceptibility to electromagnetic disturbances

**Security**

- Encryption
- Authentication
- Susceptibility to jamming

**Data Access Protocol**

- Delay constraint
- Ultra-high reliability
- Energy harvesting

Fig. 6: Requirements of energy harvesting, transceiver, data access protocol, security and electromagnetic compatibility.

The only vehicular wireless communication protocol considering the tight interaction with vehicular control systems was proposed in [21]. The protocol is based on a time division multiple access mechanism incorporating a scheduling algorithm that achieves maximum adaptivity by distributing node transmissions uniformly over time rather than allocating them immediately as they arrive. This also results in the uniform distribution of unallocated time slots, allowing the transmission of event-triggered sensor nodes with minimum delay and retransmission of lost packets before their deadline.

The vehicular communication protocols need to be extended to achieve ultra-high reliability and incorporate energy harvesting. Recently, machine-type communication with ultra-high reliability and ultra-low latency requirements has attracted a lot of interest in the research community. The extension of the in-vehicle wireless networks for ultra-reliable transmission requires analyzing the correlation of channel characteristics over time, frequency and space under various scenarios within different vehicle compartments. This allows to determine the best diversity technique suitable for in-vehicle networks. Moreover, all the protocols designed for vehicular control systems, and wireless networked control systems in general, assume the availability of constant amount of battery energy. These protocols need to be extended for the arrival of energy over time considering energy harvesting characteristics.

**Conclusion**

We highlighted the large potential of in-vehicle energy harvesting wireless networks in vehicular application innovation, cost reduction and fuel efficiency. We reviewed previous results and outlined open research problems in energy harvesting, in-vehicle wireless channel measurement and modeling, ultra-low power transceiver design, electromagnetic compatibility, security and data access protocol design to make these wireless networks a reality in the automotive world, satisfying their requirements, as summarized in Fig. 6.
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