Modeling for Deployment Techniques for Intra-Car Wireless Sensor Networks

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***Abstract*—The paper discusses the deployment of wireless sensor networks for intra-car monitoring and control in various automotive application scenarios. Major challenges consist of enabling robust radio communication protocols for challenging environments like the car body and offering high confidence guarantees on timely data collection and quality. Simulation results are introduced and discussed for radio communication modeling and power efficiency of the sensing nodes. It is argued that by effective integration with existing subsystems by means of IPv6 based network architectures or CAN-enabled embedded gateways, these can bring benefits and open up the interconnection towards inter-car communication through higher level concepts up to vehicular sensor networks.**

Keywords—wireless sensor networks; automotive applications; constrained radio environment; system integration;

I. INTRODUCTION

Among current environmental and economic challenges, along with stricter safety regulations, modern cars are being increasingly equipped with ever more advanced sensing, computation and communication equipment. This shifts the focus from purely mechanical design to intensive usage of rugged electronic and systems design using numerous sensors, actuators and intelligent devices. The various subsystems of this reference modern car, such as: drivetrain, safety, comfort, etc. are controlled by tens of electronic control units (ECUs) which are interconnected by means of complex real-time communication protocols and thick wire harnesses. Simply using such a large number of cables increases significantly the overall weight, with environmental and performance impact, and cost of the vehicle, while severely restricting design options for the manufacturer. Another notable tendency is that towards "electrification" of various subsystems inside the car, on the road towards large scale adoption of electric vehicles e.g. electric power steering, which are more suitable to monitor and control by means of digital technologies and advanced data processing and decision algorithms.

The main idea behind the paper is to investigate whether, given proper consideration in the design, implementation and testing phases, wireless sensor networks (WSNs), currently extensively used for environmental and ambient monitoring applications [1], can become a viable solution to partially replace or enhance current wired measurement and control subsystems, first for non-critical functions. Several researches have been performed in this direction but there are still open issues to be resolved. An early analysis was carried out in [2] where latency for the IEEE 802.15.4 family of protocols for low-rate wireless personal area networks (LR-WPAN) depending on network configuration and topology was performed. An ample review was done in [3] for general wired and wireless communication in car sensor networks and the potential for low-rate low-power protocols like Bluetooth, ZigBee, etc. in various applications was underlined and the conclusion was drawn that as well as in other domains, there persists a strong need for standardization in the field enabling wider adoption of such technologies.

The fundamental concept of exploiting local computation of the sensing nodes and multi-hop wireless communication that produces a small-scale decentralized monitoring and control architecture able to cope better with faults and unexpected events in central in intra-car WSNs. As opposed to the term inter-car communication or better known as vehicular sensor networks (VSN) in which the cars become collaborative entities in a multi-agent system framework for road monitoring [4] and early-warning systems, we refer to intra-car communication by means of wireless sensor networks. This is viewed as the design, analysis and deployment of such systems to increase passenger safety and comfort whilst enabling cost savings for the manufacturer. Specific advantages range from small size and autonomous operation to easy software-defined reconfiguration and role-assignment for the nodes. Though unpredictable by nature, the usage of wireless communication in such a scenario can even supply timely and high-quality data to network control devices for various car subsystems as long as some analytical and/or empirical bounds to these delays can be determined, permitting the design of robust delay-tolerant control strategies. Suitable local information processing structures have to be designed to effectively manage the collected data and direct integration with existing subsystems has to be enabled through dedicated interfaces like protocol convertors, bridges and gateways.

The rest of the paper is structured as follows. Section II discusses related work in the field of intra-car wireless sensor networks and actual implementations, establishing a context for the present contribution. Section III reviews a list of potential benefits for large scale intra-car wireless sensor network applications, the particular challenging nature of the operating environment prone to radio interference and attenuation, extreme temperatures and large temperature gradients along with mechanical vibrations. Simulation results using ubiquitous computing modeling and development tools like the Contiki/COOJA suite for prototyping wireless sensor networks in a reference scenario are given in Section IV. Section V concludes the paper and highlights future work directions.

II. Related Work

The electronic design of an embedded 2.4GHz CMOS sensing node for automotive applications is introduced in [5]. Such approach produces low-power, low-cost small, sensing and communication modules which can be easily integrated in the car to monitoring and transmit various data. The use of the 2.4GHz Industrial, Scientific and Medical (ISM) frequency band allows unlicensed radio communication with good data rates while being more prone to interference offers a broad scope. The modular system design permits the integration of several modules in a complete system. The authors of [6] use MICAz motes, sensor boards and TinyOS software to measure various aspects of an automobile journey from acceleration and fuel consumption, to tire pressure monitoring, illumination and driver's vital signs. Main contributions consists of a large range of experimental data collection in a realistic scenario along with the design and implementation of an arterial pressure monitoring prototype which feeds data into the system concerning driver status. A promising application for WSN active noise control in cars is discussed in [7]. Here the authors carry out an in-depth study for embedded sensor nodes with various controller and radio transceiver architectures and IEEE 802.15.4 communication protocols. A classification of different Medium Access Control (MAC) schemes for intra-car is performed according to specific communication metrics like packet delivery rate (PDR), average latency (AL) and power consumption. It is concluded that by using time division multiplexing (TDMA) along with guaranteed time slots (GTS), for deterministic behaviour, average latency can be under 10ms at a network level, making them suitable for active noise control applications.

III. System Modeling

Several items within the design space of intra-car wireless sensor networks have to be discussed, as a preliminary step for feasible potential deployments on a larger scale:

- **Communication**: low-power, low data rate radio multi-hop mesh communication using deterministic medium access schemes and error correction and resilience mechanisms;
- **Power supply**: conventional using batteries associated with low duty-cycle operation for long autonomous operation and maintenance [8], using a form of energy harvesting from mechanical energy, vibrations or temperature gradients e.g. self-powered window open buttons;
- **Security**: exposing car subsystems through wireless communication creates a critical entry point for malicious external entities which has to be secured, an example was highlighted in [9] where attackers hijacked the tire pressure monitoring systems (TPMS) to gain access and inject packages into the main communication bus of the car;
- **Sensors**: ranging from binary, on-off detectors, to conventional temperature, humidity, light, acceleration sensors and to specialized sensing units for air quality, acoustic and picture and video capture;
- **Integration with other subsystems**: at the gateway level the sensor network has to be interoperable with other car subsystems using other types of wired or wireless protocols, co-existence among various low-power radio protocols has also to be assured e.g. Bluetooth and ZigBee;
- **High level tools**: multi-stage development and implementation toolchain to support such applications.

A robust modeling approach should take into account these criteria in an iterative fashion, ranging from requirements definition to component selection, simulation, hardware emulation with realistic radio and operating environment models and experimental deployment for validation. Experimental results have to be incorporated back into the modeling framework in order to mitigate problems and fine tune the operation of the wireless sensor network at the network protocol, data collection and processing or energy efficient operation levels. Actual software and hardware modular components have to be tested for compatibility and compliance given the stringent regulation of the domain upon the system safety and security of automotive applications.

Figure 1 illustrates a system architecture for an intra-car wireless sensor network where the sensing nodes are integrated in the body of the vehicle. The coordinator of the network is a central gateway equipped with the suitable radio interface and connected to the other subsystems for bi-directional communication. Six nodes are tasked with measuring relevant parameters and relaying the values towards the central collection entity. Optionally, data can be aggregated within the network to produce higher level pieces of information and reduce congestion for high data rate scenarios. This can be implemented either by means of standard aggregation operators: MIN, MAX, COUNT, AVG, or by more advanced schemes and probabilistic approaches. The network coordinator performs all functions related to the operation, maintenance and time synchronization, collecting besides process data and generating commands, also statistics and metrics of the wireless communication protocols, used on-line or off-line to optimize network behaviour. Another approach would be to provide the end-user with the option of task reconfiguration or produce a generic infrastructure which can generate and process data from a variety of investigated phenomena. Also, a modular construction of the sensing nodes allows the installation (and stacking) of various sensing modules, tailored to the given application with dedicated input/output channels for digital and analog sensor interfaces and communication buses.

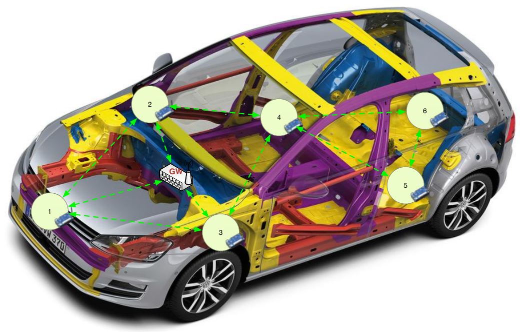

Fig. 1. Multi-hop Intra-car Wireless Sensor Network

Particular attention has to be given to sensors used to feed data in control loops for critical and non-critical processes. Depending on the sampling period, guarantees have to be imposed on timely data collection. For this case in an usual TDMA communication scheme the need for optimal network wide per-node allocation of transmission slots arises. As opposed to CSMA schemes where medium access is provided non-deterministic fashion in either collision avoidance (CA) or collision detection (CD) modes, TDMA requires the implementation of a central scheduler and time synchronization among nodes. Using techniques derived from real-time task scheduling like uniform scheduling and earliest deadline first (EDF) can lead to good results. This is applicable to periodic sensor sampling but also has to accommodate aperiodic messages sent downstream from the base station towards the end nodes and upstream non-data messages from the end nodes towards the sink. A mechanism has to be provided as well for event handling like alarms on sensed data and to compensate for lost packets leading to retransmissions. The problem of optimal uniform scheduling of nodes transmission times in subframes of periodic frames can be formulated as follows [10], with several constraints:

minimize $\max_{j\in[1,M]} \sum_{i=1}^{L} a_{ij} t_i$ // maximum active time of subframes

where

$\sum_{j=k}^{k+s_i} a_{ij} = 1$ **for** $k \in [1, M - s_i + 1], i \in [1, L]$ //periodic case

$t_i \le d_i$ **for** $i \in [1, L]$ // delay requirement

$t_i(p_i + p_{tx} + p_{rx}) \le e_i$ **for** $i \in [1, L]$ // energy requirement

$t_i = \frac{L_i}{x_i}$ **for** $i \in [1, L]$ // transmission time

Fig. 2. Uniform scheduling optimization for TDMA Intra-car WSN [10]

where t_i is the transmission time for packet i, to be optimally scheduled under energy and delay constraints, e_i and d_i. Given an active time a_i, the final goal is to assure optimal allocation of the transmission slots in a cooperative medium-access scheme with real-time bounds.

Cyber-physical Systems (CPS) approaches which can potentially be adapted to implement dependable intra-car wireless sensor networks have emerged and are applicable to such a deployment. The main advantage brought forward by this paradigm is the seamless linking of the physical (sensing and actuation) layer with the cyber domain responsible for the control decision via a networking/communication intermediate layer. This type of design produces end-to-end robust systems able to operate at desired performance indicators. Two examples of recent toolchains designed for this domain are WCPS [11] for structural health monitoring and control and GISOO [12] for flow and level control on didactic training platforms. These leverage and integrate a combination of control system design tools like the MATLAB/Simulink environment for technical computing, along with toolchains specific for WSN development and deployment like TinyOS and Contiki respectively, with the results so far showing up very promising.

IV. Simulation Results

In order to simulate our design approach, we use a dedicated environment for wireless sensor network simulation and an implementation of the 6LoWPAN IPv6 protocol. It uses the Contiki [13] operating system for resource constrained embedded networked sensors, along with the COOJA [14] framework for reliable simulation and protocol testing. Replicating the system architecture in Figure 1, the testing scenario consists of 6 sensing nodes and one data sink running an UDP protocol over RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks, in different radio medium environment configurations. We use emulated Tmote Sky nodes which have the following hardware configuration: Texas Instruments MSP430 F1611 16-bit microcontroller with 48kB Flash memory and 10kB RAM, CC2420 IEEE 802.15.4 2.4GHz radio transceiver, embedded temperature, humidity and light sensors and USB communication interface. For this purpose, the COOJA environment integrates with MSPSim for instruction level emulation of the MSP430 controller platform with dependable results. Simulation uses four radio models included in the as available options: UDGM – Constant Loss, UDGM – Distance Loss, DGRM – Link Loss and MRM – Multi-path Ray-tracer Medium. In the Unit Disk Graph Model (UDGM), two nodes can communicate if they are both within the area of a circle of radius r. The two versions use either an ideal probability in the Constant Loss version or a variable, user-defined transmission (TX) and reception (RX) probability for the nodes in the communication range, in the Distance Loss case. For UDGM, the probability of success for reception at node i can be expressed as a function of the distance between nodes, d, the radio transceiver range, r, and the success ratio rx, as in Equation 1:

$$P_{RX_i} = 1 - (d^2 - r^2)(1 - rx) \quad (1)$$

The Directed Graph Radio Medium (DRGM) offers two significant enhancements over UDGM: the ability to introduce asymmetric links between nodes with different transmission probabilities depending on the vertex orientation and also propagation delays. Finally, the most realistic radio environment option is Multi-path Ray-tracer Medium (MRM) which and can account for more complex environments with obstacles producing attenuation, refractions, reflections and diffractions. Figure 3 illustrates our test network with radio coverage in UGDM – Distance Loss model and simulated radio traffic overlay. The green circle denotes the transmission range of the radio transceiver of node 7, acting as radio base station, whilst the grey area illustrates the interference domain with other neighboring radios.

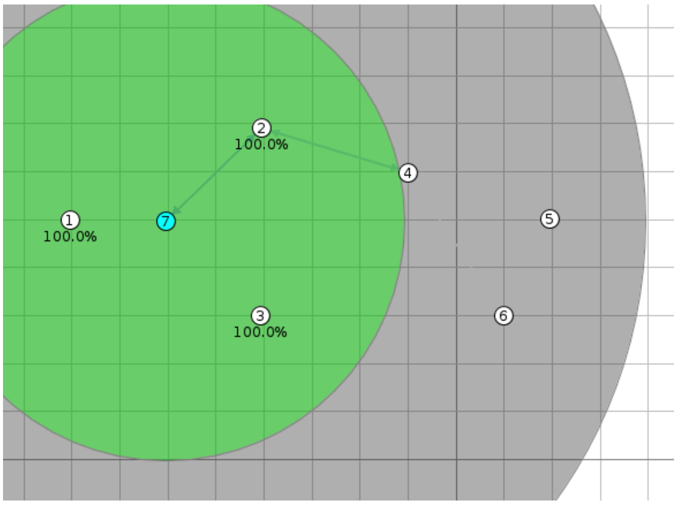

Fig. 3. COOJA Simulation Environment with Unit Disk – Distance Loss Radio Model and RPL-UDP Communication

Experimental results collected through the sink node ID 7 are shown in Figures 4-6. Based on the reported data, the simulation environment computes the average power consumption, average radio duty cycle and the Estimated Transmission Count (ETX) metric for each of the nodes. ETX is computed at both link and route level, with the route ETX being the sum of the link-level ETX form data source to sink. The power consumption is decomposed in categories, considering the contribution of the low-power memory, CPU and the radio in listen and transmit modes, shown in Figure 4. It can be seen how a majority of power consumption occurs in the radio listen stage, giving an insight on the best approach to implement power efficiency routines by reducing the time in which the node sits in idle-listen mode, waiting for messages from neighboring nodes or the sink. Based on these values, a software module can be implemented to estimate node life-time in relation to the power source or energy harvesting efficiency of the individual nodes. In Figure 5 the radio duty cycles in the range from 0.7% to 1.35% are shown. These are computed as the time the chip is on, either in listen or transmit modes, relative to a reference time period. Due to its positioning within the network acting as a router at a larger number of hops from the sink, node 5 has higher power draw in the initial set-up phase. Overall, as this is a typical collect-store-send application, power draw in listen mode is larger than in transmit mode as nodes spent most of their active time listening from packages from the sink/network coordinator and routing requests and route updates from neighbours than transmitting their own data. Collected data is exported and stored from the simulation environment for off-line analysis.

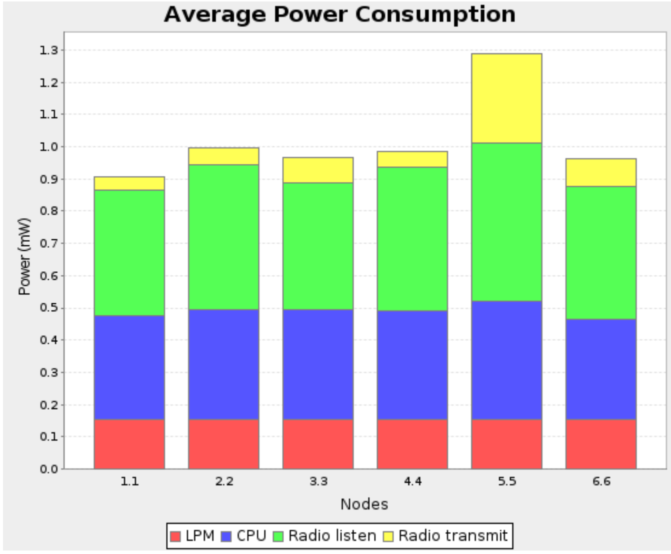

Fig. 4. 6 Node IPv6 WSN Simulated Average Power Consumption

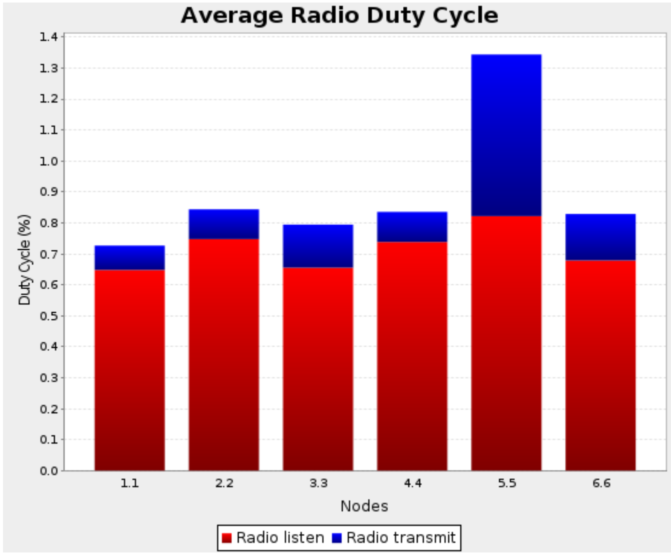

Fig. 5. Per-node Radio Duty Cycle

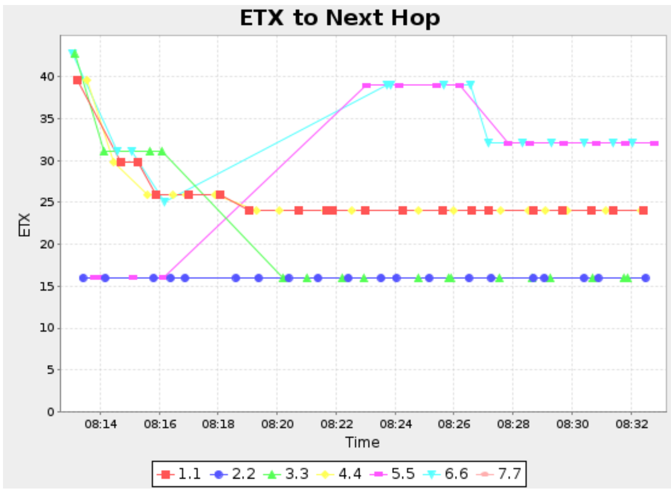

Fig. 6. Estimated Transmission Count Metric

Selectively varying simulation parameters enables us to quantify in a controlled fashion the system response to various stimuli. In this case, Figure 7 lists the routing metric variations upon changing the TX/RX probability for the network from 100% to 75/50%, introducing link asymmetry. The sharpest response is for nodes farthest away from the sink: 4, 5 and 6. Gathering data from a real intra-car scenario, the simulation could be enhanced by dynamic models of link behaviour which would bring a greater degree of confidence in the simulation outcome. The transient response of the routing metrics at the beginning of the simulations account for the network discovery and formation period when the sink and the individual nodes attempt to identify their neighbours in order to assemble the routing tables. Scalability tests have to be performed as well in order to check how the overall network metrics, relevant to control applications, like latency and jitter, change with the introduction of new nodes. As, in general, wireless sensor network protocols are highly data-dependent i.e. aware of the constraints on the transmitted data, this can be used to carefully tune the network in order to attain specified quantitative and qualitative performance indicators.

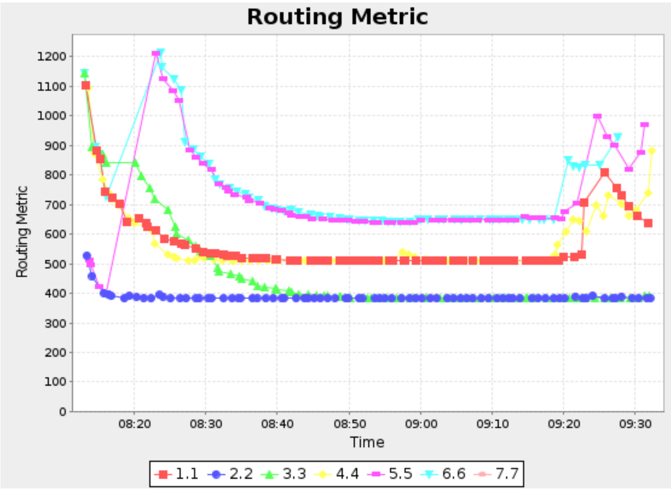

Fig. 7. Contiki RPL Routing Metric and TX/RX Probability Change Impact

V. CONCLUSION

We have introduced a design methodology for the deployment of intra-car wireless sensor networks. Arguing the opportunity and advantages: weight reduction, lower cost and size, of these systems for monitoring and control of various subsystems of a modern automobile, we provide simulation results and a perspective on data collection, networking and energy efficiency issues for this class of devices. Our proposed approach, using the integrated Contiki/COOJA toolchain for WSN modeling under realistic constraints has shown promising results. We aim at extending this work in application-specific scenarios for in-car deployments for monitoring and control.

A clear necessity arises as future work for experimental validation on real sensor nodes. To this scope an implementation on a generic 10-15 sensor network test-bed is underway along with the deployment of an embedded gateway equipped with a CAN-module for integration tests with other in-car measurement and control subsystems.

ACKNOWLEDGMENT

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