Intra-vehicular Wireless Networks

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Abstract— **Automotive wiring harnesses that provide the wiring infrastructure for electrical and electronic sub-systems inside vehicles have grown in size over the years. Significant engineering challenges are posed due to increased weight / decreased fuel economy, increase in production steps, increased cost and labor in harness manufacturing and installation, increased design complexity, etc. Wireless communications provides an intriguing alternative to wiring. This paper investigates the issues around replacing the current wired data links between electrical control units (ECU) and sensors/switches in a vehicle, with wireless links.** We present a wide range of engineering issues and discuss potential solutions. We also provide recommendations with regard to future wireless intra-vehicular networks. Specifically, we provide a discussion on limitations and opportunities, based on simulation results, for network operations over an IEEE 802.15.4 stack protocol.

Index Terms— **automotive wireless ECU, intra-vehicular networks, wireless sensor networks, 802.15.4 PHY and MAC.**

I. INTRODUCTION

MODERN automobiles contain an ever increasing number of powerful electronic control units (ECU) and associated distributed sensor and actuator components. For example, more than 50 sensors are deployed nowadays in a mid-range vehicle and the industry estimates for the automotive sensor market volumes exceed 665 million units and 2237 million units, in North America and globally, respectively [1]. This represents a multi-billion dollar market in electronic sensors alone in 2007 [2] and analysts estimate more than 80% of new functions in automobiles to be electronics based. As such, the design, manufacturing and installation of wiring harnesses for transmission of power and data for all these sensor components require considerable engineering effort. A present day wiring harness may have up to 4,000 parts, weigh as much as 40 kg, and contain more than 1900 wires for up to 4 kilometers of wiring, and can be very costly [3][19]. Eliminating, or greatly reducing, the number of wires in the harness can potentially provide part cost savings, assembly savings, mass savings and warranty savings. In addition to these savings, wireless sensing would enable new sensor technologies to be integrated into vehicles (e.g. tire pressure monitoring systems) which would otherwise be impossible using wired means. Another major benefit of wireless networks is the flexibility to accommodate the growing demand for on-board sensors without adding physical

capacity. With current intra-vehicular wired network architecture based on the well-established Controller Area Network (CAN) protocol [15], the nodes and the messaging needs to be re-engineered with every production cycle. Wireless sensor integration to the vehicle offers an interesting prospect to address this inflexibility, thus enabling an inter-connected wireless network grid for sensing, actuation and infotainment inside a vehicle.

In this paper, we explore the idea of replacing low-current wires such as those that feed sensors and switches, with wireless links, inside the vehicle. Such networks are not just another type of wireless sensor networks: they are differentiated by very specific design demands driven by latency guarantees, reliability, integration, that raise interesting questions from a networking point of view. Note that infotainment devices (music, video, etc.) inside a car represent a different class of applications that we do not address in this paper. We limit our attention here to replacing wires between ECUs and sensors/switches because the solution space for this class of sensor networking applications are most rigidly constrained by vehicular performance requirements.

Our objectives are to explore suitable wireless technologies that may be applicable within the context of vehicle networks, to highlight unresolved network system architecture issues for automobiles, to provide a framework for the design of such networks, and to suggest solutions from a case study based on an emerging network standard. In section II, we discuss the characteristics of a prospective intra-vehicular wireless network, followed by a survey of current short-range wireless standards and evaluate their suitability for wireless automotive sensor networks (WASN). We also lay out the design requirements for a WASN, and discuss issues spanning several layers of the protocol stack. In section III, we integrate these design ideas and discuss candidate wireless network architecture, and its limitations. We follow this up with an analysis of a critical parameter: the latency and its impact on the MAC design. In the last technical section, we provide simulation results that verify and provide key insights into the analytic models developed in earlier sections of the paper. Finally, we conclude with some technological and business implications of the proposed intra-vehicular wireless sensor network concept.

II. WIRELESS NETWORKS FOR VEHICLES: OVERVIEW

Mobile Ad hoc Networks (MANET) have been studied in the domain of automotive applications primarily for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [20] and for information retrieval and

infotainment [14]. However, less scrutiny has been directed towards intra-vehicular wireless sensor networks. Unlike inter-vehicle MANETs, intra-vehicular nodes are stationary, with fixed network architecture. Unlike unattended wireless sensor networks, energy-efficiency for WASNs is not the only major challenge. Stringent latency requirements that can reach sub-milliseconds for some automotive sensors present challenges in the design of WSNs for the automobile. The high level of reliability required by some applications is another major challenge.

Table 1: Comparison of existing standards

Market Name Standard	RFID (Passive) [4]	Bluetooth™ [7]	ZigBee™ [5]	UWB [6]
Data Rate (Kbps)	28	720	20-250	20-250
Transmission Range (m)	0.1 - 10	1 – 10	1 – 100	1 – 100
Network Size	1000	7	255/65536	256/65536
Device Setup Time	~ tens of msec	~ seconds	~ 30 msec	<< 1 sec
Network Topology	Star	Fixed (Star)	Flexible (Star, Mesh, Hybrid)	Flexible (Star, Mesh, Hybrid)
MAC Protocol	Q	TDMA	CSMA/CA &TDMA	CSMA/CA &TDMA
PHY Waveform	ASK	FHSS	DSSS	DS-UWB
Memory Requirements	4KB	250 KB+	4-32 KB	4-32 KB
Tx Power Requirements	0	1 mw	< 1 mw	1mw/Mbps
Application Focus	Supply Chain Managment	Cable Replacement	Monitoring & Control	High precision ranging / location, Multimedia

A. Comparison with Conventional Wireless Networks

An intra-vehicular wireless network differs from a conventional wireless network, such as the popular 802.11-type networks, in several key aspects. For example, for network topology, vehicular sensors and actuators are arranged in essentially a star-configuration with an associated ECU serving as the central computer. This topology is different from a traditional ad-hoc network configuration, where nodes can form routes to any other node. Data rate requirements are also different for WASNs—typically bits to kilobits for command, control and sensor/situation data. Finally, the protocol requirements and data reliability requirements are quite different for WASNs as compared to generic ad hoc networks. For example, most two-way wireless data applications nowadays use the TCP/IP suite of network protocols. The notable exception here is cellular telephony. However, an IP based network is most likely inappropriate for an intra-vehicular sensor network. The main rationale is that given the application behavior, data rate and reliability requirements for intra-vehicle networks, the overhead associated with TCP/IP networks is too costly for most in-vehicle command/control/sensing applications. Furthermore, the wireless data integrity/reliability for WASNs has to equal or exceed the wired equivalent performance if

wireless is ever to be deployed for in-vehicle applications. Typically, in ad hoc wireless network operations, applications try to mask network heterogeneity by protocol wrappers that try to serve a quality of service (e.g. via TCP/IP or OSI stack models). Such generalized schemes are inappropriate for protocol-light automotive applications. Often the data being shuttled from source to destination in automotive applications is simply a few bytes, representing an instance of a sensor reading, but which must be delivered with extremely high reliability.

In summary, 802.11x solutions are not appropriate for WASNs because of a variety of reasons including chipset cost and size/weigh/power requirements, protocol overhead, lack of real-time latency guarantees. Furthermore, it is surprising that other common wireless standards-based solutions are not entirely appropriate either. Table 1 gives a summary of these technologies in terms of several parameters.

The main problem is that most wireless standards have not been developed with the intra-automotive application space in mind and thus the technical specifications do not match the requirements (either overkill or falls short). Second, short-range wireless technologies are currently in their infancy (at least as far as market penetration and volume pricing is concerned) and we can expect several more iterations of these technologies in the near future to determine which standard or technique emerges as the low-cost/high-performance clear winner in the marketplace.

RFID PHY layer waveform and simple MAC protocol design (coupled with high cost of RFID readers) makes it unsuitable for WASN reliability and latency requirements whereas for Bluetooth, the system complexity, cost and power consumption requirements are too high. For Zigbee technology that is based on the IEEE 802.15.4 standard [13], as well as for the emerging ultra-wideband (UWB) technology. UWB as a PHY layer alternative is adopted in both the IEEE 802.15.4a [21] and the ECMA-368 [22]. Based on our survey, 802.15.4 nominally appears to be the closest suitable match, despite its limitations. Together with some suitable modifications, it is our contention however, that IEEE 802.15.4 represents the most promising solution for WASNs. Thus, we base our system design and analysis on this choice. Note that throughout the paper, we use IEEE 802.15.4 and ZigBee interchangeably.

B. System Design Issues

An overriding requirement for a WASN is subsystem reliability. A review of current vehicle sensors reveal that the most demanding sensor will require a latency of approximately less than 1 msec with data throughput rate of 12 kbps. Further, the network will need to support about 15 sensors with this requirement. The least demanding sensor will require a latency of approximately 50 msec with data throughput rate of 5 bps and will need to support about 20 of these types of devices. Hence, the requirements cover a wide spectrum, with a latency ratio, defined as the inverse ratio of the most demanding latency to the least demanding, of 50 and a throughput ratio, defined as the ratio highest throughput to

the smallest throughput, of 2400, resulting in a highly heterogeneous network.

Given the overriding concern for system reliability, state-of-the-art ad hoc or wireless networking techniques, taken as-is, are not adequate to solve the problem. A solution that is at one extreme is to engineer a highly custom network stack for each wireless subsystem in the vehicle. This is typically the solution that is currently favored for add-on functionalities (audio/video, telematics, etc.). At the other end of the spectrum is to implement a standard networking architecture (e.g. 802.11-type protocol stack based on TCP/IP) for all the applications in the vehicle. This approach also has obvious advantages (standardized networking architecture reducing development/deployment costs). The fundamental disadvantages are: no easy guarantee of meeting latency bounds, and protocol bloat for low to moderate rate data applications, which is precisely where most in-vehicle wireless network applications lie. Thus, neither extreme solution is suitable. In consideration of all advantages and disadvantages, for in-vehicle wireless networks and especially for non-safety applications, it is desirable to eliminate or minimize these overhead by optimizing radio and protocol
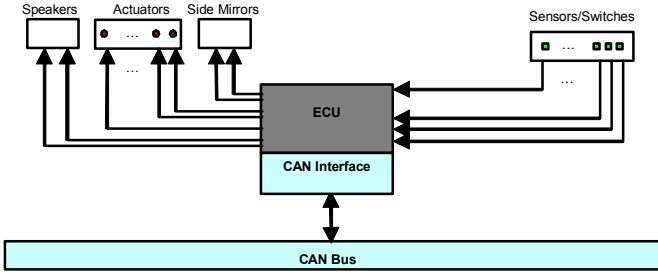
Figure 1: Schematic diagram of the wiring of example CAN-based door sub-system.

stack for low-duty-cycle networks while maintaining reasonable end-to-end network performance. We briefly examine these optimization choices across the network layers.

At the PHY layer, waveform propagation studies for inside a vehicle cabin [8]-[12], [17], [24] are still preliminary with no definite conclusion. However, UWB waveforms are indicated to be suitable for the short ranges that are needed for connectivity inside automobiles [25]. At the MAC layer, in order to quantify the latency guarantees supported by short-range wireless technologies, we model a wireless in-vehicle subsystem as a star network. Even though some nodes might not be able to reach the ECU over a single-hop we focus on single-hop star configurations in this preliminary study, and focus on contention-free multiple access schemes due to its collision-free nature which is essential for providing latency guarantees. Therefore, we focus on slotted scheduled MAC schemes, through the guaranteed time slots (GTS) in the contention-free period (CFP) of 802.15.4, where each sensor/switch reading fits exactly in a single time slot. We focus on the MAC and interference issues within a single in-vehicle subsystem rather than interference between different subsystems. Mitigating inter-subsystem interference and

external sources of interference at the unlicensed 2.4 GHz band requires the development of interference-resilient PHY layer waveforms which is out of the scope of this paper and is a subject of future research. Furthermore, we assume that uplink and downlink communications are separated, in a manner similar to cellular systems, either via Time Division Duplexing (TDD) techniques or via Frequency Division Duplexing (FDD) techniques. Note that the traffic between a sensor node and a base station (or coordinator node) is highly asymmetrical.

III. CANDIDATE WIRELESS NETWORK ARCHITECTURES

Figure 1 depicts a schematic diagram of an example door sub-system and its associated wiring. The wires in CAN-based architectures can be classified to three types: *i)* Subsystem wiring: for input from sensor/switches to the electronic control unit (ECU) and output from ECU to displays/actuators, *ii)* Wire(s) that interconnect the ECU to the CAN bus and *iii)* CAN bus. Each sub-system constitutes a star network where all nodes in the sub-system either feed input to or receive output from the ECU. We focus on the first class of wires, i.e. we investigate the feasibility of replacing the wires for switches and low-current sensors. This class constitutes approximately 20% of the wires inside the vehicle.

A. Latency Analysis of IEEE 802.15.4 MAC

The two most important network design considerations for wireless intra-automobile sensor networks are: *i)* architectural issues relating to interfacing to the wired CAN-based backbone, and *ii)* data latency as observed from the point of view of the sensor application. In this section, we analyze the latency issues. Specifically, we determine the level of latency to expect from a given sensor network architecture. The result is of great interest, since it directly determines the class of wireless applications that we can realistically hope to implement for a vehicle. Among the myriad of combinations of possible PHY and MAC layers, we determined earlier that the most promising and appropriate candidate is the IEEE 802.15.4 standard. Thus, in the remainder of this section, we limit our latency analysis to this protocol. Some of the following analysis was originally presented in [23] and will be reproduced here for convenience.

1) Sensor-to-ECU Latency Definition

Our main target in this section is to quantify the latency guarantees that can be provided by the IEEE 802.15.4 standard when used for moderate-data-rate in-vehicle wireless applications.

Figure 2 shows the data path for a typical packet from the sensor to the sink. The overall latency to communicate a reading from the uplink node to its corresponding downlink node can then be quantized as follows:

Overall_Latency(i)=UL_Latency(i)+ECU_Processing_Latency + DL_Latency(i)

U(i)	Uplink node *i*.

D(i)	Downlink node i
UL_Latency(i)	Uplink latency in communicating a sample measurement from node U(i) to the ECU
DL_Latency(i)	Latency incurred for communicating the ECU output to downlink node D(i)
ECU_Processing_Latency(i)	Time required for the ECU software modules to process the input data received from the uplink nodes.

The *ECU_Processing_Latency* is due to microprocessor operations and is thus orders of magnitude less than communication delays. Thus, it will be ignored. In this analysis, we focus primarily on the uplink latency due to: *i)* It is upper bounded by the latency requirements of in-vehicle
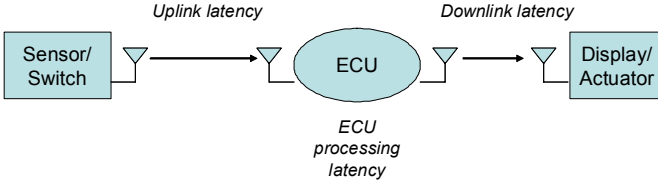
Figure 2: Packet latencies from source to destination.

subsystems (hereafter denoted as *Required_Latency*) and is defined as the deadline by which the sensor sample should be available to the ECU software module and *ii)* It has direct impact on the design and performance of MAC protocols.

Thus, the problem simplifies to the following: $UL\_Latency(i) \leq Required\_Latency(i)$ for all *i*. In this case, the uplink latency itself accounts for the following types of latencies: $UL\_Latency(i) = QLatency(i) + Tx\_Time(i) + Propagation\_Delay$, where, $QLatency(i)$ is the time spent by the packet queued in the buffer of node *i*, $Tx\_Time(i)$ is the time needed for transmitting the packet over the air and is given by $Packet\_Size(i)/Link\_Bit\_Rate$, and propagation delay can be ignored due to the short distances of wave propagation inside the vehicle. Next, we characterize the $QLatency(i)$ for an arbitrary sensor node *i*. We limit our attention to the case where all uplink nodes in the subsystem are homogenous, i.e. packet arrival rates, packet sizes and latency requirements are the same for all sensor nodes communicating with the same ECU. Assuming a slotted MAC scheme, each uplink node is assigned one slot per frame. Note that the packet arrival process at each node is deterministic and the packet transmission time is deterministic too, however, $QLatency(i)$ may still vary depending on the instant of node *i*'s packet arrival within the frame relative to the location of the slot assigned to node *i*. Since all nodes experience the same performance under the homogenous node assumption, we will drop the node index *i* in the rest of the analysis. Under the best-case scenario, a packet arrives at node *i* within the slot immediately preceding the slot assigned to *i* and, hence: $0 \leq Min\_QLatency \leq 1$ slot. On the other hand, when a packet arrives at node *i* within the slot assigned to *i* or the one immediately following it: $N-1 \leq Max\_QLatency \leq N$ slot. Later, we quantify the worst-case latency of 802.15.4 as a function of the number of uplink nodes *N*.

2) IEEE 802.15.4 Parameters

Table 2 shows the 802.15.4 PHY parameters adopted in the analysis. The 802.15.4 supports two types of MAC schemes,

namely contention-based CSMA/CA MAC during the contention access period (CAP) and contention-free MAC during the contention-free period (CFP) using the notion of guaranteed time slots (GTS). The CAP and CFP periods alternate and they both constitute what is referred to as the MAC super-frame (Figure 3). The superframe is divided into 16 equally sized slots, where the beacon is transmitted in the first slot in the superframe. Even though we focus on 802.15.4 in this analysis, the derived results would apply also to the emerging 802.15.4a standard which adopts an ultra wide band (UWB)-based PHY waveform instead of DSSS. We assume: *(i)* The UWB PHY for 802.15.4a will support the same data rate (250 Kbps) as 802.15.4 at 2.4 GHz and *(ii)* 802.15.4a will adopt exactly the same MAC of 802.15.4.

Table 2: PHY parameters used in analysis

Waveform	DSSS	# bits/symbol	4
Operating frequency	2.4 GHz	# chips/symbol	32
Data rate	250 Kbps	Data Frame PPDU	15+payload to 31+payload Bytes
# Channels	16		

B. IEEE 802.15.4 Latency Guarantees for In-vehicle Star Networks

We assume that uplink nodes operate on a single channel. A fundamental step towards quantifying the uplink latency is to understand the minimum slot/frame duration supported by the IEEE 802.15.4 standard. Referring to the standard, the superframe duration is defined as:

$Superframe\_Duration = aBaseSuperframeDuration * 2^{SO}$ symbols,
$aBaseSuperframeDuration$ (symbols) $= aBaseSlotDuration$ (symbols) $* 16$,
$SO = macSuperframeOrder, 0 \leq SO \leq 14, aBaseSlotDuration = 60$ symbols

For guaranteed low latency applications, it is evident that we should utilize the minimum superframe duration (hence, minimum slot duration) which is attained when SO = 0. Accordingly, S*uperframe_Duration* becomes 960 symbols. Given the 250 kbps bit rate supported by the IEEE 802.15.4 standard at 2.4 GHz along with the 16-ary orthogonal modulation scheme, the symbol rate is found to be 62.5 Ksymbols/sec. Hence, the symbol duration turns out to be 16 µsec which yields the shortest superframe supported by the standard: *Superframe_Duration = 15.36 msec*. Although the 802.1.5.4 superframe accommodates 16 slots, each of duration 0.96 msec, the standard supports only up to 7 GTSs in the CFP. This is attributed to the fact that a minimum CAP of length aMinCAPLength = 440 symbols (i.e. 8 slots for SO=0) has to be supported in each superframe to ensure that MAC commands can still be transferred to nodes when GTSs are being used. Therefore, even though we are interested in utilizing only GTSs for the in-vehicle WSN traffic, 8 CAP slots have to be set aside in each superframe in order to support MAC commands.

Finally, we attempt to characterize the latency variation, for in-vehicle star networks, with the number of uplink nodes. For instance, for $N = 7$, $SO=0$ supports up to 7 GTSs and, hence, each node is assigned 1 GTS per superframe which yields worst-case queuing latency of $9+7 = 16$ slots (i.e. 1 superframe duration). For $N = 14$, $SO=3$ would support up to
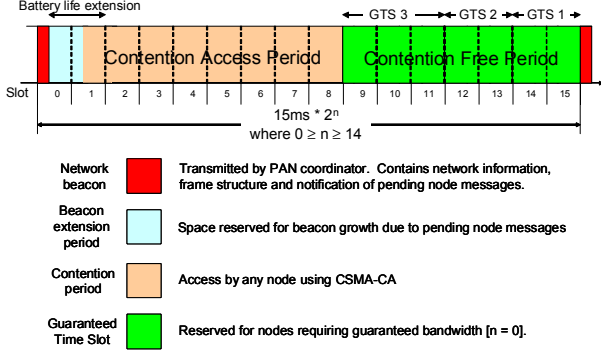

Figure 3: 802.15.4 MAC superframe.

14 GTSs per superframe and, hence, each node can be assigned 1 GTS per superframe. This, in turn, yields a worst-case queuing latency of 16 longer slots due to the higher SO. For $N \leq 14$, each node can be assigned a single GTS every superframe which yields a worst-case queuing latency of $16 * \left\lceil \frac{N}{MaxGTS} \right\rceil$ slots, where MaxGTS is the maximum number of GTS slots that can be supported per superframe depending on the SO. Hence, the worst-case uplink latency is given by,

$$802.15.4\_UL\_Latency = QLatency + Tx\_Time$$

$$= (16 * \left\lceil \frac{N}{MaxGTS} \right\rceil * Slot\_Duration) + \frac{Packet\_Size}{Link\_Bit\_Rate}$$

Based on a Packet_Size = 17 bytes (or, 2 bytes payload) and Link_Bit_Rate = 250 Kbps,

$$802.15.4\_UL\_Latency = Superframe\_Duration * \left\lceil \frac{N}{MaxGTS} \right\rceil + 0.544$$

For $N>14$, the maximum CFP of 802.15.4 can not support 1 GTS for each node per superframe. For instance, if $N=28$, then each node is assigned a slot every 2 superframes at $SO=3$. This can be achieved only through: 1) allocating GTSs to the first group of 14 nodes in superframe i, 2) utilizing the GTSs in the CFP of superframe i+1, and 3) Nodes explicitly de-allocate the GTSs in superframe i+2. Afterwards, these three steps are repeated for the second group of 14 nodes in superframes i+3, i+4, i+5. Notice that if the de-allocation is done implicitly by the PAN coordinator, as supported by the standard, then we will need only 4 superframes (instead of 6) in order to change the GTS assignments to different groups of nodes. This, in turn, suggests that IEEE 802.15.4 would be highly inefficient for N>14 since the first term of the uplink latency given in the equation above will be multiplied by 2 (or 3) in order to reflect the GTS allocation, utilization, de-allocation sequence of events. Two observations can be made based on the equation above. First, the UL-Latency grows linearly with the number of nodes and 802.15.4 could support up to 14 nodes with latencies of approximately 123 msec. Second, 802.15.4 *can not* support latencies smaller than 15.9

msec for any star network of any size. This, in turn, implies that 802.15.4 MAC can not support in-vehicle subsystems with sub-millisecond latency requirements.

C. Networking in the Presence of a Vehicular Backbone

As discussed earlier, the vehicle has a wired communications backbone that runs on CAN protocol. The evolution of wireless sensor networks in the vehicle will experience an interaction with the existing backbone. Therefore, certain engineering trade-offs will need to be considered. In this section, we focus on a single aspect of this problem and analyze how the backbone traffic will be impacted with the introduction of wireless sensor networks in an automobile, and consequently derive a feasibility condition.

Consider a vehicle data network with K ECUs. K_w of the K ECUs has wireless communication capability. The set of all ECUs is denoted by E and the set of ECUs with radios is denoted by $E_w \subseteq E$. WECU will refer to those ECUs with wireless communication capability. Without loss of generality, we will assume that if $K_w = k$, then $E_w = \{E_1, E_2, \cdots, E_k\}$ where E_j denotes the jth ECU. There are N sensor/switch (S/S) nodes, which communicate with the rest of the communication network of the vehicle through wireless links to the WECUs. The set of S/S nodes, or end-nodes, is denoted by S. The jth S/S node is denoted by S_j. The overall network architecture is a wired-wireless hybrid, where the backbone is wired, but the link between end-nodes and their corresponding ECUs are wireless.

We are assuming that all traffic from S/S goes through an ECU and the S/S does not interface directly with the bus. We are also assuming that a single data bus connects all ECUs to one another. In practice, a vehicle would have multiple buses, each supporting a local network of ECUs, which are connected through a specialized gateway ECU. Current vehicle architectures represent the special case, where $E_w=\varnothing$.

In this model, each S/S has a designated ECU to which it is physically wired. The ECU that is designated for node S_j is denoted as E_{S_j}. Let M_j denote the membership set containing the set of S/S nodes that are designated to E_j. The data that is provided to an end-node is either entirely consumed by its designated ECU or it is shared with other ECUs through the backbone bus. Any data that is on placed on the bus can be *heard* by any other ECU, i.e. all messages are broadcast. Note that the ECU designation does not change with different topologies that will be considered here. The *designated* ECU for a S/S node is not necessarily the same ECU that the node is *connected* to. The *connected* ECU will refer to the ECU with which the S/S node has a communication link. In the case of the completely wired topology of today's vehicles, the designated ECU and the connected ECU are identical for any given S/S. In our formulation, f_i fraction of the total traffic offered by end node S_i is also broadcast on the common bus. This parameter has resulted from observing the way the network currently operates. It has been observed that the data provided to its designated ECU by a S/S node is also broadcast on the bus, possibly at a slower rate. It is worth noting that we

are assuming a one-way communication from the end-nodes to their designated ECUs and omitting the traffic generated in response to messages from end-nodes. Another important assumption is that the bus traffic resulting from a specific end-node is scheduled perfectly, i.e. there are no contention errors resulting from multiple ECUs transmitting data from various sensor/switch nodes on the same physical data link.

1) Offered Traffic

We decompose the total traffic on the bus into two parts: *i*) traffic due to non-S/S activity and *ii*) traffic due to S/S activity. We will denote the former part by R_B and we will assume that this is the *base* traffic that the network would have to handle in the absence of *any* data input by the S/S end nodes. The latter is denoted by R_S, which is a function of K_w. The data rate offered on the data bus by end node S_j is denoted by r_j. The total traffic offered on the bus is expressed as:

$$R_T(K_w) = R_B + R_S(K_w) \qquad (1)$$

2) Alternative Hybrid Topologies

When determining the exact hybrid topology of the in-vehicle data network, several considerations make the decision complicated: System Cost, End-to-end latency (maximum constraints), Single point of failure versus redundancy tradeoff, Scalability, Traffic on the CAN bus (capacity constraint), S/S node energy consumption (node lifetime). There are two extreme configurations for our wired-wireless hybrid network: *1)* Global Star (Single wireless ECU for all S/S nodes), *2)* Local Star (All ECUs are wireless)

For a more general formulation, we consider the case where number of wireless ECUs in the network is k:

$$R_S(K_w = k) = \sum_{S_j \notin M_1, \cdots, M_k} r_j + \sum_{i \le k} \sum_{S_j \in M_i} f_j r_j \qquad (2)$$

Note that the offered traffic for the case of no WECUs and K WECUs are the same. This results from the fact that, in the case of all WECUs, we are assuming that the S/S node has the same ECU as its designated ECU as well as its connected ECU. Consider the simplified case where all sensors operate with the same rate, $r_j = r, \ \forall S_j \in S$. Furthermore, assume that all sensors contribute the same fraction of their total rate onto the common bus, $f_j = f, \ \forall S_j \in S$. We also assume that the number of sensors that are dedicated to a specific ECU is distributed uniformly across all ECUs. With these simplifications, (2) can be reduced to:

$$R_S(K_w = k) = (N - \frac{N}{K} k)r + \frac{N}{K} krf$$
$$= Nrf(\frac{k}{K} + \frac{1}{f} - \frac{k}{fK}) \qquad (3)$$

3) Feasibility – Hybrid Network Requirements

Due to limited bus bandwidth, there are certain hybrid network configurations that are not feasible. It is realistic to assume that the wired bus architecture supports current traffic levels, that is,

$$R_s(0) + R_B \le C \qquad (4)$$

where C denotes the bus capacity. Using the simplified homogeneous network assumptions:

$$R_S(K_w = 0) = Nrf \le C - R_B \qquad (5)$$

The feasibility condition can be expressed as

$$R_S(k) + R_B \le C \qquad (6)$$

Using the simplified expression in (3) and rearranging terms we get,

$$k \ge \frac{Nr - (C - R_B)}{\frac{Nr}{K}(1 - f)} \qquad (7)$$

Note that the expression in (7) bounds the minimum number of WECUs. As the number of WECUs increases the traffic on the bus due to S/S traffic decreases. For instance in the case of a single WECU, all S/S traffic has to go through that single WECU, creating a traffic bottleneck, thus maximizing the traffic on the bus due to S/S nodes. As the number of WECUs increase, the burden is taken on by those ECUs which connect to their designated S/S nodes, thus decreasing the S/S node traffic on the bus. When the number of WECUs is equal to the total number of ECUs in the vehicle, then the bus traffic reduces to the level it is in the wired architecture. It is worth noting that if our assumption that a S/S node has to be connected to the WECU that happens to be its designated ECU is lifted, the argument is no longer true.

Based on the above formulation, the network architect is forced to choose between a hybrid network with a minimum of WECUs as given by (7), or a completely wired, conventional network. It is fair to say that the above assumptions simplify the problem to the level where the actual value of k in (7) is meaningless. However, there are some key takeaways even with the above simple result: *i*) the desirable configuration from a cost perspective is to accommodate all wireless S/S nodes through as single WECU. However, depending on the level of existing bus traffic, this option may not be feasible, *ii*) in the presence of multiple WECUs, the best S/S node-WECU pairing is not necessarily the highest-quality-signal assignment, contrary to our conventional thinking about wireless networking, *iii*) deployment of WECUs will require a re-evaluation of the wired-bus architecture in the existing vehicle in order to make optimization across both domains possible.

IV. SIMULATION RESULTS

To evaluate the network architecture proposed for in-vehicle applications we created a simulation and evaluation environment on the well-known *ns-2* network simulation platform [18]. Our goal was to validate our latency analysis as presented in the previous sections and to investigate solutions for any shortcomings revealed by this exercise (both for the simulation engine itself, and for the MAC/PHY architecture as defined in the IEEE 802.15.4 standard). In *ns-2*, we define four types of devices: radio-enabled ECU, radio-disabled

ECU, sensor node, and actuator node. Radio-enabled ECU has two communication interfaces: wired and wireless. Wired interface (i.e. CAN bus) is used to communicate with radio-disabled ECU while wireless interface is used to communicate with sensor node and actuator node. Figure 4 shows our hybrid architecture of wireless CAN bus in *ns-2* on the top, which corresponds to the Zone Star architecture shown on the bottom. For ECUs that are on the CAN bus, there are two communication stacks in *ns-2*. Essentially, these radio-enabled ECUs serve to route messages from CAN bus to wireless network and from wireless network to CAN bus. For the radio-disabled ECUs, the wireless stack is disabled during simulation. Similarly, sensor nodes have only the wireless communication stack.

Both IEEE 802.15.4 and the CAN bus are implemented as MAC/PHY components in *ns-2*. This is to resemble the fact that both are link layer protocols. We decided to bypass *ns-2*
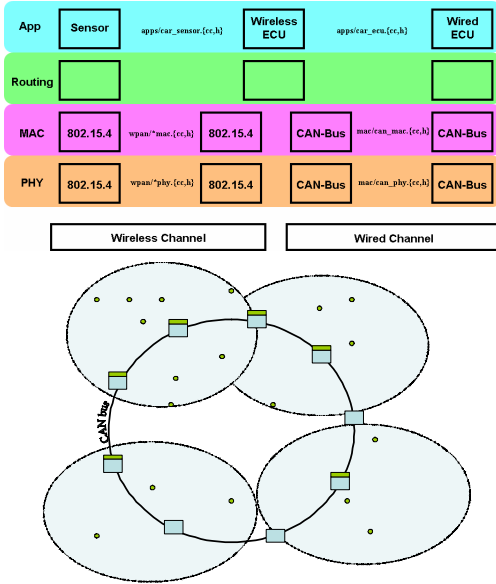
Figure 4: Hybrid architecture in *ns-2* and the zone star configuration. One ECU per zone is radio-enabled.

IP layer for reasons discussed earlier. To verify the need of GTS transmissions in the simulation, we implemented IEEE 802.15.4 in *ns-2* both with slotted CSMA and GTS slots. Each beacon is transmitted at every *Beacon Interval* (BI), which is defined as *aBaseSuperframeDuration* (equal to 15.36 msec) multiplied by two to the power of the *Beacon Order* (BO). Varying BO allows one to adjust how often a beacon is transmitted. The Superframe Duration (SD – the active period within each BI) is further divided into 16 slots. The first slot is always reserved for beacon transmission while the other 15 slots allow CSMA transmission in each slot or up to 7 slots can be used for GTS transmission. We set *SD* equal to *BI*.

For automotive applications where the focus is on meeting tight latency requirements, the interesting case occurs for *BO* equal to 0. Thus for the simulations, we use one radio-enabled ECU, and vary number of sensor nodes. The sensor nodes use both the Contention Access Period (CAP) and the GTS slots

for uplink to the ECU, according to the simulation parameter setup. The sensor nodes periodically transmit an application data payload of two bytes according to a specified duty cycle or *data rate*, and each node is spaced *d* distance apart. To capture the effects of potential hidden terminals in the CSMA/CA network, we choose *d* to be uniformly distributed between 0 and 10 meters. Note that the node's transmission range is 10 meters. We conducted multiple simulation runs with different topologies and averaged over the multiple runs varying the simulation periods.

Since our data payload is very small, GTS can in theory be used to transmit within the smallest 15.36 millisecond slot with SO equal to zero. Therefore, the maximum wait time in the queue, in theory, is 15.36 milliseconds. The aim of our simulations is to ascertain/verify the following: minimum latency metrics, whether slotted CSMA can achieve desired latency requirements for different data rates, where/why CSMA is found to be inadequate; impact of using GTS; performance tradeoffs, etc. The first set of simulations (Figure 5) does not use any GTS slots and investigates the performance of the CSMA/CA based contention access period (CAP) on packet delivery behavior. The figure shows the situation as experienced by packets (MAC payload) being uploaded from the sensor to the ECU. Green indicates packets which end up being buffered in the sensor's MAC queue and never gain access to the wireless medium throughout the simulation lifetime; red indicates packets that are successfully transmitted but fail to meet the required latency requirement at the delivery time (i.e. packets that arrive too late); blue indicates packets that were successfully transmitted and that meet the latency requirement, while yellow indicates packets that were lost due to channel errors (i.e. collisions in the CSMA/CA channel) and other wireless impairments.

We note that for high data periods (1-5 ms), almost all the generated data ends up being buffered at the source and most packets do not even get a chance for transmission because the channel is always being contended for. As the load is reduced by increasing the data period, the buffered packets are transmitted, but do not meet the latency requirement for that data period. Until about 30 msec data periods, most transmitted packets arrive late while others are still buffered, and only after this data period do we start seeing the buffer being drained and packets successfully meeting the latency requirement. Thus, CSMA/CA achieves higher than 90% packets meeting 45 msec and higher latency requirements, even though the MAC frame that we are using is 15.36 msec wide. The contention for the channel effectively limits the perceived latency seen by the sensor to 45 msec or higher. This has the direct implication that any wireless sensor application inside the car that requires response times of less than 45 msec will mostly fail if CSMA/CA is used. For 45 msec or higher, the packet delivery is still not 100% guaranteed since the access protocol is best-effort with random back off and packet collision events have non-zero probability. Since it is impossible to provide any latency guarantees using a pure contention-based MAC and, we turn to contention-free MAC schemes supported by 802.15.4 using

the notion of GTSs.

The second set of simulations focus on the impact of using GTS (Figure 6). In this case, the sensor nodes transmit during assigned slots in the guaranteed time slots of the 802.15.4 MAC at the data periods shown. We note that as in the CAP case, for data periods in the 1-5 ms range, the transmit buffer again builds up since the application data period is less than the MAC frame period of 15.96 msec at SO=0. Thus, data is being produced faster than one cycle of the MAC can clear out, and most packets are forced to wait in the buffer. The few that are transmitted end up failing to meet the latency requirement. As the network load decreases (due to increased data periods), the buffered packets (green) diminishes faster than the CSMA/CA scenario, but the transmitted packets still

> **Simulation Setup:**
> *ns-2 2.29* running 802.15.4 PHY/MAC, 2.4 GHz, 250 kbps data rate, customized UWB channel model
> Transmission range up to 10 meters. No multi-hop routing due to modeling single-hop ECU-to-sensor communication.
> Sensors periodically push sample measurements (packet size = 2 bytes payload + 15 bytes header) to ECU
> # of uplink nodes (sensors) = 7
> Latency requirements: 1, 2, 5, 10, 12, …, 500 msec
> Simulation time: 1000 data transmissions (each data point average of 10 simulations with differing topologies)
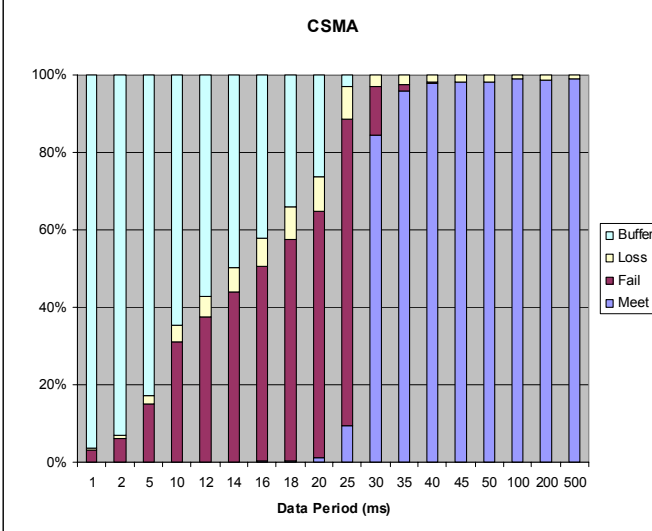
Figure 5: Packet delivery performance for 802.15.4 in Contention Access Period (CAP).

fail to meet the latency requirement. When the data period is 16 ms or greater, however, the GTS slots in the MAC frame of 15.96 msec guarantees a collision-free slot for each of the sensors, so we see a dramatic jump and almost all the packets now being transmitted meet the latency requirement.

Theoretically, all packets should meet the latency requirement as long as data generation period is greater than SD of 15.96 msec. In our simulations, however, about 2-3% of the packets fail to achieve the latency requirement of 16 msec. This is primarily due to measuring application-to-application packet latency (as opposed to MAC-to-MAC packet latency). We stamp and de-stamp packets at the application layers of the transmitter and receiver, respectively. This abrupt change

occurs around the 15.96 msec frame duration thus is in complete agreement with the latency analysis conducted earlier and verifies that 802.15.4 can not support any in-vehicle wireless application requiring less than 15.96 msec latency, *for any size* star network! This is a fundamental limitation of 802.15.4 that has implications for certain classes of applications requiring quick response times. This suggests that the 802.15.4 standard needs to be augmented with some method of enabling priority/flash messages as a fix to this problem. On the flip side, it is seen that for applications requiring latencies greater than 16 msec or so, the standard guarantees reliable packet delivery for small star configurations.

V. Summary and Discussion

This paper has attempted to tackle the broad range of issues surrounding the architecting of a wireless sensor network for intra-automotive applications. We can draw a few conclusions
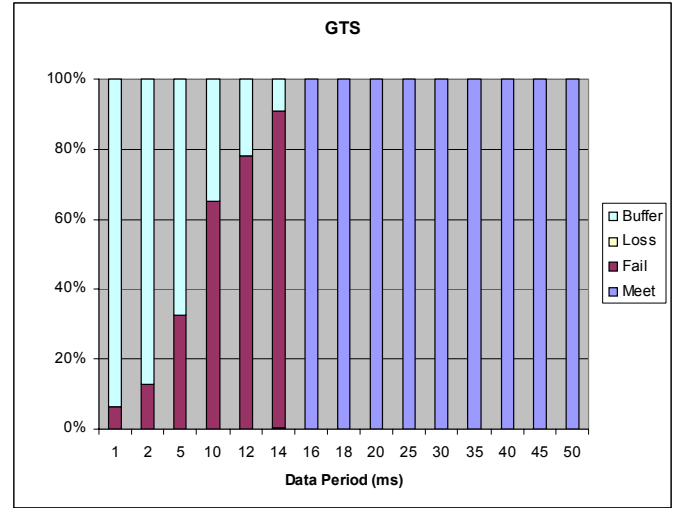
Figure 6: Packet delivery performance for 802.15.4 in Guaranteed Time Slots (GTS).

based on the results of our preliminary study. Specifically, the intra-vehicular application space imposes a unique set of constraints that no current technology can yet fully solve. But with suitable modifications to current standard approaches, most if not all these problems can be overcome. Chief among the issues is the support of guaranteed sub-millisecond data latency for essentially small payloads. Other issues are the need for overhead-lean protocols, simplified PHY waveforms, and transceiver complexity (and thus cost). Our analysis and preliminary design ideas, verified via simulation, indicates that the 802.15.4 suite of protocols together with the emerging ultra-wideband waveform proposals come closest to meeting the needs of the WASNs. For future work, we note that appropriate modifications need to be made to 802.15.4 MAC to meet the sub-millisecond latency requirements. Furthermore, a better UWB waveform can be designed to tackle the unique propagation constraints for intra-vehicular deployment.

In conclusion, we point out that aside from technical

considerations, the issues relating to the economic and business side of this concept are perhaps of greater importance if this technology is to come to fruition at all. An in-depth and quantitative discussion of these issues is outside the scope of this paper, but a few comments can be made. Vehicle manufacturing/ assembly costs include routing wires for a number of sensors individually (as opposed to just harnesses) from point to point. Being able to eliminate this wiring step translates directly to elimination of a step within a station on the assembly line. However, if the wireless solution cost is greater than the cost of the wire and wiring, then the technology appeal is moot: there simply is no business case. As things stand today (2007), unfortunately, wire replacement technologies and wireless sensors do not present a strong business case. This is precisely because off-the-shelf wireless sensor/switch hardware, for whatever protocol standard being considered, costs at least tens of dollars per node, at best. This level of cost is unsustainable as a wire replacement alternative for a parts-cost-driven commodity such as vehicles. But there is hope. If standards can be established for the hardware components and software interface for the radios for the sensors and subsystems, then parts vendors can integrate the technology into their process flow, thereby allowing volume manufacturing, and as has been the case historically for all silicon-based microelectronics products, silicon costs then will eventually approach zero per unit device.

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