INTRA-VEHICLE ULTRA-WIDEBAND COMMUNICATION TESTBED

Weihong Niu, ECE Department, Oakland University
Jia Li, ECE Department, Oakland University
Shaojun Liu, ECE Department, Oakland University
Timothy Talty, General Motors Corporation, Warren, MI

ABSTRACT

Modern vehicles are increasingly equipped with more sensors which are connected to control units through cables for transmitting crucial real-time sensing data. To reduce the complexity and cost brought to the automotive design and production by the sensor wiring harness, replacing cables with wireless links has been proposed in [1].With its fine capability of solving multi-path fading and interference resilience, as well as its freely available spectrum, the ultra-wideband (UWB) technology is considered as a highly promising candidate for such intra-vehicle wireless network. For the purpose of evaluating UWB based sensor network, compared with wired system, from the aspects of performance and reliability in transmitting automotive sensing data, an UWB communication testbed is needed. In this paper we present our first attempt in building an intra-vehicle UWB wireless sensor network to transmit automotive speed data from four wheel speed sensors to the electronic control unit (ECU)[1]. Assembly of the testbed consists of ABS motor control simulating system, wheel speed sensors, UWB transmitting nodes and the UWB network coordinator interfacing with ECU. The paper also includes the description of the main testbed software modules and the report of initial measurement result. Future measurement plan and further work needed to improve the testbed are discussed in the conclusion section.

1 INTRODUCTION

Electronic subsystem and sensors are essential components of modern vehicles. Driven by the regulations of environment-friendliness and the issues of fuel economy, safety, comfort and convenience, more sensors are being designed and deployed in the newly manufactured automotives. The average number of sensors per vehicle exceeded 27 per vehicle in 2002 [2] [3]. Currently, all sensors are wired with cables to communicate with control units. The total length of these cables adds up to more than 1000 meters, which greatly increases complication in the automotive design. Furthermore, the required wiring harness also contributes nearly 50kg to the weight of a car, which not only has a negative impact over fuel efficiency but also increases the pricing of automotives [4]. Motivated by the expectation to lower such complexity, weight and cost from physical sensor connections and wires, T. ElBatt etc. proposed wireless network as a potential way to replace intra-vehicle sensing control and data cable bundles [1]. For the wireless communication in intra-vehicle environment, featuring short range and dense multi-path, great challenge is to provide the same level of reliability, end-to-end latency and data rate as that offered by wiring system in transmitting real-time sensing data. As a result, a properly selected reliable physical layer technology is crucial in the design and construction of such a network. UWB technology is considered by us as a competitive candidate to construct the intra-vehicle wireless sensor network, due to its robustness in solving multi-path fading problem, low power consumption, resistance to narrow band interference, safe and high rate of data transmission as well as free availability of bandwidth.

FCC defined UWB as those signals having a fractional bandwidth greater than 0.2 or occupying more than 500MHz of bandwidth and ratified 7.5 GHz of free spectrum from 3.1GHz to 10.6GHz for commercial UWB devices to use on the condition that they operate at low power with an EIRP less than -41.3dBm/MHz [5]. Because of the very short pulse width in time domain, UWB system demonstrates good robustness to multi-path fading and to interference from narrow band signals, thus makes itself a viable technology in short-range, low power and high data rate communications [6]. Currently, several vendors such as Freescale/XtrememSpectrum, Wisair, Time Domain, Intel etc. are offering CMOS chips to support UWB-based wireless communications.

In order to evaluate the feasibility of applying UWB technology in constructing intra-vehicle wireless sensor network, we started a project aiming to build an end-to-end intra-vehicle UWB communication testbed. The testbed can operate around or inside a car to collect and transmit sensing data from sensors to ECU. Based on the current performance of wired sensor network, we expect to implement and evaluate an experimental UWB

[1] this work is supported by General Motors Corporation through Grant No. GM046156.

communication system against the following high-level requirements:

- The capability to support 100 sensors with each sending at least one sample of 16 bits to ECU per second.
- The sample data delivery failure rate should be no more than 10^{-8}.

In the first phase of the project, we focus on building a testbed collecting wheel speed from sensors located at automotive wheels and transmitting them to ECU under line-of-sight cases.

2 OVERVIEW OF THE TESTBED

To design a UWB network testbed for the transmission of automotive wheel speed data, basic hardware and software platform, UWB chipsets and antennas, and network topology are key components to be considered.

When choosing appropriate hardware platforms, desktop PCs and laptops are excluded by the fact that they will be installed at the side of automotive wheels for road testing and measurement. Considering the cost, size and operating flexibility, we picked commercial embedded devices from Freescale with running OS of Linux as the basic platform for the testbed.

As for the UWB products, we decide to take the FCC certified chips and the antennas from Freescale/XtremeSpectrum because of their early availability and the fine configurability on physical layer parameters such as transceiver power etc. The chips are provided on a mini-PCI board which could be conveniently adapted and installed onto the hardware platform mentioned above.

On the precondition that the testbed is used to evaluate the feasibility of replacing existing automotive wheel speed sensor cables, the best choice for topology of the new UWB transmission network is a star configuration as illustrated in Figure 1:

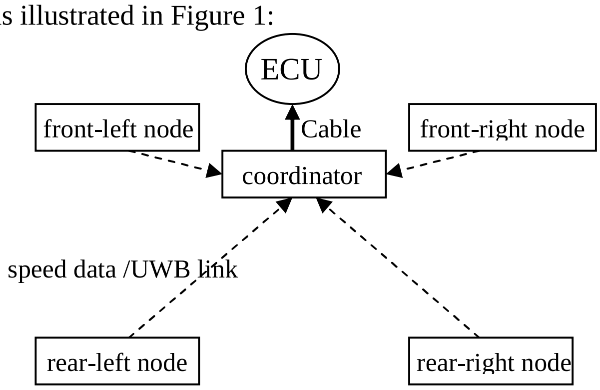

Figure 1. Star topology of the intra-vehicle UWB network

Located at the central point in the star topology is the device interfacing with ECU. It not only receives wheel speed data but also act as the access coordinator for the UWB network. The other four nodes detect the speed of corresponding automotive wheels and transmit the data via UWB links. The distance between two rear nodes and the coordinator is 3~5 meters while that of the front nodes is 1~2 meters.

Aside from the key components mentioned above, to support in-lab testing and measurement, an automotive ABS motor control simulating module is also integrated into the testbed. To summarize, our testbed assembly consists of six types of entities including ABS motor control simulating system, wheel speed sensor, sensor signal conversion module, central control module, UWB transceiver module and ECU interface module. Figure 2 is the illustration of these modules, their interfaces and the end-to-end data flow direction. The detail design and implementation of the testbed are explained in the next two sections.

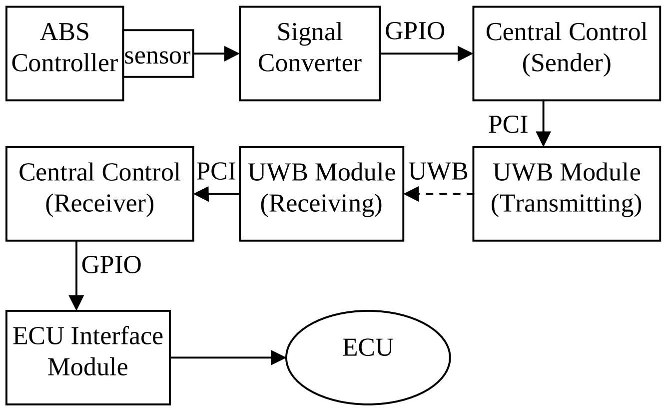

Figure 2. Testbed components and data flow

3 IMPLEMENTATION OF THE TESTBED ASSEMBLY

This section presents the implemented testbed assembly by describing the functionalities and operation procedures of its six components.

3.1 ABS Motor Control Simulating System

This simulating system was constructed by mounting two wheels with gear teeth, one motor driving the wheels, a power supply and an ABS single motor controller to a flat chassis. It provides the mechanical environment in which sensors are installed for the generation of wheel speed signals. Figure 3 shows the above hardware components of the simulating system. The ABS single motor controller is model KEI-871 from KEMKRAFT Engineering Inc.

3.2 Wheel Speed Sensor

Wheel speed sensors integrated in the testbed are of exactly the same type as those equipped with automotives manufactured by General Motors. They are the Hall-Effect Gear-Tooth Sensor of model ATS640LSH provided by Allegro MicroSystems Inc. The sensors are mounted beside the wheels, facing their gear teeth. When supplied with proper power, the sensors are capable of detecting the movement of gear teeth edges and generate digital information that is representative of the profile of a rotating speed of the wheels. These sensors provide two-wire communication interface which gets power supply on the one hand and outputs digital signal in the form of electric current on the other hand [7]. In our testbed, four sensors are mounted on the ABS motor control simulating system as shown in Figure 3.

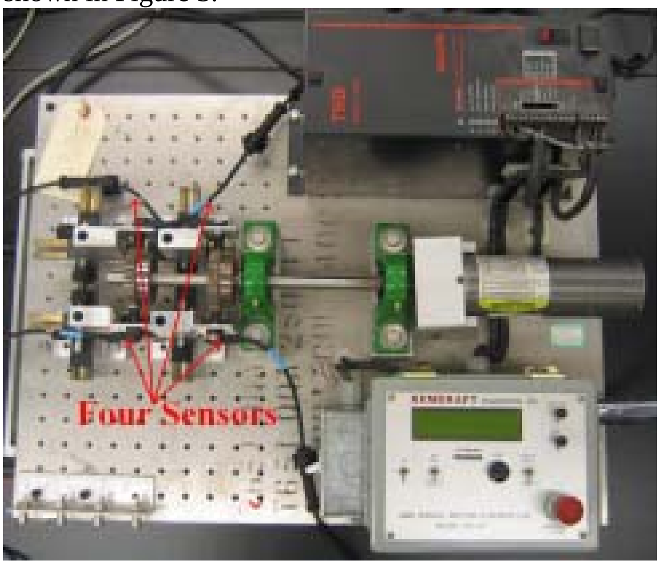

Figure 3. ABS motor control simulating system and wheel speed sensors

3.3 Sensor Signal Conversion Module

This module is the interface between the wheel speed sensor and the central control module. The output signal from the sensor is in the current format. It cannot be directly fed to central control unit which requires voltage input. In addition, the central control unit is the only module connecting with power supply, but none of its output interface could directly supply the sensor with the required 12V of DC voltage. Our solution to these issues is the design and development of a conversion circuit board[2]. This board can be mounted to the central control platform as an interface card. At the same time, it also provides connection points to accept the two wires from a sensor. An implemented sensor signal conversion board, sitting on top of the central control module, with two sensor wires connected, can be found in Figure 4.

3.4 Central Control Module

Central control module provides the basic hardware platform to support the other electronic modules as well as the basic software environment in which to develop the applications. As mentioned in the introduction, we use the commercially available Lite5200/B board from Freescale for this module. Lite5200/B is a development platform based on a 400MHz embedded PowerPC processor. Among the interfaces supported by this board are Ethernet (10/100 BaseT), Universal Serial Bus (USB), General Purpose Input/Output (GPIO) and Peripheral Component Interconnect (PCI) [8] [9]. To construct a wireless node in our UWB network, one sensor signal conversion card is seated on top of the Lite5200/B motherboard via GPIO pins and one UWB card is mounted via the PCI connectors. Such a node captures the output signals of a sensor, converts the signals into data representing wheel speed in RPM (round per minute) and transmits these data via UWB network. Figure 4 shows a complete UWB node assembly consisting of the Lite5200/B motherboard, the sensor signal conversion card and the UWB card.

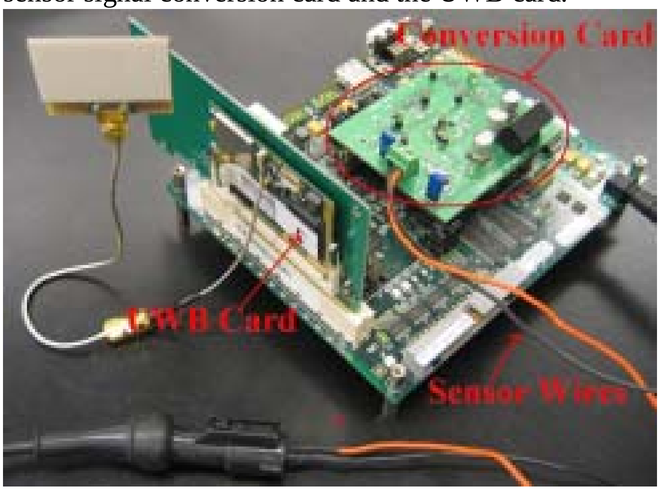

Figure 4. Central control, sensor signal conversion and UWB module assembly.

3.5 UWB Module

[2] The research on supplying power to sensors by new techniques such as vibration energy harvest etc. is beyond the scope of the project described in this paper.

This module provides the function of transmitting and receiving data via UWB pulses. When building the testbed, we take advantage of the UWB card and antennas from Freescale/XtremeSpectrum as those shown in Figure 4. The UWB card only support mini-PCI interface and a mini-PCI to PCI adapter card is used when it is installed on the host Lite5200/B motherboard. The UWB chipset integrated on the mini-PCI card includes three chips, UWB RF transceiver, UWB base-band controller and UWB medium access controller. Together with the UWB antenna, the transceiver transmits and receives RF analog signals, while the base-band controller implements the functions of RF control, data encoding, interleaving and multipath mitigation. The declared values of physical layer parameters implemented by these two chips are listed in Table 1 [10] [11]. Moreover, the UWB medium access controller chip implements IEEE 802.15.3 MAC protocol. It not only provides the MAC layer function to support a data transfer rate up to 114Mbps but also supports the configuration and control of the other two chips [12].

Table 1. Physical layer parameters of Freescale UWB chipset

Parameter	**Value**
Frequency range	3.1 ~ 5.2 GHz
Modulation	BPSK
Center frequency	4.104 GHz
Multiple access	Ternary CDMA
Pulse length	731ps
Forward Error correction	Soft-decision convolutional encoding and Viterbi decoding
Multipath mitigation	Decision feedback equalization and two-arm RAKE
Transmit power	-41.3 dBm/MHz

3.6 ECU Interface Module

In the existing automotive sensor network, the two wires from each wheel speed sensor directly connect with ECU. Considering the difficulty in changing any interface at ECU, we decided to develop our testbed in such a way that it provides exactly the same interface to ECU. Similar to the sensor signal conversion module, this ECU interface module works as a GPIO interface card at the coordinator node, the only one configured as receiver (refer to Figure 1) in the UWB network.

4 IMPLEMENTATION OF SOFTWARE MODULES

As far as software is concerned, the first important issue to be considered in designing the UWB communication testbed is the selection of operating system. Among all the real time operating systems supported by Lite5200/B, embedded Linux is chosen for the benefit of low cost and high operability. Limited by the size of flash memory integrated on Lite5200/B, we tailored Linux to include only the kernel and a basic file system when building the software image for the board and the final image size is 32M. To summarize, the software development environment in our project is listed in the Table 2:

Table 2. Software development environment

Operating system	Linux 2.6.19
Lite5200/B image tool	Linux target image builder (LTIB) from Freescale
Software language	Standard C
Cross compiler	GNU gcc-3.4.3

Two applications were developed to run on the node and the coordinator respectively as shown in Figure 1. The node application reads signals from the sensor conversion card via the GPIO interface, calculates the wheel speed, encapsulates the data in UDP package and then writes it to UWB mini-PCI card for transmission. On the contrary, the coordinator application reads the UDP encapsulated speed data received by the UWB card and stores the data to USB disk for post processing or writes them to the ECU interface card via the GPIO interface. Figure 5 shows the protocol stack for sending and receiving the wheel speed data between node and coordinator applications. Here, UDP is used instead of TCP because of the real-time nature of the wheel speed data.

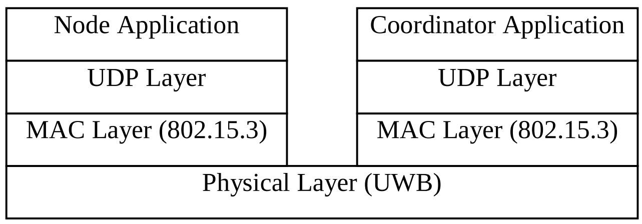

Figure 5. Protocol stack.

In order to allow the communication between the sensor signal conversion card and the applications running on the Lite5200/B motherboard, a Linux version GPIO device driver was developed. Similarly, the UWB card also woks with a PCI driver.

In addition to the above modules, a software tool is also developed to measure the wheel speed data transmission rate and loss rate.

5 TEST ENVIRONMENT AND EXPERIMENTAL RESULT

In the first phase of our project, the measurement with the testbed was performed in lab and only for the line of sight (LOS) case. Values set for the configuration parameters of the UWB card are shown in Table 3.

Table 3. UWB card parameters

Parameters	**Values**
Forward error correction coding/decoding rate	0.75
Over-the-air data rate	114 Mbps
UWB radio frame payload size	32768 bytes
802.15.3 Piconet superframe duration [13]	25000 μsec

During the testing, the four transmitting nodes and the one coordinator are configured to work in one piconet [13]. The measurement results shows that when there is only one transmitting node, at maximum 6667 wheel speed sampling data of 32-bit can be received without failure per second, and two transmitting nodes increase this number to 13,333. However, the maximum total lossless sample transmission rate in the cases of three or four transmitting nodes keeps unchanged at 20,000. To identify the bottle neck leading to this, we replaced the host computer of embedded Lite5200/B in the receiving coordinator with a desktop PC. As a result, the sample transmission rate for the three and four nodes cases changed to 20,000 and 26,667 per second. This measurement result shows that it is the processing capability of the host computer that sets the limits for the transmission rate of wheel speed data. These measurement results show that the high level requirement mentioned in the introduction section can be satisfied by the UWB sensor network when the testbed works in the in-lab environment.

6 SUMMARY AND FUTURE WORK

In this paper, we reported the design and implementation of a UWB testbed for constructing intra-vehicle wireless sensor network. The testbed was developed to evaluate the reliability and efficiency of UWB based wireless network in transmitting automotive sensor data. Our first phase measurement result in the lab with a network consisting of four transmitting nodes and one receiving coordinator shows that in one second at most 20,000 wheel speed sensor data of size 32-bit could safely reach the UWB receiver without message loss.

In the future phase of our project, more tasks are going to be completed. Firstly, the testbed will be installed in a vehicle and the measurement will be performed in the static automotive environment for both line of sight (LOS) and none line of sight (NLOS) cases. In addition, the testbed is going to be installed in a moving automotive and the measurement is going to be performed for LOS and NLOS cases as well. Finally, EMC testing for an automotive with the testbed installed will be performed. In addition, to evaluate the system performance, data transmission rate and packet loss rate will be measured when an automotive equipped with the testbed is running across different outdoor interference environments.

7 ACKNOWLEDGEMENT

The authors would like to thank Bill Lindeman from TRW Automotive for his help to assemble the ABS motor control simulating system.

REFERENCES

[1] T. ElBatt, C. Saraydar, M. Ames, T. Talty, “Potential for intra-vehicle wireless automotive sensor networks,” *2006 IEEE Sarnoff Symposium*, 27-28 March 2006, Princeton, NJ.
[2] T. Costlow, “Sensing significant growth,” *Society of Automotive Engineers (SAE) Automotive Engineering International*, pp. 74-78, May 2004.
[3] W. J. Fleming, “Overview of Automotive Sensors,” *IEEE Sensors Journal*, Vol. 1, No. 4, pp. 296-308, Dec 2001.
[4] G. Leen and D. Hefferna, “Vehicles Without Wires’, *Automotive Electronics, Computing and Control Engineering Journal*, pp. 205-211, Oct 2001.
[5] FCC, First Report and Order 02-48. February 2002.
[6] S.S. Ghassemzadeh, R. Jana, C.W. Rice, W. Turin, V. Tarokh, “Measurement and Modeling of an Ultra-Wide Bandwidth Indoor Channel,” *IEEE Transactions on Communications*, Vol. 52, No. 10, pp. 1786-1796, Oct 2004.
[7] ATS640LSH User Manual, Allegro Microsystems Inc.
[8] MPC5200B User Manual, Freescale Inc.
[9] Lite5200B User Manual, Freescale Inc.
[10]Advance Information of MC270113 Ultra-Wideband RF Transceiver, Freescale Semiconductor.
[11]Advanced Information of MC270123 Ultra-Wideband Baseband Controller, Freescale Semiconductor.

[12]Advanced Information of MC270143 Ultra-Wideband Medium Access Controller, Freescale Semiconductor.
[13]IEEE 802.15, Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs), IEEE, June 2003.