M.S. Thesis

Wireless Sensor Networking for Vehicle Environments

차량 환경에서의 무선센서네트워킹에 대한 연구

Siheon Ryu

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School of Electrical Engineering and Computer Science
College of Engineering
Seoul National University

Wireless Sensor Networking for Vehicle Environments

지도 교수 이 용 환

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위 원 장 ________ 박 세 웅 ________ (인)

부위원장 ________ 이 용 환 ________ (인)

위 원 ________ 김 성 철 ________ (인)

Abstract

Recently, wiring has become a critical consideration due to rapid increasing number of automotive electronics. In this respect, wireless network is considered a suitable solution for connections between electronic control units (ECUs). Wireless connection of ECUs can reduce the weight of harness system can directly result in cost and fuel efficiency. However, research on wireless networks which guarantee transmission delay and reliability of conventional vehicle network is barely studied.

This thesis proposes to replace wire harnesses with ZigBee based 2-hop cluster tree wireless networks for non-safety-critical application of vehicle. Considering wireless network is connected to CAN bus, we design a gateway to ensure interoperability between conventional CAN bus and wireless network. We also propose a system which controls devices in the vehicle network through remote controllers. In addition, we design the broadcast-based data transmission structure which effectively reduce the transmission latency. We ensured transmission reliability through repeated transmission, taking into account the vehicle environment in which wireless local area network (WLAN) interference exists. Computer simulations confirm that the proposed scheme satisfies the transmission requirements of conventional vehicle body networks.

Keywords: In-vehicle network, Controller area network, ZigBee

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Chapter 1. Introduction

In recent years, in-vehicle electronic systems are rapidly advanced and the number of ECUs are increased. Therefore, wiring has become a critical consideration as increased wire harnesses results in low fuel efficiency and high mounting complexity [1]. In this respect, wireless network is considered a suitable solution for connections between ECUs. There are some studies about wireless network for the purpose of controlling the interior space of the car [2-4]. However, research on wireless networks which guarantee transmission delay and reliability of conventional vehicle network is barely studied.

In order to achieve satisfactory performance through wireless network, it is important to ensure transmission requirements of vehicle application. However, communication environment of vehicle is very harsh due to factor such as WLAN interference, which degrade the transmission performance of wireless communication. Therefore, wireless network is needed to ensure transmission reliability in an interference environment, while still meeting the transmission delay requirements of the vehicle body network.

In this thesis, we consider replacing wire harness with wireless network for non-safety-critical vehicle body applications such as windows, door locks and sunroofs. We propose a 2-hop cluster tree network structure which is connected to conventional CAN bus and controls the devices of vehicle body network through remote controllers. We design the broadcast-based data transmission structure to meet the transmission requirements of the vehicle body network in the IEEE 802.15.4 beacon-enabled mode structure. We analyze broadcasting parameters that satisfy transmission requirements of vehicle body network in WLAN interference environment. In addition, we design a gateway between Zigbee and CAN bus which provide interoperability of disparate network protocol.

The rest of this thesis is organized as follows. Chapter 2 and 3 describe system model and previous works of vehicle network, respectively. Chapter 4 describes the proposed scheme. Chapter 5 evaluates the performance of the proposed schemes by computer simulation. Finally, Chapter 6 concludes this paper.

Chapter 2. System model

As illustrated in Figure 1, we consider an IEEE 802.15.4 beacon-enabled 2-hop cluster-tree structured network which is connected with conventional vehicle wired network, CAN bus. The wireless network comprises four types of devices; a coordinator, routers, end devices and remote controllers which located in presence of WLAN interference. A coordinator and routers operate as a parent device which can have routers and end devices as a child device. The coordinator is then connected to the CAN bus to act as a gateway for the wired and wireless networks. The remote controller controls the devices in the wireless network and can have end device as a router.

A beacon-enabled cluster-tree network can have multiple clusters, each of which comprises a cluster head and its child devices. We assume that each cluster operates using its own periodic super-frame structure. At the beginning of the active period, the cluster head transmits a beacon frame for synchronized transaction with its child devices. The beacon interval and the super-frame duration are determined as, respectively,

$$T_{BI} = \left(aBaseSuperframeDuration \cdot 2^{BO} \right) t_{sym}, \quad \text{for } 0 \le BO \le 14 \tag{2.1}$$

$$T_{SD} = \left(aBaseSuperframeDuration \cdot 2^{SO} \right) t_{sym}, \quad \text{for } 0 \le SO \le BO \tag{2.2}$$

Where BO is the beacon order, SO is the super-frame order and t_{sym} is the symbol time. The child devices in each cluster can make communications with their parent device only during the active period, while entering a power-saving idle mode during the inactive period. The child device activates its receiver before the beginning of the super-frame and searches for a beacon frame transmitted from its parent device [7].

We assume wireless communication targets control that are not safety critical, for example, vehicle body application such as electronically controlled seats and mirrors. We assume a network with 50 nodes considering scale of conventional vehicle body networks. For instance, a high-end vehicle can have around 250 sensors, and 20% of this number is related to non-safety-critical applications which can be migrated to short-range wireless links, we would have a WSN with a node population of around 50 sensor nodes [5].

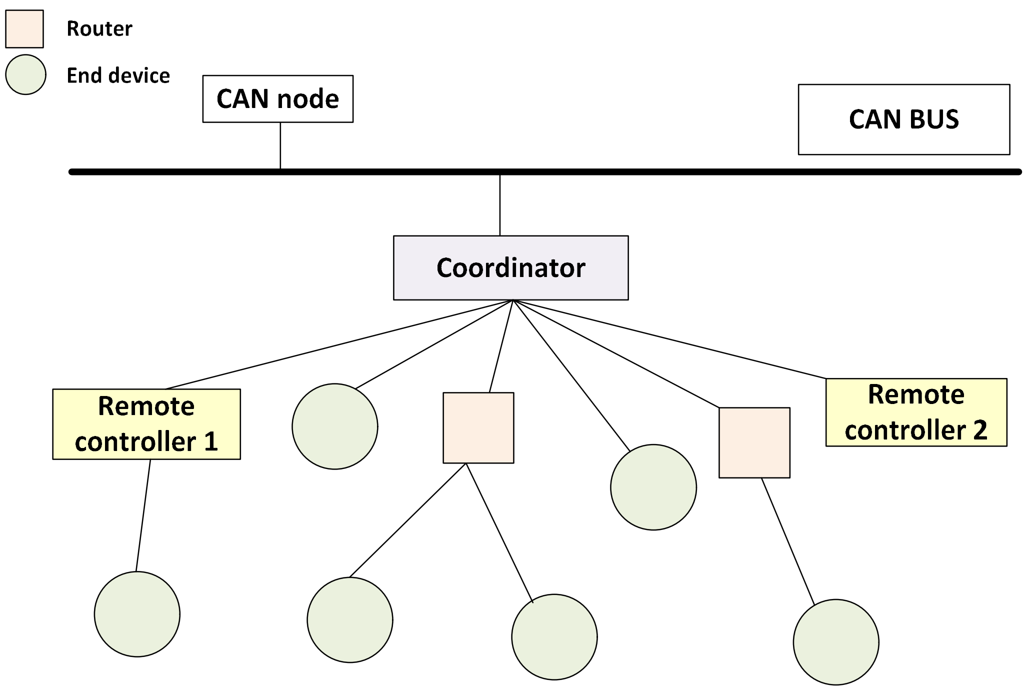

Figure 1. Example of CAN - ZigBee wireless network

We assume data traffic in a vehicle body network is divided into control and update traffic. Control traffic is event-triggered traffic which the messages are transmitted when significant events occur (e.g., a door has been locked). In this case, the network shall have the ability to transmit any asynchronous events as soon as possible. Therefore, the generation frequency of control traffic depends on the device's use environment, and assume that the data is generated by the Poisson distribution of the mean λ (packets / second). Update traffic is primarily the periodic traffic that is transmitted periodically as traffic to transmit the status of devices in an in-vehicle application. Therefore, it is assumed that each device generate data periodically every T_ul second.

The vehicle ECU performs body, diagnosis, powertrain/chassis, infotainment and safety functions as shown in Table 1 [6]. Unlike powertrain/chassis and safety area ECUs which require high transmission reliability and a low transmission delay of 1 ms or less, the ECU that forms the body area network operates at reliability of packet error rate 10^{-3}, and a relatively large transmission delay of 500 ms.

Table 1 Vehicle ECU Classification

<table>
<tr><th>Classification</th><th>Application</th><th>ISO Standard</th></tr>
<tr><td>Body</td><td>Light, Door lock, Window</td><td>LIN, Low Speed CAN</td></tr>
<tr><td>Diagnostic</td><td>Fault Diagnosis</td><td>Low Speed CAN</td></tr>
<tr><td>Power train & Chassis</td><td>Engine, Break</td><td rowspan="3">High Speed CAN</td></tr>
<tr><td>Infotainment</td><td>Navigation, Videos</td></tr>
<tr><td>Safety</td><td>Airbag</td></tr>
</table>

Chapter 3. Previous works

3.1. CAN Bus

CAN is a highly reliable serial bus system, which is the most widely used protocol in vehicle networks. CAN sends messages to connected devices using twisted pair in a broadcast manner using carrier-sense multiple access with collision detection (CSMA/CD). CAN uses a data frame structure consisting of an arbitration field, a control field, and a data field as shown in Figure 2 [8]. CAN protocol allow nodes on the network to start transmitting if the bus is idle. A process called bus arbitration is used to avoid conflicts if multiple nodes start transmitting at the same time. Arbitration process is based on the priority of the frames, which is transmitted in the arbitration field or identifier of the frame.

CAN frames are divided into standard message frames (CAN 2.0A) with an identifier of 11-bit and extended message frames (CAN 2.0B) with an identifier of 29-bit. The data frame contains messages up to 8 bytes and the maximum transmission speed is supported up to 1 Mbps. In addition, the control field 6 bits of this field represent Reserved bits (2 bits for extended CAN frame) and Data Length (4 bits to indicate data bytes), and the ACK field uses a single bit each for ACK slot and ACK delimiter subfields. ACK slot is used to acknowledge the successful reception of the message frame.

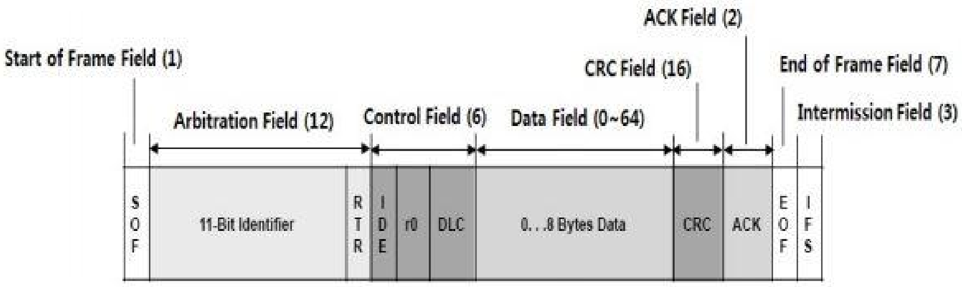

Figure 2. Standard CAN data frame format (2.0A)

3.2. LIN BUS

LIN is for low-cost applications kept on increasing and today it has become a technology of choice for low data-rate (20 Kbps) automotive applications [9]. A large number of small mechatronic elements in body domain require only local communication. LIN networks are well-suited for such local control operations, for instance, controlling door locks, electric window operations, seats adjustments, wipers, rain sensor, light control and climate control functions. For subsystems requiring low data-rate, expensive CAN network are replaced by small LIN sub-networks. This solution fits in at the low end of automotive networking. Interconnection among LIN sub-networks is achieved using CAN network as backbone. An advantage of creating sub-networks is to reduce the data load on the main bus. In this scenario, a hierarchical structure of CAN-LIN nodes and their sub-networks is formed.

LIN utilizes a Master/Slave protocol in which Master determines the order and priority of the messages. The Master node uses a schedule table which contains the frames to be transmitted and their associated time slots. There can be 2-16 Slave nodes on the LIN bus. A Slave node receives or transmits data when an appropriate ID is sent by the Master node. In addition, maximum latency of the transmitted signal is guaranteed.

Consider LIN bus in which time scheduled with M slots as shown in Figure 3. The delay of LIN bus can be represented as

$$D = T_A + T_p + W_q \quad (3.1)$$

Where T_A is access delay which is the time between its arrival and the end of the frame time. When packets arrive uniformly during each frame time, the maximum access delay will be $T_s M$, where T_s is duration of base time slot. T_p is propagation delay which is the time it takes to reach its destination excluding access time and queuing delay and can be represented as $L_{data} / R \cong T_S$, where L_{data} is size of data and R is data rate of LIN bus. W_q is message delay in the queue, which is the delay while the message is at the header of the queue, and waits for the turn of its time slot. The maximum message delay in the queue is $T_S(M-1)$, when the assigned timeslot is the last slot of the schedule. Therefore, the maximum latency $D_{\max}$ can be represented as

$$D_{\max} = T_A + T_p + W_q = T_S M + T_S + T_S(M-1) = 2T_S M \quad (3.2)$$

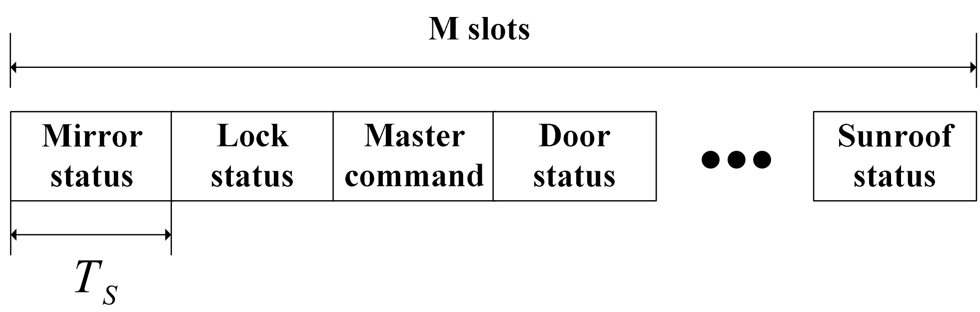

Figure 3. LIN bus time schedule structure

3.3. ZigBee / IEEE 802.15.4

ZigBee is an appropriate technology for local area wireless networking based on the physical (PHY) layer and the media access control (MAC) layer of IEEE 802.15.4, with transfer speeds of up to 250 Kbps. ZigBee based on IEEE 802.15.4 supports the construction of networks in multi-hops, which allows the coordinator, the primary node, to build networks in a variety of topologies with routers and end devices.

The uplink transmission in the IEEE 802.15.4 employs a carrier sense multiple access with collision avoidance (CSMA/CA) to support competition-based packet transmission [10]. The child device attempting to transmit packets first performs channel sensing, referred to the clear channel assessment (CCA), after a random back-off delay. It transmits packets only when the channel is clear. When the channel is busy, the child device exponentially increases the maximum back-off delay to reduce the contention.

The downlink transmission in IEEE 802.15.4 is shown in Figure 4. Parent device send beacon to child device with beacon pending, which specifies whether the parent device has data to send to its child through pending field in the beacon frame. Child device which received the beacon frame checks pending field and sends data request if its address is in the pending field. Upon receiving the data request message, parent device responds with ACK and transmits the downlink data. Since the data request message and corresponding ACK are required for each data packet, there is a protocol overhead in the pending method.

If the transmission of data fails due to factors such as external interference, the parent device maintains the pending of the data for a certain period of time when sending beacons instead of retransmitting the data. The subsequent process is as described above. However, this transmission method is limited to a maximum of one attempt to transmit data within a beacon interval (BI), which has the disadvantage of transmission delay and reliability performance. As a result, the performance of the downlink transmission in the interference environment will be less than that of the uplink transmission.

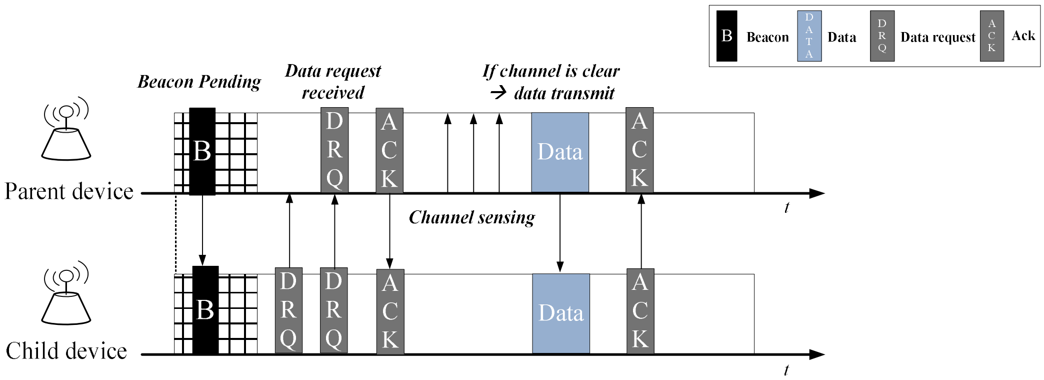

Figure 4. IEEE 802.15.4 downlink transmission with pending method

Chapter 4. Proposed schemes

4.1. Proposed broadcast-based transmission structure

We consider the alleviation of latency and reliability problem in IEEE 802.15.4 based WSNs by means of allocating control traffic only frames and repeated broadcast transmission. IEEE 802.15.4 based data transmission has the disadvantage of requiring a 3-hop transmission (1 uplink, 2 downlink transmission) when remote controllers control devices located at two hops, resulting in a high transmission delay. However, this delay can be reduced because transmission over broadcasting can be sufficiently transmitted through up to 2-hops. Figure 5 shows broadcast based 2-hop transmission of remote controllers.

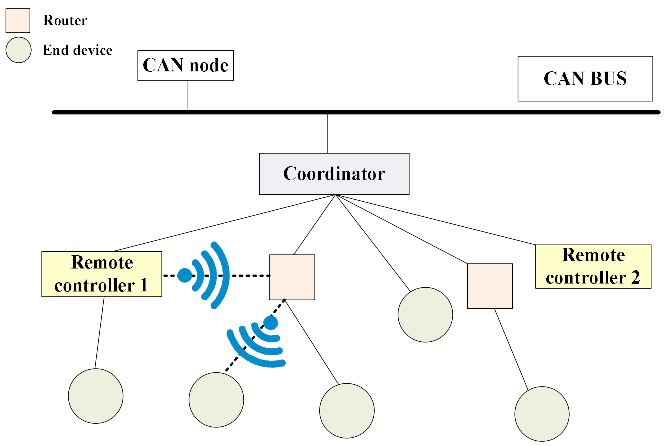

Figure 5. Broadcast-based remote control

We design a transmission frame structure in a 2-hop WSN as shown in Figure 6. Coordinator, routers and remote controllers operate using its own periodic super-frame structure for synchronized network operation with non-overlapped channels. Moreover, remote control frames are assigned to each remote controllers which allows to transmit control traffic only. After remote control traffic is generated, remote controllers broadcast data repeatedly using its own remote control frame. During remote control period, all routers should be switch to listen mode to prepare for receive control traffic data. Upon receipt of control message, a router transmit a beacon frame with a broadcast pending. After the transmission of the beacon frame, it broadcasts repeatedly to child devices. Figure 7 illustrates the overall procedure of the proposed scheme.

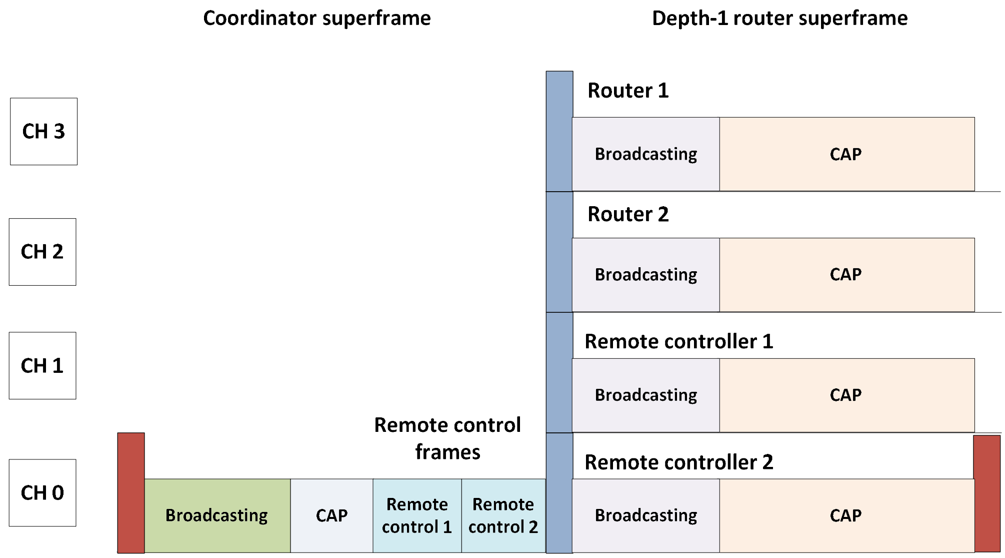

Figure 6. Concept of data transmission structure

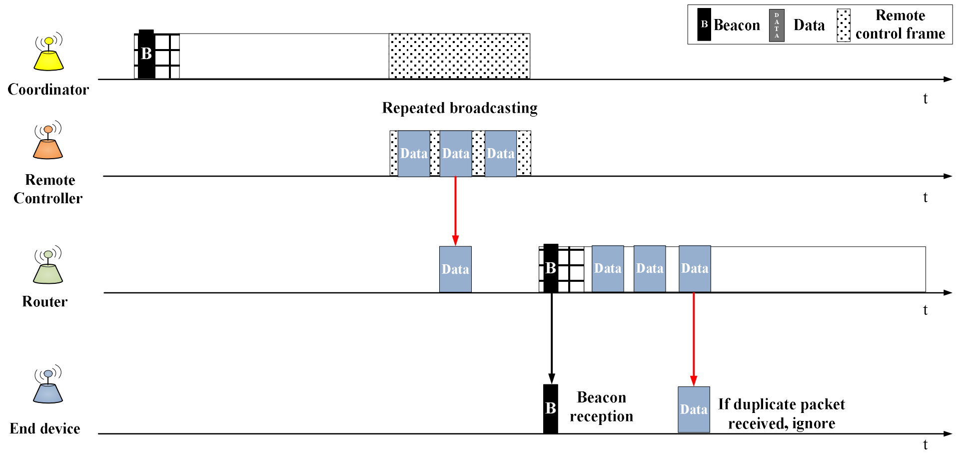

Figure 7. An example of proposed remote control

4.1.1. Repeated broadcasting in the presence of interference

We describe the channel occupancy by WLAN using a two-state semi-Markov model [12, 13], where the busy period of WLAN traffic lasts for a fixed time of T_W and the idle period follows with probability distribution function (PDF) $f_{T_I}(t_I)$. We assume that the idle period can be approximated as an exponential random variable with mean $E_T(t_I) = \lambda^{-1}$. Then, the channel occupancy ratio (or loading factor) of WLAN traffic can be defined by

$$\rho = \frac{T_W}{T_W + \lambda^{-1}},\ \rho \in [0,1) \tag{4.1}$$

Since no device in contending during the broadcasting frame, a simple ALOHA scheme may be used to transmit downlink data. Then, the expected collision probability of data transmission can be represented as

$$p_{col}[c] = \rho\, p_{col}[c \mid Busy] + (1-\rho)\, p_{col}[c \mid Idle] \tag{4.2}$$

Where $p_{col}[c \mid Busy]$ and $p_{col}[c \mid Idle]$ denotes the collision probability when the transmitter attempts to transmit data in the presence and absence of WLAN traffic respectively. $p_{col}[c \mid Idle]$ can be represented as

$$p_{col}[c \mid Idle] = 1 - \exp\{-\lambda \frac{L_{Data}}{R_{Data}}\} \tag{4.3}$$

Where L_{Data} denotes length of data packet and R_{Data} is the data rate. Since $p_{col}[c \mid Busy] = 1$, the expected collision probability can be represented as

$$p_{col}[c] = 1 - (1-\rho)\exp\{-\lambda \frac{L_{Data}}{R_{Data}}\} \tag{4.4}$$

Therefore, the transmission failure probability of N_b repeated broadcasting can be represented as

$$p_{col}[c] = \left\{1 - (1-\rho)\exp\{-\lambda \frac{L_{Data}}{R_{Data}}\}\right\}^{N_b} \tag{4.5}$$

The simulation and analysis result shown in Figure 8. It can be seen that the reliability of the vehicle network can be ensured through repeated broadcasting even in extreme interference environments.

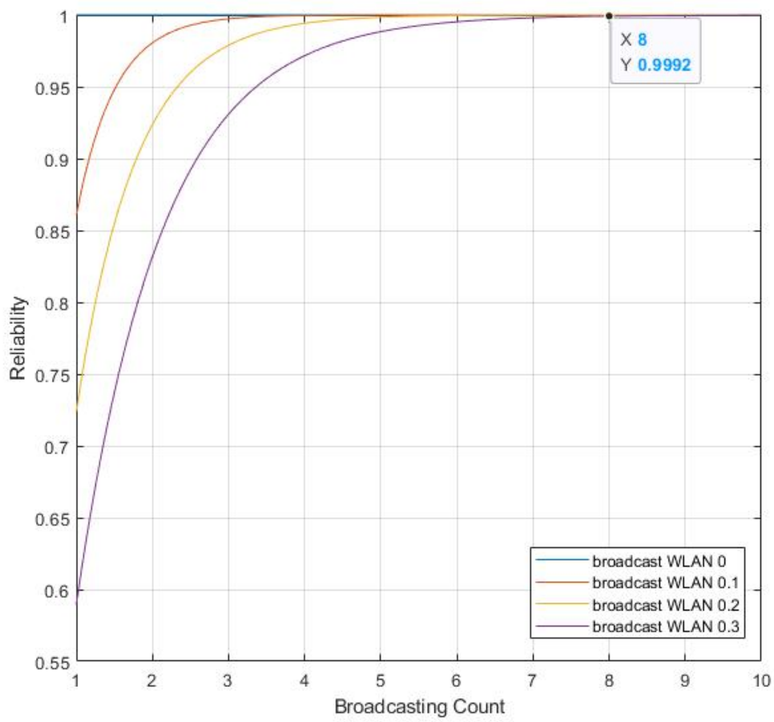

Figure 8. Expected reliability of repeated broadcasting

4.2. Design of CAN / ZigBee gateway

We design a gateway between CAN bus and ZigBee, which connected to the CAN bus and also operates as a single network of ZigBee based wireless network. The wireless network is then connected to the CAN via the gateway. The gateway is to act as a gateway between CAN and the wireless network which is coordinator for the ZigBee wireless network and operate as a single CAN node on the CAN bus.

Figure 9 shows the data frame structure for communication between the wireless network and CAN. The frame of SAE J1931 which is widely used in commercial CAN protocols defines a data frame based on an extended message frame, which allocates 8 bits for the designation of destination address and source address [14]. Since the address field is an address on the CAN protocol, address response on each protocol is required to convert the data frame to a wireless network.

For this purpose, the conversion to a wireless network data frame is made through an address table held by gateway, which contains matching information of the wireless network address and the address of the CAN. Converted address of source and destination wireless network MAC headers can be configured with source and destination addresses determined by ZigBee routing. The CAN frame is encapsulated in the network payload to form the frame.

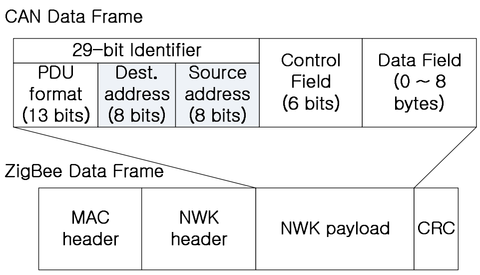

Figure 9. Frame conversion of CAN / ZigBee

Chapter 5. Performance analysis

The performance of the proposed scheme is evaluated by computer simulation. For the computer simulation, we construct a 2-hop cluster tree structured network, where nodes are distributed in a square area of $(2.5 \times 5)m^2$ considering a normal size of vehicle body. The simulation parameters are summarized in Table 2, which considers the operation of 2-hop wireless sensor network. It is also assumed that the environment in which WLAN interference is loaded 0.3 factor across all bands. For comparison, we also evaluate the performance of LIN bus and IEEE 802.15.4 pending method.

We assume that the beacon order is 4 (i.e., the beacon interval is 245.76 *ms*), and the maximum network depth is 2. To consider the various cases of ECU deployments, the routers are newly selected in each iteration of computer simulation for connecting all nodes randomly deployed in the network. End devices are connected to routers or the coordinator either. The size of data payload is 8 bytes, which is the maximum payload size of CAN, and LIN bus. We assumed that the user can control devices once a second, remote controllers generate control traffic with Poisson distribution. In addition, considering the transmission cycle of non-safety-critical applications, the update traffic cycle is assumed to be 5 seconds.

Table 2 Simulation parameters

Parameters	Values
Beacon order (BO)	4
Super-frame order (SO)	3
Maximum number of child devices(Cm)	20
Maximum number of child routers(Rm)	4
Number of remote controllers	2
Network Depth	2
Data rate	250 *kbps* (IEEE 802.15.4 PHY)
Data payload size	8 byte
Number of nodes	51 (Coordinator included)
Deployment area	2.5 *m* * 5 *m*
WLAN busy time duration	1 *ms*
Traffic generation period (λ)	1 packet / sec (Poisson dist.)
Traffic generation period (T_ul)	5 *s*

오류! 참조 원본을 찾을 수 없습니다. and Figure 10 shows latency cumulative distribution function (cdf) in a WLAN 0, 0.3 environment when controlling devices in a wireless network. It can be seen that the transmission delay performance of the proposed scheme has been significantly reduced in transmission delay compare to the IEEE 802.15.4 based pending method. This difference comes from increase of transmission delay due to transmitting on up to 3-hops and failure of transmission due to WLAN interference. This result indicating a significant difference in reliability performance due to repeated transmission of broadcasting. Compared to the performance of LIN bus, it can be seen that the proposed system satisfies both the transmission requirements of the conventional vehicle body network in terms of reliability and latency.

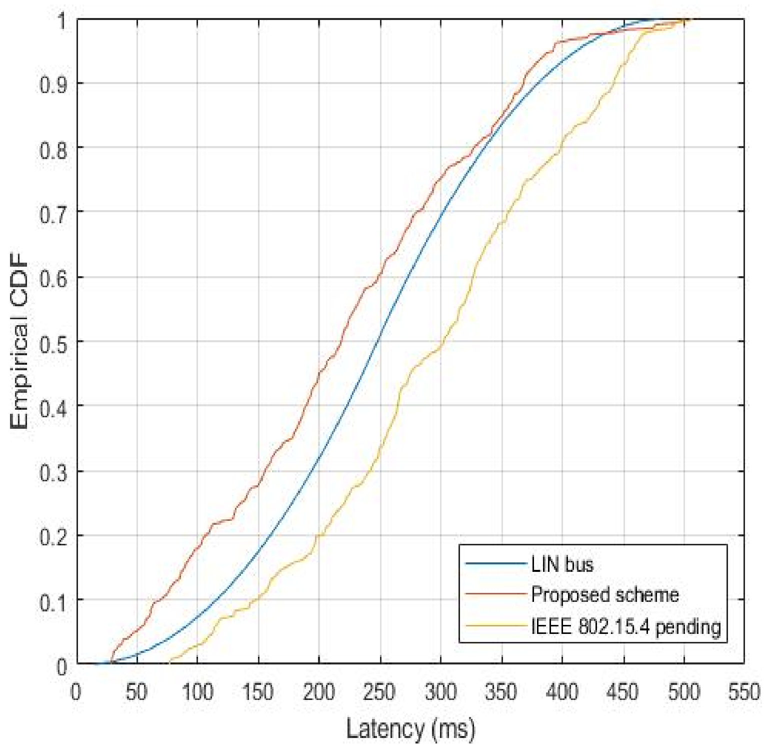

Figure 10 Latency cdf of remote control traffic (WLAN 0)

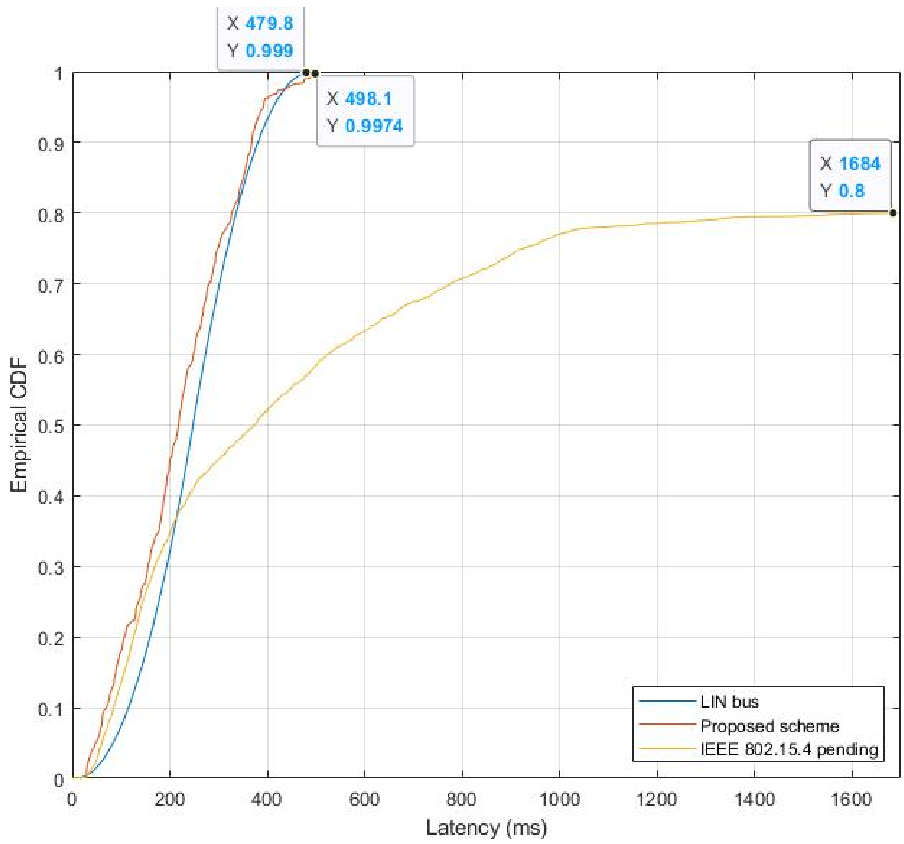

Figure 11 Latency cdf of remote control traffic (WLAN 0.3)

Chapter 6. Conclusions

In this thesis, we propose to replace wire harnesses with ZigBee based 2-hop cluster tree wireless networks for non-safety-critical application of vehicle. Considering wireless network is connected to CAN bus, we design a gateway to ensure interoperability between conventional CAN bus and wireless network. We also propose a system which controls devices in the vehicle network through remote controllers. In addition, we design the broadcast-based data transmission structure which effectively reduce the transmission latency. Remote control frame section is assigned to the remote control controller, which allows remote controller broadcast control traffics. Proposed scheme provides reliable transmission of control messages even if WLAN interference exists by repeated transmission of data through broadcasting. Computer simulations confirm that the proposed scheme satisfies the transmission requirements of conventional vehicle body networks.

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Korean Abstract

차량에 장착된 전자 컨트롤 유닛(electronic control unit: 이하 ECU)는 유선으로 연결되고 있지만 ECU 수의 급격히 증가로 인해 차량 실장 복잡도가 크게 증가하고 필요한 와이어의 무게가 크게 증가했다. 이러한 점에서 무선 센서 네트워크(wireless sensor network)는 ECU 간 연결에 적합한 솔루션으로 고려된다. 그러나 대부분의 차량에서 사용되고 있는 차량 유선 네트워크인 CAN(controller area network) 버스와 상호운용성을 유지하면서 기존 차량의 전송요구사항을 충족하는 무선 솔루션은 부족하다.

본 논문은 창문, 도어락, 선루프 등 안전에 민감하지 않은 차량 바디 네트워크의 응용에 대하여 와이어 하니스(wire harness)를 지그비(ZigBee) 기반의 2-hop 클러스터 트리 무선 네트워크로 대체하는 방법에 관한 것이다. 제안기법은 먼저 기존 CAN 버스가 무선네트워크의 백본으로 연결되기 때문에 서로 상이한 네트워크 간의 연결을 위해 게이트웨이를 설계하여 상호운용성을 보장하였다.

또한 기존 IEEE 802.15.4 비컨 모드에서 차량 바디 네트워크의 전송요구사항을 만족하는 브로드캐스트(broadcast) 기반의 리모트 컨트롤 전송구조를 설계했다. 리모트 컨트롤러는 리모트 컨트롤 프레임(remote control frame)에서 브로드캐스트를 통해 제어 메시지(control message)를 전송하며, 상기 프레임 구간에서 네트워크 내 모든 기기는 수신모드(listen mode)로 동작하여 메시지를 수신한다. 한편 제어 메시지 전송 시 반복

전송을 통하여 메시지 전송의 신뢰성을 높이며 분석을 통해 WLAN 간섭환경에서도 기존 차량 유선네트워크와 동일한 전송신뢰성을 보장하는 브로드캐스팅 전송 횟수를 도출하였다. 컴퓨터 시뮬레이션을 통해 제안 기법이 기존 차량 바디 네트워크의 전송요구사항을 만족함을 나타내는 것을 확인하였다.

주요어: CAN 버스, 차량 내 무선네트워크, 지그비

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