A Study on Reliable Wireless Communication in Vehicles

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List of Publications by Author

I. Journals

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II. International Conferences

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IV. Patents

[1] 細川元気，國立忠秀，“代理通信完了通知の効率化，” 特願 2018-197441.

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[3] 國立忠秀，“無線通信端末および通信制御方法，” 特願 2018-131648.

[4] 小湊靖裕，中村悟朗，國立忠秀，松下健治，“着座センサ，” 特願 2018-074593.

[5] 國立忠秀，“無線通信端末および通信制御方法，” 特願 2018-010542.

[6] 池田浩太郎，國立忠秀，“車両用無線通信システム，” 特願 2018-005789.

[7] ワンシット，金森勝美，國立忠秀，“車両用無線通信システム，” 特願 2017-126343.

[8] 松井研輔，國立忠秀，木村恒人，金森勝美，池田浩太郎，“車両用無線通信システム，” 特願 2017-126342.

[9] 金森勝美，國立忠秀，木村恒人，松井研輔，池田浩太郎，“車両用無線通信システム，” 特願 2017-126341.

[10] 木村恒人，國立忠秀，金森勝美，松井研輔，池田浩太郎，“無線信号の干渉検出方法、無線通信システムおよび無線受信機，” 特願 2017-117779.

[11] 池田浩太郎，國立忠秀，木村恒人，金森勝美，松井研輔，“車両用無線通信システム，” 特願 2017-095773.

[12] 國立忠秀，木村恒人，金森勝美，松井研輔，池田浩太郎，“車両用無線通信システム，” 特願 2017-095772.

[13] 國立忠秀，“中継装置、タグ端末、及び通信システム，” 特願 2017-083780.

[14] 國立忠秀，木村恒人，“製造システムおよび冶具板と誘導装置との接続方法，” 特願 2017-068066.

Abstract

Wireless communications is the fastest growing segment of the communications industry and is researched IoT which attach sensors to various things existing in the real world such as furniture and home appliances. Recent works on enhancing the comfort and convenience of vehicles have shown the appeal of information collection by various wireless sensor nodes due to their ease of installation and their small size. It seems that the importance of sensors in vehicles will increase in the future since many sensors are installed in the vehicle. The wire harnesses that connect sensors must be complicated and constrained to avoid seats and handle, etc. The obvious solution is to use wireless links. Communication between equipment in a vehicle must meet strict requirements in terms of success ratio and delay constraint. Target success ratio is 99.999% and required delay constraint is 20 ms when a device not related to operation communicates. At this time, the drastic changes in the radio wave environment of wireless links used in vehicles are problems. The conventional wireless network standards achieve insufficient reliability for practical in-vehicle communications. In this thesis, first, we clarified the radio wave environment of the several vehicle types. Moreover, since it can be assumed that Electric Vehicles (EV) will spread in the future, the Battery Management System (BMS) which to monitor the battery cell information must be considered. Again, the battery sensor plays an important role for safe EV operation. Therefore, we focus on a seat sensor system and the BMS of EV. Our solution is to propose Reliable Wireless Communication based on Substitute Forwarding (RWCSF). RWCSF achieves high success ratios with single flow at the transmission power −36 dBm or more. However, in RWCSF, the relay nodes overhear a packet and retransmit it if the communication fails. As many packets will flood the network, several nodes can relay the same packet, communication is delayed in the multi-flow scenario expected. Here, it can be considered that the sensor and BMS communication are representative of multi-flows. Then, we proposed RWCSF with Data Aggregation (SFwDA) to communicate with fewer packets and improve the

reliability. SFwDA aggregates packets of the same destination of battery sensors or seat sensors into one packet. We simulate the communication using the proposed method under the radio wave environments in different type of vehicles. In addition, we confirmed the noise environment in vehicle and clarified their significant characteristics. We confirm that the proposed method is effective in multi flow and noisy environments in common vehicles when the packet aggregate size is 2.

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Chapter 1

Introduction

Wireless communications is the fastest growing segment of the communications industry [1].

Drums were among the first telecommunications systems, and it was not until the 1830s that electrical telecommunication systems started to appear.

The first experiment in electrical telegraphy was the 'electrochemical' telegraph created by the German physician, anatomist, and inventor Samuel Thomas von Sömmerring in 1809 [2]. The principal disadvantage to the system was its prohibitive cost. Charles Wheatstone and William Fothergill Cooke patented a five-needle, six-wire system, which entered commercial use in 1838 [3]. This system used the deflection of needles to transmit messages and started operating over twenty-one kilometers of the Great Western Railway on 9 April 1839.

Samuel Morse developed a version of the electrical telegraph which he demonstrated on 2 September 1837. This was successfully demonstrated over a distance of five kilometers on 6 January 1838 and eventually over sixty-four kilometers between Washington, D.C. and Baltimore on 24 May 1844. The patented invention was rapidly adopted and by 1851 the United States had over 32,000 kilometers of telegraph lines.

The first successful transatlantic telegraph cable was completed on 27 July 1866, allowing transatlantic telecommunication for the first time.

Electric telephones were invented in the 1870's, Bell went on to submit a patent application on the telephone in 1876. This was the first recognizable phone. Commercial telephone services were started in 1878 and 1879 on both sides of the Atlantic in the cities of New Haven and London. Telephone technology grew quickly after the first commercial services emerged. Thereafter, inter-city lines and telephone exchanges were built in every major city of the United States by the mid-1880s [4]. Transatlantic voice communication became possible in January 7, 1927 when a connection was established using radio wave. Also, more stable connections were realized on September 25, 1956 with opening of a wired submarine cable.

Another device using radio waves is television. Television demonstrations were common by 1925. Video telephony development started in the mid-to-late 20th century. Only in the late 20th century with the advent of powerful video codecs and high-speed broadband connections did it become a practical technology for regular use.

A new era in telecommunication was created by the first cellular phone in 1945. This is now called 0G, the zero generation of mobile telephony via mobile radio telephones. Unfortunately, the sets were very large and heavy and calls to other base stations were not possible.

"Wireless telephones" were exhibited at the Osaka World Expo in 1970, and service began in 1971. Called 1G, this is the first generation of wireless cellular technology, and analog signals were used.

In the 1990's, 2G, the second-generation cellular technology, was launched and digital signals were used.

3G, the third generation of wireless mobile telecommunications, was released in 1998, and various communication standards such as UMTS, Universal Mobile Telecommunications Service, system, CDMA 2000 system, etc. were approved. 3G can realize wireless voice telephony, mobile Internet access, fixed wireless Internet access, video phones and mobile TV. Further research yield 4G, the fourth generation of broadband cellular network technology; it makes ultra-high-speed and large capacity communication possible.

Looking to the future, it is expected that further high-speed, large-capacity communication will be realized by 5G, the fifth generation of cellular mobile communications, and "Beyond 5G".

An interesting trend is the expanded use of communication inside homes and buildings. With regard to wired connections, Ethernet was commercially introduced in 1980 and first standardized in 1983 as IEEE 802.3 [5]. It has since been refined to support higher bit rates and longer link distances. 10Gbase-T with its 10Gbps has been standardized.

With regard to wireless connections, Wireless LAN was developed in the 1990's, but remained impossible to connect different products since early developments focused on industry-specific solutions and proprietary protocols. In order to solve this problem, IEEE 802.11 was standardized in 1997. IEEE802.11b with its 2Mbps was standardized in 1999. Subsequent work yielded increased speeds and higher frequencies as specified in the series of IEEE802.11a, IEEE802.11g, IEEE802.11n, IEEE802.11ac, and IEEE802.11ad.

These communications standards are being used in the fields of Wide Area Networks (WANs), metropolitan area networks (MANs), A personal area network (PAN), body area networks (BANs), and local area networks (LANs).

A WAN is a telecommunications network or computer network that extends over a large geographical distance/place. Wide area networks are often established by leasing telecommunications capacity.

MANs are used interconnect networks in a city to create a single larger network which may then offer efficient connection to a wide area network [6].

PANs are computer networks for interconnecting devices centered on an individual person's workspace. A PAN provides data transmission amongst devices such as computers, smartphones, tablets, and personal digital assistants. Whether PAN is wired or wireless is not defined, wired interfaces such as USB are also within the category of PAN. In recent years, the Wireless Personal Area Network (WPAN) is beginning to be used.

BANs are networks constructed by wireless communication among small terminals located on the surface of the human body, in the body or in the immediate vicinity [7]. LANs are computer networks that interconnect computers within a limited area such as a home, school, laboratory, university campus or office building [8].

As a simple and reliable method for connecting devices, wire continues to be utilized. However, it is expected that wireless connections will predominate in the future, and M2M, Machine To Machine, communications will be wireless.

Here, M2M is a generic name for communication that connects equipment and equipment to a network for the exchange of information and control signals. In particular, research is very active in the IoT (Internet of Things) which attaches sensors to various things existing in the real world such as furniture and home appliances and connects them to the Internet [9].

Through the innovation provided by the IoT (Internet of Things) in the information-oriented society, it is expected that mobile phone networks and short range communication technologies will be adopted in many fields [10].

Fig. 1 shows the relationship between the connection and the network. In each connection, various networks are used. A double line is a relationship with a most used network.

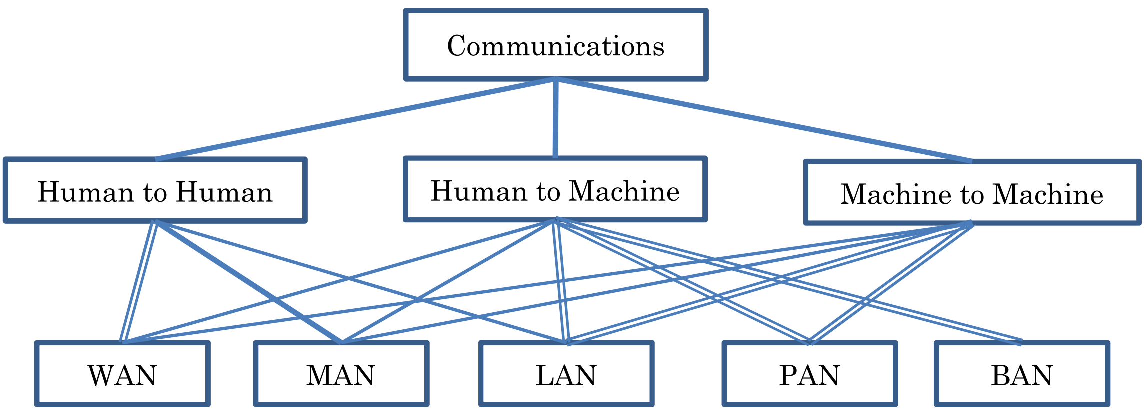


Fig. 1 Relationship between the connection and the network.

Here, Wireless communication is used often between countries and cities, inside the office, inside the home, and around the human body. Unfortunately, Vehicle and ICT links mostly use wired connections. Table 1 shows this relationship.

Table 1 List of communication distance, application and connection method.

Distance	Area	Application	Connection method
WAN	Town	Cellular, Mesh network	Wiring/Wireless
⇕	Office	Intranet, Factory network	Wiring/Wireless
	Home	Home network	Wiring/Wireless
	Human	Computer network, Body area network	Wiring/Wireless
	Vehicle	CAN, LIN	Wiring
Short range	ICT equipment	Dedicated lines	Wiring

Here, comparing vehicles with inside the home and inside the office, there is a big difference in the form of equipment connection.

In other words, wireless communication for ICT equipment and for vehicles is an undeveloped area. In particular, vehicle manufacturers are eagerly anticipating wireless communication to eliminate a lot of wiring as this will maximize passenger space.

While vehicles are seen as comfortable and convenient tools, traffic accidents are a major social issue. According to the statistics of the Metropolitan Police Department, more than 60% of traffic accidents are caused by the driver's negligence. Therefore, it is expected that advanced driving support and alert systems will lead to a decrease in traffic accidents [11].

In recent years, supporting drives by sensing vehicle characteristics and driver alertness has been studied actively [12]-[18]. The research is expected to yield technologies critical in reducing the number of traffic accidents. In such studies, sensors play an important role for safe and comfortable driving [19] [20]. The crew sensors, heartbeat / respiration sensors, temperature and humidity sensors are used for comfort and optical sensors, rain sensor, engine sensors are used for convenience [15]-[19]. The importance of vehicle sensors will continue to increase and the number of sensors attached to the vehicle will continue to increase [21]. Therefore, electric wiring in the vehicle will increase year by year. In order to deal with this, more intensive LAN usage is being considered, but the weight and complexity of metallic wiring continues to increase [22]. Fig. 2 shows the trend lines up to 2030.

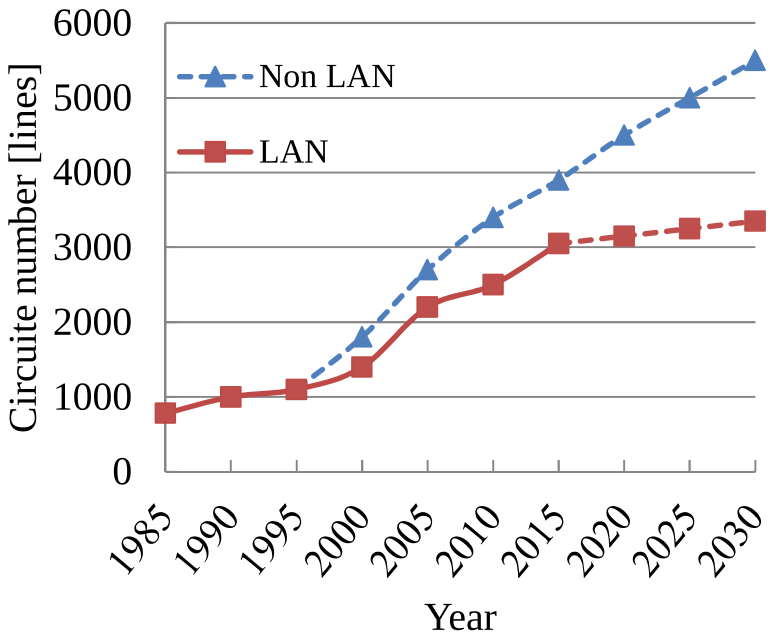


Fig. 2 Transition of the wire harness circuit number (luxury vehicle).

Since the inside of the vehicle is reserved for passengers, and there are many openings, hatches, and seats, using metallic wire to connect the devices will be infeasible as wiring harnesses will too long, inflexible and heavy.

Wire harnesses use metals such as copper and/or aluminum. The weight of a wire harness is in the region of 20 to 50 kg per vehicle [23]. Depending on the vehicle type and optional parts, the lines used for signaling can occupy about 20% of the total weight.

Fig. 3 shows the impact of vehicle weight on fuel economy. Reducing the weight by 1 kg can improve the fuel efficiency by an average of 0.01 km / ℓ [24].

Reducing vehicle weight is essential for improving the fuel economy and driving range of Electric Vehicles (EVs). In other words, minimizing wire harness weight is an important factor in improving overall performance.

Fig. 4 provides a summary of CO2 emissions versus vehicle weight [24]. It can be seen that reducing vehicle weight by 1 kg can reduce 0.13 g-CO 2 emission.

In this way, we will contribute to the environment by reducing signal lines with the increase in future wire harness. Therefore, sensors and equipment are expected to be connected via wireless links.

Here, we expect to be able to replace at least 10 to 30% of signal lines with wireless links.

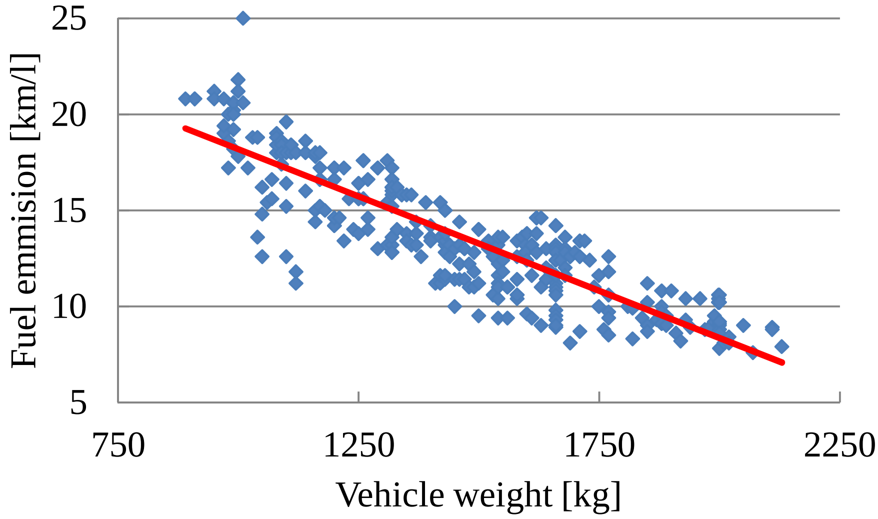


Fig. 3 Fuel economy in vehicle weight.

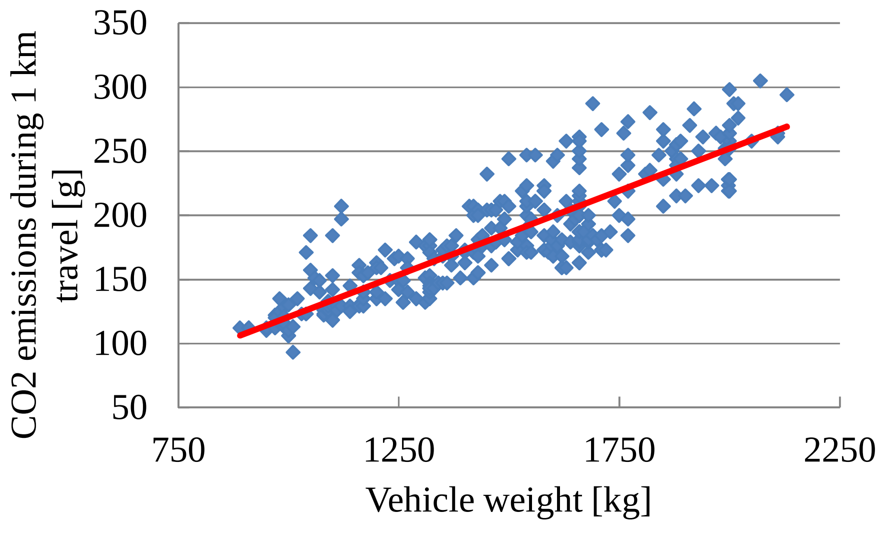


Fig. 4 CO2 emission in vehicle weight.

While EVs are expected to greatly reduce CO2 emission, they use even more electric wiring. Then, it is said that the CO2 emissions incurred for manufacturing EVs will increase [25].

Minimizing the wiring harness and thus reducing the vehicle weight can ease the problems of fuel consumption and CO2 emission. Therefore, sensors and equipment are expected to be connected via wireless links.

Note that [26] insists that safety is the fundamental objective of any vehicle system and guarantees are essential that the entire system response time, from sensor detecting some event to actuator response, should be within a deadline. While transmission delay is not an urgent concern in wired networks due to their high speed, it is indeed a concern in wireless networks.

This thesis proposes to establish and use reliable wireless connections for vehicle. In order to achieve reliable wireless communication, various techniques from the lower layer to the upper layer of the OSI reference model shown in Table 2 are considered.

Table 2 The Open Systems Interconnection model (OSI model).

Layer		Protocol data unit	Function
Host layers	7. Application	Data	High-level APIs, remote file access
	6. Presentation		Translation of data between a networking service and an application; data compression and encryption/decryption
	5. Session		Managing communication sessions
	4. Transport	Segment, Datagram	Segments between points on a network, acknowledgement and multiplexing
Media layers	3. Network	Packet	Structuring and managing a multi-node network, including addressing, routing and traffic control
	2. Data Link	Frame	Reliable transmission of data frames between two nodes connected by a physical layer LLC: Logical Link Control MAC: Media Access Control
	1. Physical	Symbol	Transmission and reception of raw bit streams over a physical medium

Conventionally, devices in a vehicle communicate in a point-to-point manner using wired connections. Recent increases in the use of electric wiring have triggered interest in the use of LANs. CAN which is the most well-known vehicle network, is a very simple network design. CAN is a broadcast bus and many processors are connected to the bus via an interface. The maximum bit rate as standardized by ISO 11898 and IOS 11519-2 is 1 Mbps.

However, it is necessary to compensate for the transmission delay and loss since it is a best-effort type communication method. Therefore, it is necessary to prioritize each ECU and to reduce the communication bus load below a certain percentage. This makes it difficult to add new devices. Fig. 5 shows the basic CAN architecture.

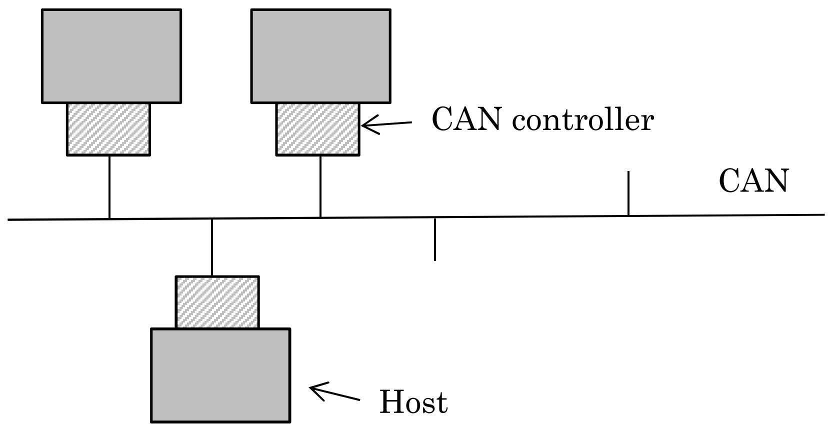


Fig. 5 CAN architecture.

CAN has a typical BUS structure and connections involve the use of twisted wire pairs to realize high noise immunity. The CAN controller handles the CAN protocol, and the Host implements applications that use the CAN network. Note, that the CAN controller and the Host may run on different ICs.

The CAN protocol has a remote frame, a data frame, an overload frame and an error frame, and operates in CSMA/CA manner. Transmission works as follows.

First, each node synchronizes when the bus level changes from recessive to dominant. Next, communication is realized by a remote frames, which requests the data and data frames, which transmits the data. In the current CAN, the node that holds the transmission data transmits the data with the priority set.

Here, overload frames and error frames are transmitted automatically according to the communication state.

On the other hand, automotive network is considered to be a domain hierarchical architecture [27] [28]. It has four domains for each network as shown in Fig. 6. These domains are "Control domain" for operations such as running or turning or stopping, "Safety domain" for ADAS (Advanced Driving Assistance Systems), "Body domain" for seats and power windows, and "Information domain" for car navigation system or display for rear seat information system.

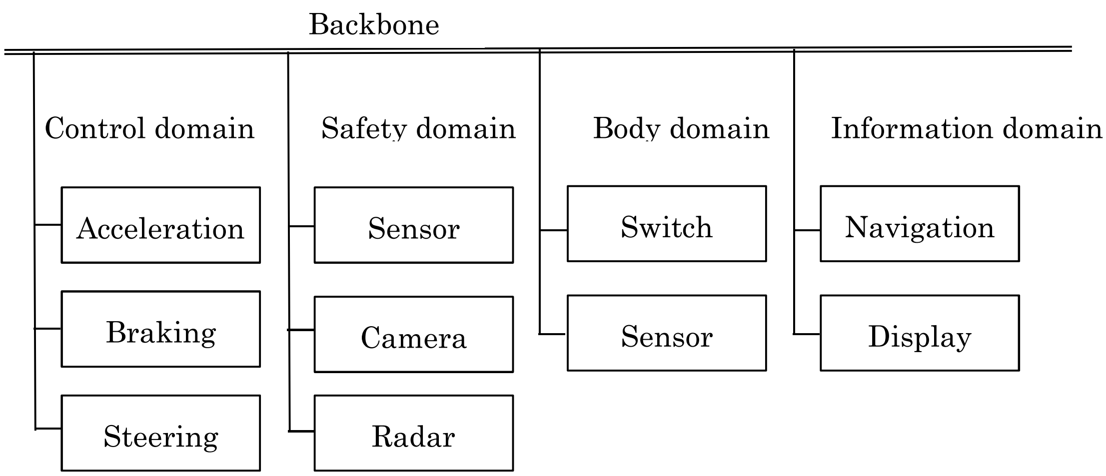


Fig. 6 Overview of automotive network.

For in vehicle networks, high speed Ethernet will be used as the backbone to connect between ECUs. Each domain network mainly uses conventional methods. “Body domain” is a network that can be improved first.

As shown in Fig. 7, this automotive Ethernet network will be structured as a logical network that links ECUs for each domain [28]. Large processing systems configured on this logical network integrate and control each ECUs and sensors.

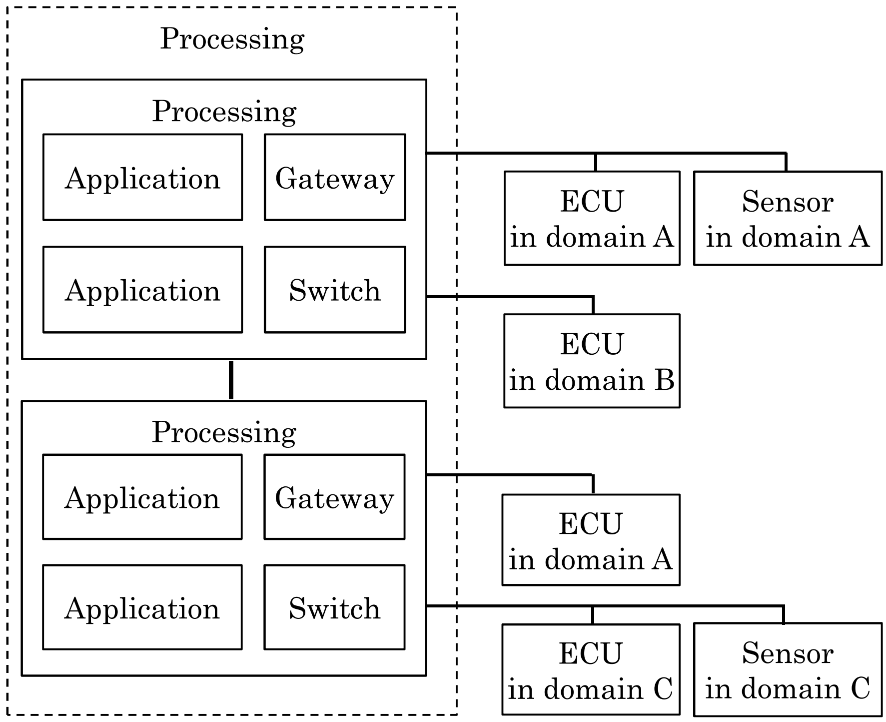


Fig. 7 Logical network architecture used in future vehicles.

Here, in this Logical network, the connections provided by wired or wireless links are not questioned. There is a possibility that a network may use both wired and wireless links.

However, we focus on using wireless communication since the main target of this thesis is reducing wire harness. Thus, it can be regarded as communication to the part of connection with wiring since data is collected to sink. However, this architecture is another consideration.

Fig. 8 shows the configuration of a typical wireless module. The radio consists of three parts: an antenna, a radio frequency (RF) part, and a baseband part. The antenna receives the electromagnetic wave and converts it into an electric signal, or converts an electric signal into an electromagnetic wave. In this thesis, we use a basic dipole antenna. The RF part processes signals in the frequency band of the air transferred electromagnetic waves. It modulates the baseband signal into the RF bands for transmission and demodulates signals in the RF bands into a baseband signal for reception. The baseband part performs the signal processing functions of error detection/correction, transmission timing control, acknowledgment control, etc. This control is called medium access control (MAC).

Processing of these physical layers and the MAC layer is generally performed by a processor and an application specific integrated circuit (ASIC) and supplied as a module. We use commercial wireless modules and achieve high reliability by controlling the LLC of Data Link layer and Network layer without changing the modulation or using codecs.

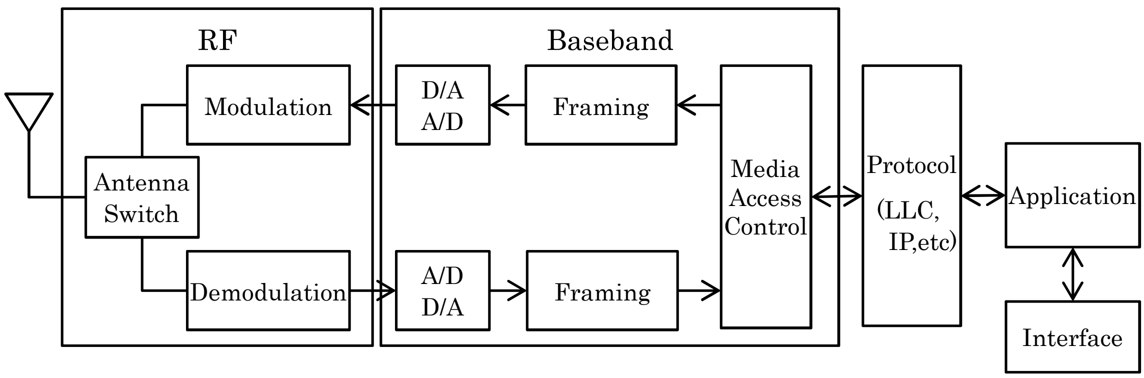


Fig. 8 Configuration of a typical wireless module.

Here, we consider to use reliable wireless communications with low delay of 20 ms based on Controller Area Network (CAN), in different way.

[29] proposes a point-to-point wireless communication architecture that simplifies in-vehicle wiring by bridging the remote CAN bus. This paper insists that reliability is a significant factor for many in-vehicle applications when wired links are replaced by wireless links. Furthermore, in [30], in-vehicle wireless networks based

on IEEE 802.15.4 are evaluated with Class B in Society of Automotive Engineers (SAE) classification [31]. This requires a success ratio of 99.999% and delay constraint of 20 ms. We also use the same criteria.

In recent years, with the increasing adoption of EVs, the importance of the battery management system (BMS) must be considered.

Note here that EV batteries are very dangerous due to their high capacity and voltages. Lithium-ion (Li-ion) batteries used for power supply are popular due to their high energy density, high voltage, tiny memory effect, and low self-discharge. However, they are highly sensitive to deep discharge or overcharge. Moreover, overcharge may cause not only self-damage but also explosion and ignition in the worst case. Therefore, they are located away from other systems. And, to reduce the battery damage, a battery charging method that monitors the charge voltage has been proposed [32]. The performance of this method is entirely dependent on battery cell monitoring.

The concept car of BMW i3 with wireless BMS was exhibited at Electoronica 2016 [33]. This system uses SmartMesh wireless mesh networking products from Linear Technology. SmartMesh is a wireless sensor network technology under the Dust Networks brand. Dust Networks is characterized by low power, time diversity, frequency diversity, and physical diversity to assure reliability. They are established by time synchronization function and time management function of the Time Slotted Channel Hopping (TSCH) method adopted in 802.15.4e [34]. In TSCH a time slot is mapped to a channel in a pre-assigned hopping sequence. A network manager called “mote” collects network status. The mote allocates frequency and route to all nodes based on the collected information and synchronizes the packets. No packets collide on the network since every packet is scheduled and synchronized. Furthermore, the mote creates redundant routes. When one route fails, rerouting is triggered immediately. Consequently, it achieves 99.999% reliable connectivity by employing path and frequency diversity. In order to maintain this reliability, the mote reallocates frequency and route according to the radio wave environments between the nodes at regular intervals.

However, little attention has been given to the delay time in information gathering.

Unfortunately, BMS control units should be collocated with other systems. It is difficult to wire the two areas, which makes wireless communication the attractive solution.

Furthermore, there are many sensors in a vehicle to collect data from or about the engine, brakes, tires, rain detector, and seat occupancy. We should provide an integrated solution to the communication of these sensors in the vehicle.

The environment within a vehicle is quite constrained and the body is metal, so the radio wave propagation environment is changed by the reflection, shielding, etc. created by the movement of passengers. The drastic changes imposed on the radio wave environment are an issue when wireless links are used in a vehicle.

We have measured and clarified the radio wave propagation characteristics in a vehicle by conventional tests [35]. Based on our analysis of the results, we proposed Reliable Wireless Communication based on Substitute Forwarding (RWCSF).

Here, considering BMS, two or more sensors are very likely to send simultaneously since each vehicle has so many sensors. In this situation, RWCSF fails to complete some communications within 20 ms [35]. This is the main issue considered in this thesis. Our solution is substitute forwarding with data aggregation (SFwDA) to enhance RWCSF.

In addition, we should consider the variety of radio propagation environments experienced in actual use. We should evaluate communication performance of vehicle with more complicated shapes, e.g. a sedan type. Furthermore, it is necessary to consider the noise environment within the vehicle since vehicle equipment, motors, etc. are strong artificial noise sources. This is the other issue considered in this thesis.

This thesis is organized as follows. Chapter 2 describes the changing problem of the radio wave environment within the tight passenger spaces and related work. Chapter 3 introduces the target system, proposed method, and enhancements. We assume a target model, consider the influence of noise and radio waves from outside the vehicle, and clarify the effectiveness of the proposed method in Chapter 4. Finally, Chapter 5 makes some conclusions.

Chapter 2

Radio Wave Propagation in Vehicle and Problematic Issues

2.1. Introduction

2.4GHz is focused on automotive environment in "Wireless Automotive Coexistence", which is the study group of the IEEE 802.19™, Wireless Coexistence Working Group. This frequency also used in this thesis.

Theoretical radio wave propagation loss [36] is

$$\mathrm{L} = 20\log\left(\frac{4\pi r}{\lambda}\right), \tag{1}$$

where r (m) is distance from a transmission node and λ(m) is wavelength.

According to Equation (1), the theoretical 2.4 GHz radio wave propagation loss without considering the influence of the vehicle is a distribution depending on the distance as shown in Fig. 9 when radio waves are transmitted from the node at the position of the door switch in the driver's seat.

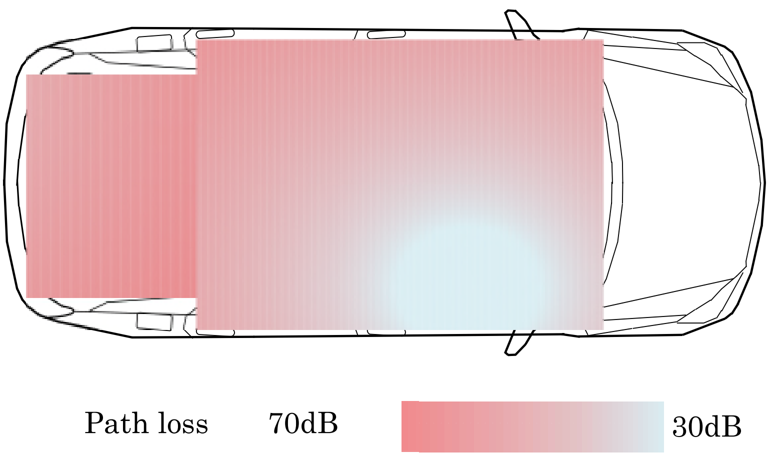


Fig. 9 Theoretical path loss in vehicle.

But, the inside of vehicle is a small space covered with metal. Therefore, multi-path is a serious issue. Moreover, radio wave in the cabin is interrupted by seats, passengers and/or other equipments. Therefore, in the cabin does not have uniform propagation characteristics as shown in Fig. 9. [37] measures the propagation of seat feet spaces and luggage space, and does not show the state of the whole space in vehicle. [38] shows the spatial and frequency dependent characteristics of the electrolytic distribution in a scale model of the vehicle. [39] simulated in a scale model and observed a uniform standing wave in the vehicle as shown in Fig. 10. However, they did not consider the complicated shapes such as inside the vehicle, and do not consider internal structures such as handles and seats.

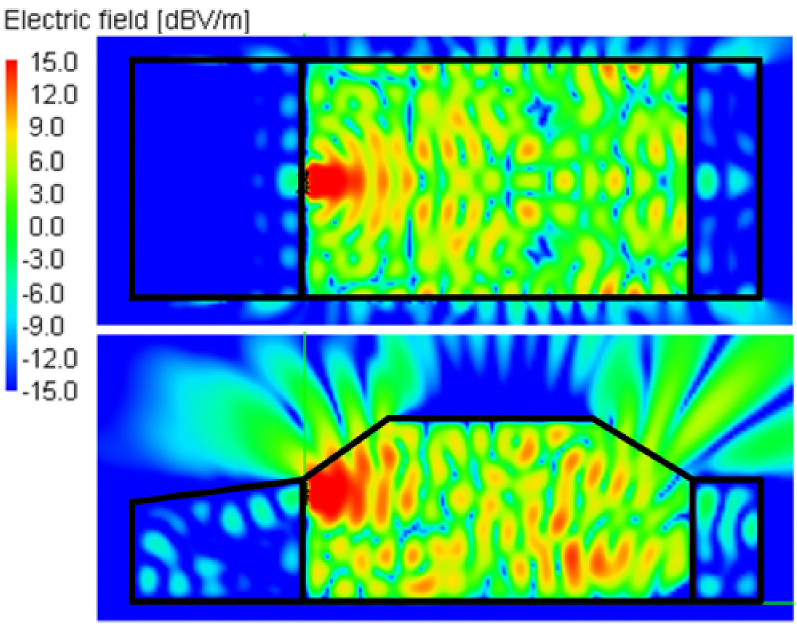


Fig. 10 Electric field distributions in the vehicle model.
Data from [39] (by courtesy of S. Horiuchi et.al.).

Our first step was to measure the status of the radio wave propagation in the cabin. Next we investigated wireless communication technology which enhances reliability in a narrow space of complicated shapes such as inside the vehicle.

2.2. Measured a radio wave propagation characteristic

2.2.1. The influence of radio wave environment

Fig. 11 shows the carrier wave generator/receiver was set 40cm above the floor in the cabin. The block diagram of this module is as shown in Fig. 12, which is roughly the same as the structure of Fig. 8. The wireless module is ADF72422 of Analog Devices, Inc., which has Low Noise Amplifier (LNA), Digital Analog Converter (DAC) / Analog-to-Digital Converter (ADC), FSK modulator / demodulator, Radio Control and so on. ADuC7020, which is an ARM microcontroller, controls this wireless module [40]. The ADuC7020 has a 32-bit RISC microprocessor core, 62 kbytes of flash memory, 8 kbytes of SRAM, parallel interface and serial communication interface. It is possible to implement applications other than control of the wireless module.

Fig. 11 Experimental setup.

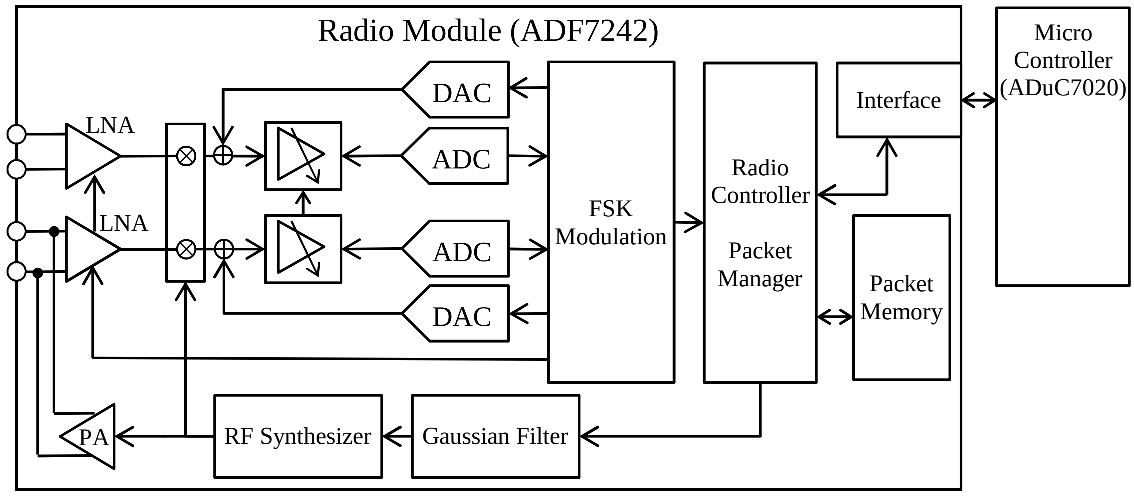


Fig. 12 Functional block diagram.

We measured the radio wave propagation using this module in vehicle. The vehicle is wagon type which is one of the most popular hybrid wagon types in Japan [41]. All windows were closed. Its antenna was omnidirectional to allow reception from all directions. The operating frequency is 2.4GHz. The measurement grid had spacing of 32mm along the vehicle and 5mm across its width. It is impossible to measure the whole inside the vehicle since the inside of the vehicle is a narrow space and there are structures such as steering wheel and seat. Therefore, we measured the radio wave propagation characteristics for three parts of the cabin space, there are driver's seat, passenger's seat, and back seat. Fig. 13 shows the result. In the vehicle, it was confirmed that there was a position where the propagation loss suddenly increased, only by a slight movement of the place

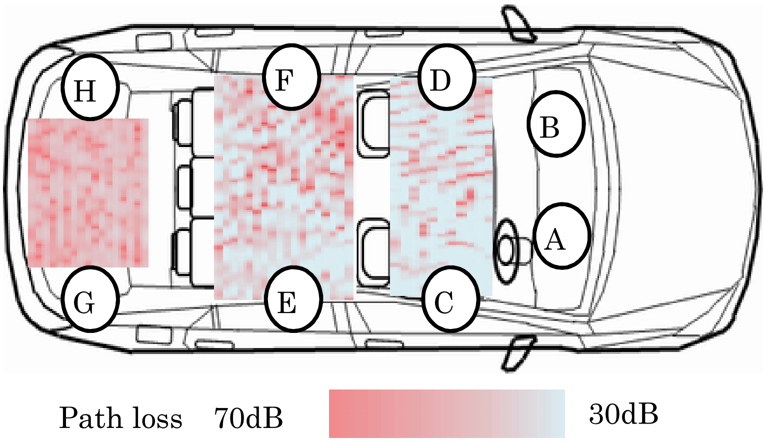


Fig. 13 Measured path loss in the vehicle.

Moreover, we measured a loss of radio wave propagation characteristics when four passengers, which is a driver, a passenger in front seat and two passengers on the back seat performed general movement as follows. The driver steered the vehicle. The passenger operated the navigation and audio system. Two people on the back seat sat and talked.

Fig. 14 and Fig. 15 plot the change of radio wave propagation characteristics as a function of elapsed time. The terminal number is shown in Fig. 13. Fig. 14 shows the case that there are passengers between the source node and the destination node. It clarifies a significant propagation loss. In addition, Fig. 15 shows another case that there are no people between nodes. In this case the propagation loss is relatively stable.

That is, it can be seen that fluctuations in the radio wave environment are affected by passengers.

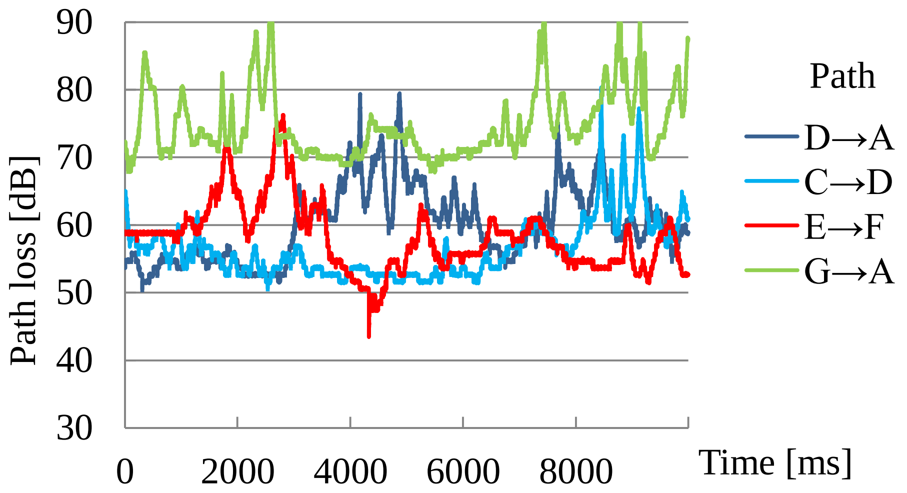


Fig. 14 Path loss fluctuation of a path traversing passengers in wagon type vehicle.

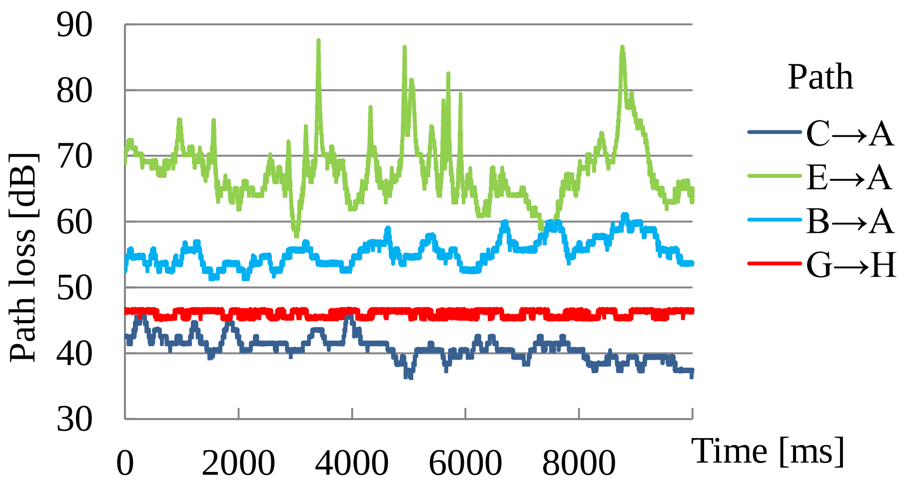


Fig. 15 Path loss fluctuation of line-of-sight path in wagon type vehicle.

Note here that the minimum sensitivity of this equipment, a general module ADF7242, has −95 dBm [40]. For example, when the transmission power is −35 dBm, the reception power may become less than –100 dBm, since the path loss may be more than 70dB as shown in Fig. 14 and Fig. 15. In such a case, the S/N ratio is not sufficiently, a transmitted packet is not demodulated successfully and discarded. It is treated as a packet loss.

Sensor nodes in a vehicle have to communicate with high success ratio and low delay time under such a severe environment.

Next, we confirmed the influence of the shielding of conductors and dielectrics in the passenger compartment on the radio wave propagation characteristics. A transmitter and receiver antennas were installed on the left and right side of the front seat, and a metal shield of 400 mm × 400 mm was placed between them. The antennas were separated by 1000 mm. The propagation loss is expected to be constant since the fixed metal shield blocks the direct wave. However, it has been confirmed that the radio wave propagation environment varies due to reflection, shielding, etc. as shown in Fig. 16 since the passenger compartment creates a multi-path environment. From this, it can be seen that the radio wave environment greatly changes with not only in node position but also the position of shielding objects in the passenger compartment. This means that designing vehicle communications systems requires consideration of the body structure as well as the radio wave environment fluctuation triggered by various loads.

In this way, the simple model does not provide valid results for radio wave propagation of the actual vehicles. Therefore, for a more practical consideration, the evaluations in this thesis use measurements made in an actual radio wave environment.

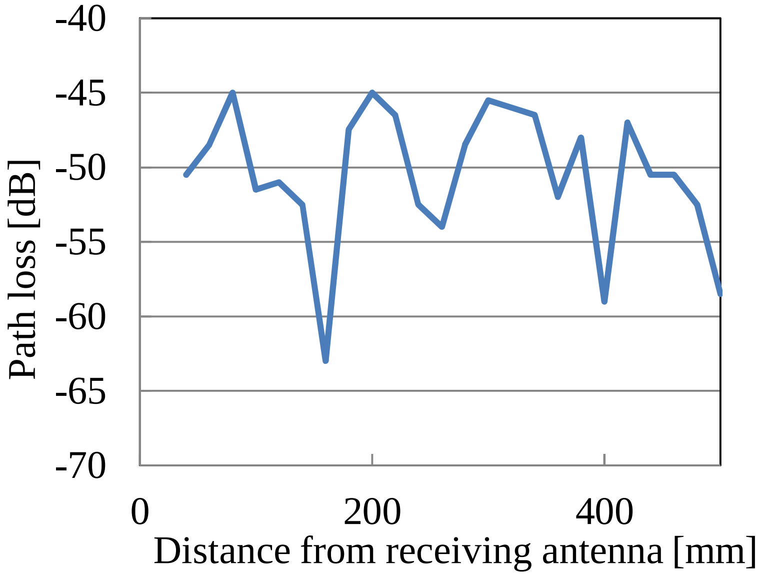


Fig. 16 Radio wave attenuation with an obstacle.

2.2.2. Radio Wave Propagation in other kinds of vehicle

In section 2.1.2, we evaluated radio wave propagation in simple cabin of a wagon type vehicle. In this section, we measured radio wave propagation in a sedan, a vehicle with more complicated shapes. Fig. 17 plots the change in radio wave propagation characteristics as a function of elapsed time. The terminal number is the same as in Fig. 13.

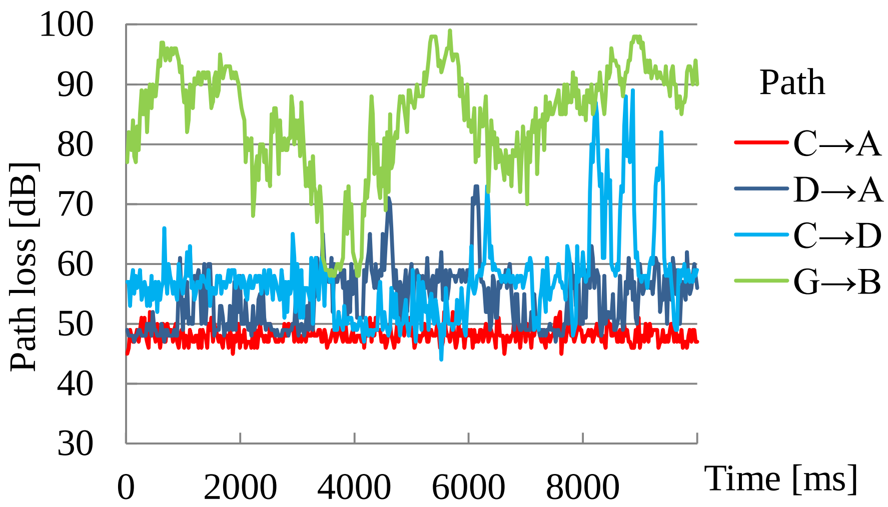


Fig. 17 Path loss fluctuation in sedan type vehicle.

We evaluate the changes of radio wave propagation due to differences type of vehicle. Fig. 17 shows the results. Here, the maximum path loss is node A to node H for both types. This path has the longest distance in each vehicle.

The propagation loss depends on the architecture and materials of the structure given the broadband link and constrained propagation space [42]. However, in a vehicle, the rear seat greatly influences the path loss characteristics since the cabin space is tightly separated by the back seat in the sedan type vehicle. It was considered that the change of the radio wave propagation in Fig. 17 was the maximum since sedan type vehicles are usually divided by seats. Also, the maximum value of path loss of this vehicle was different from the maximum value of path loss in Fig. 14, but the radio wave propagation tendencies were the same. Fig. 14 and Fig. 17 also show the path loss with four passengers. Note here that, the radio wave propagation change in vehicle is greatly affected by the number of passengers since the shielding of radio waves and the multipath state change due to the movement of passengers.

Next, we changed the number of passengers in the vehicle and measured the fluctuation in the path loss determined by averaging the losses of the paths between all pair's nodes, see Fig. 13. Six loads were examined. Here, two passengers: a driver and one rear seat passenger. Three passengers: a driver, a navigator, and a rear seat passenger. Four passengers: split evenly between front and back seats. Five passengers: a driver, navigator, and three in the rear seats. Table 3 shows the maximum, minimum, average and variance of the path loss between all nodes for the different numbers of passengers. Fig. 18 plots the results. There are no major fluctuations in the maximum and minimum values with changing numbers of passengers; however, the average and variance values increased with the number of passengers, so the path loss fluctuation also increased.

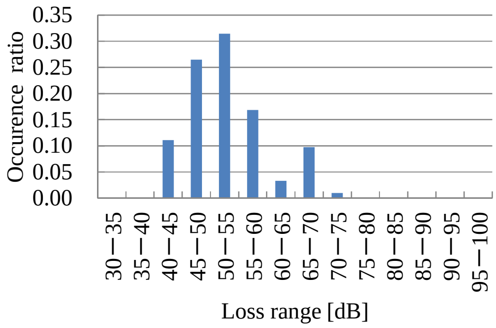
Fig. 19 shows the path loss fluctuation for the path from node A to node H with one, two, and four passengers.

Even in the time fluctuation, it was the same as the trend by the number of passengers. Equipments in a vehicle have to communicate with high success ratio and low delay time under such a severe environment.

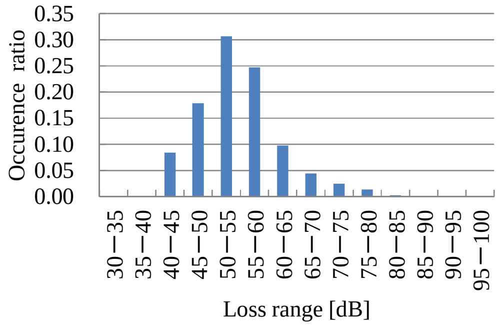
Table 3 Summary of path loss fluctuation for each number of passengers.

[dB]

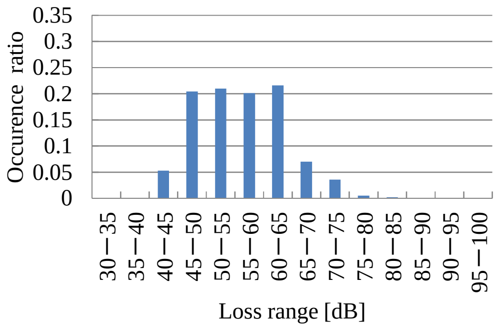
Passengers	Non	1	2	3	4	5
Maximum	82	98	96	100	98	99
Minimum	40	37	39	39	40	40
Average	53	54	55	57	57	58
Variance	50.9	55.0	59.4	72.6	75.4	80.4



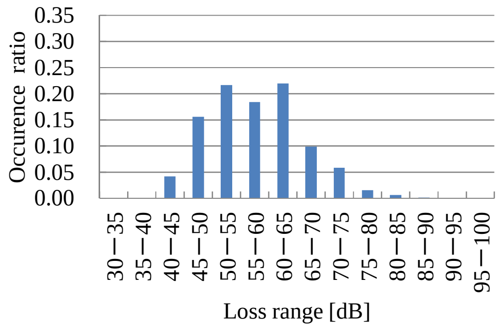
(a) No passenger



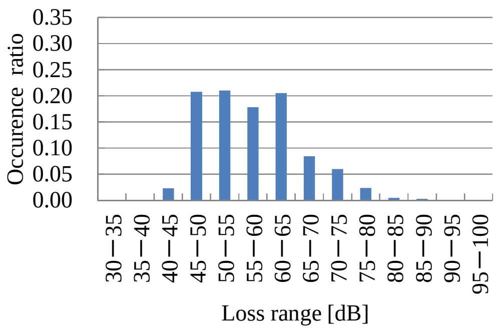
(b) One passenger



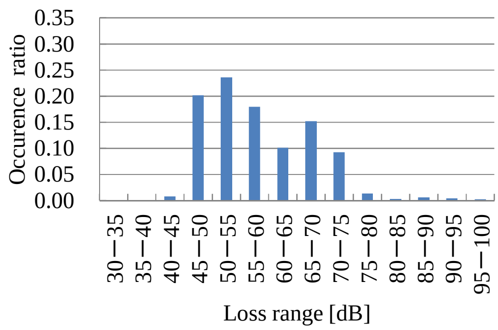
(c) Two passengers



(d) Three passengers



(e) Four passengers



(f) Five passengers

Fig. 18 Path loss occurrence ratio by number of passengers in sedan type vehicle.

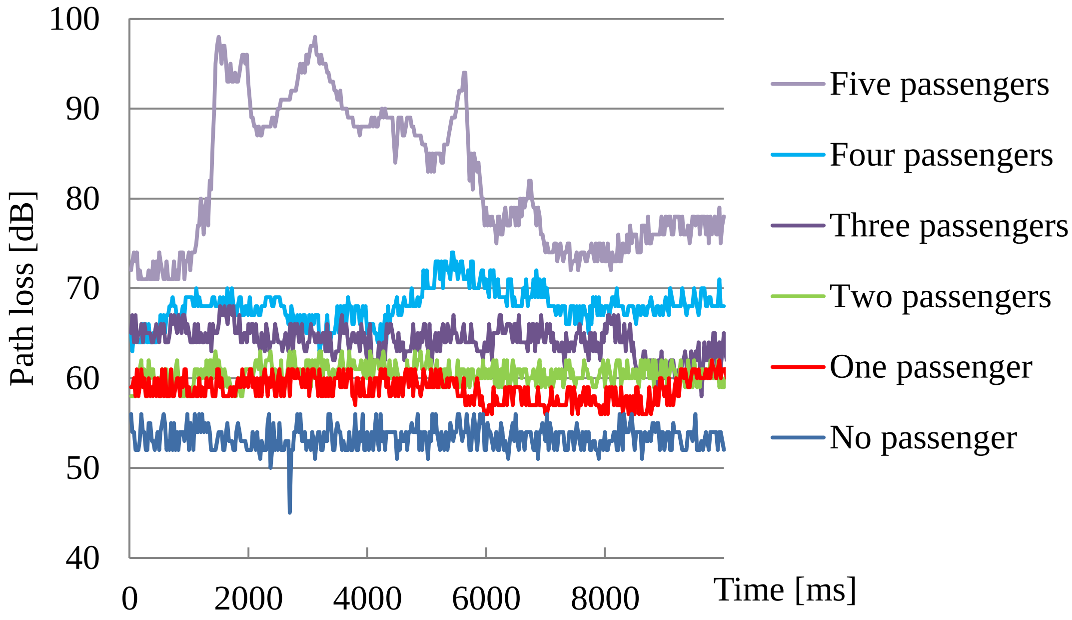


Fig. 19 Path loss fluctuation for each number of passengers.

2.3. Success Ratio of Direct Communication

We evaluated the basic performance of wireless communication in the vehicle.

We confirmed the success ratio of direct communication between nodes without using RWCSF. If a frame is lost, it is retransmitted by the source node; the upper limit is set to 10 attempts. Table 4 shows the result. Almost all communication fails due to the significant radio wave propagation loss. In addition, communication fails when the radio wave propagation fluctuation is large. Therefore, stable communication by regular direct communication is difficult to achieve.

It is necessary to achieve high success ratio with low delay and low cost in vehicle communication even in the environment as shown in Fig. 13 to Fig. 15 and Fig. 17.

Table 4 Success ratio with direct communications.

Node / Node	B	C	D	E	F	G	H
A	0.73943	1.00000	0.33012	0.08811	0.00000	0.27639	0.00000
B		1.00000	0.84723	0.98020	0.14849	1.00000	0.00000
C			0.83651	1.00000	0.98794	0.84423	0.00000
D				0.84205	1.00000	0.40242	0.00000
E					0.41331	1.00000	0.02478
F						0.94714	0.00000
G							1.00000

2.4. Related Work

The environment in vehicle can be considered as a kind of wireless multi-hop network and should be considered reliable communications. But all nodes can communicate directly (via 1 hop) each other if radio wave environment is not so drastic.

Therefore, some existing methods may be applied. Note here that, however, the application assumed in this thesis requires reliable communications with very low delay in a very unstable radio propagation environment.

Optimized Link State Routing (OLSR) is one of the most conventional proactive-routing methods for wireless multi-hop networks [43]. OLSR has control messages of HELLO, Topology Control (TC), Multi Interface Declaration (MID), and Host and Network Association (HNA), and performs effective flooding by Multi Point Relay (MPR). This is effective in short distance transmission with low delay. In OLSR, any routes are established before communication. That is why it can send a packet quickly. IoT equipment and other system with covered metal is available since the influence of radio wave environment is not so drastic. In other words, it is not useful in a vehicle since the route selection is often performed due to fluctuation as shown in Fig. 14, Fig. 15 and Fig. 17.

Ad hoc On-demand Distance Vector routing (AODV) is one of the most traditional reactive-routing methods [44]-[46]. AODV selects the most suitable route by Route

Request (RREQ) and Route Reply (RREP) before a transmission starts. A typical example is shown in Fig. 20. The source node transmits the RREQ packet by broadcast, and the node that has received this packet updates the routing table and retransmits the RREQ. When destination node receives it, the RREP packet is sent by unicast according to the routing table. And the packet is transmitted based on this route. This is robust for drastic changes of the environment, such as node join, leave and move. But communication delay tends to be large due to route setup overhead. To overcome this problem, some extended versions are proposed.

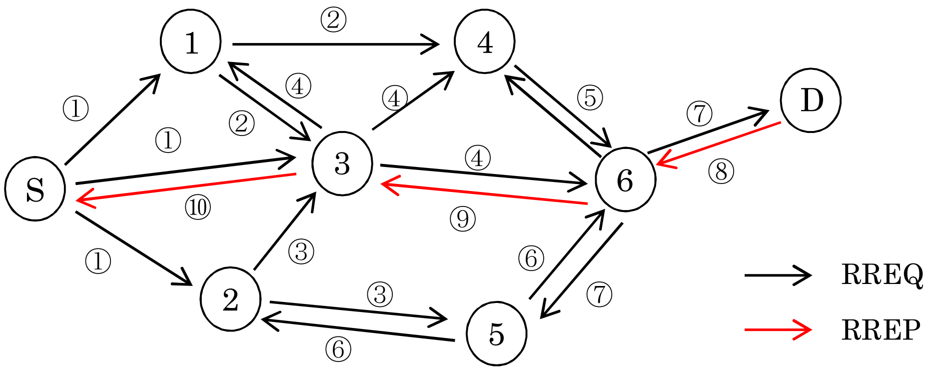


Fig. 20 Route selection message of AODV.

Dynamic Multi-Hop Shortcut (DMHS) adjusts the average number of hops of a route created by AODV and improve end-to-end packet delivery rate remarkably to make up for the routing setup overhead [47]. If a node of two hops ahead receives the packet, it transmits the packet before reception of the packet from the relay node. This is effective when a previous route is available, since the influence of radio wave environment is insignificant. However, communication delay tends to be still large in drastic changes of the environment.

Energy Delay Index for Trade-off (EDIT) is a routing method to use a distance and a Hop-count for an energy-efficient clustering according to Equation (2) [48]. It considers delay-constrained applications, but it does not discuss the success ratio.

$$\mathrm{EDIT} = \left(\frac{\mathrm{Total\_Neighbors}}{\mathrm{Total\_Nodes}}\right)^{\alpha} + \left(\frac{1}{\mathrm{Average\_Distance\_from\_Sink}}\right)^{\beta} \quad (2)$$

Network coding (NC) improves throughput by encoding several packets from different source nodes into one and relaying it to other nodes [49]. In a network as shown in Fig. 21, the communication from the node 3 to the node 4 is a bottleneck if the source node sends a packet to the destination. Therefore, node 3 encodes two packets with XOR and delivers two packets per unit of time. However, it causes longer delay due to encoding/decoding.

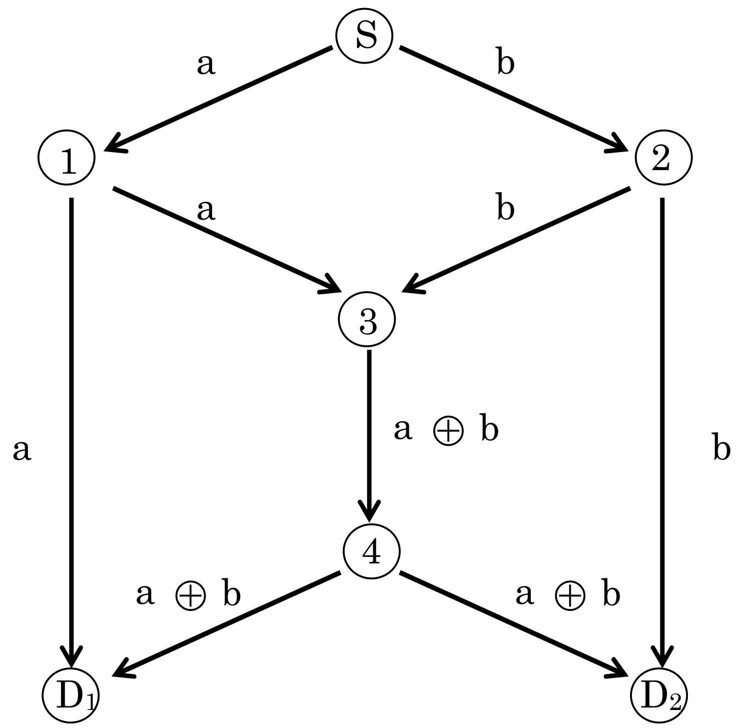


Fig. 21 Example of network coding.

Time Slotted Channel Hopping (TSCH) realizes high reliability by time synchronization and time management [50]. In TSCH, a time slot is mapped to a channel in a pre-assigned hopping sequence as shown in Fig. 22. A network manager collects network status data and allocates frequency and routes to all nodes based on the collected information. Thus, the packets are synchronized for all nodes. It achieves 99.999% reliable connectivity. However, it gives little attention to the delay in information gathering since slots are skipped whenever overlapped by a slot in a higher priority schedule.

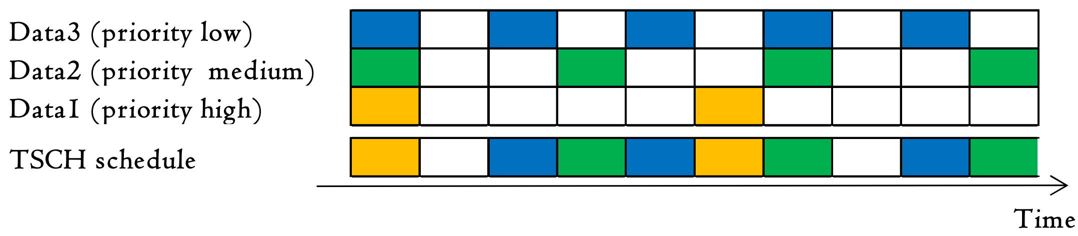


Fig. 22 TSCH schedule.

Derivative-Based Prediction (DBP) can reduce communication overheads by predicting the main data trends [51]. In DBP, each node constructs a mathematical model to approximate future data. As long as data falls within the value predicted by the model, data is transferred intermittently to reduce traffic. This technique abates up to 99% of application messages. In addition, energy consumption is also suppressed by enter a sleep mode. However, it only suits non-critical environmental data such as light and temperature. In other words, it is not useful for switches and sensors that do not change linearly.

[52] reduces the weight of the cable and attempts to use UWB-IR to make maintenance easier. Based on the theoretically derived radio wave propagation environment for known vehicles, it proposed an ideal arrangement of radio communication devices. The antennas were located at the line-of-sight (LOS) path without passengers, which is the lower side or the upper side of the passenger compartment. Unfortunately, this arrangement does not match the actual position of devices that actually communicates, such as switches and motors in the vehicle.

Gossip protocol is another approach. MHVB uses an efficient gossiping based on the distance to the destination node and the number of surrounding terminals [53]. They focused on improving packet delivery ratio. However, it does not consider the fluctuation of propagation loss in a short time. [54] also proposes a gossip protocol based on flooding, which decides whether to discard or forward a received packet based on an index such as a pre-specified hop count. It also ignores the fluctuation of radio wave environment in a short time.

Therefore, several methods based on the over-hearing approach have been proposed to realize reliable communication while satisfying the delay constraints expected. [55] uses broadcast communication with relay repetition. This method overhears a packet, and upon confirming that it was successfully delivered by another node deletes its copy of the packet. This reduces collision and improves the success ratio.

[56] confirms the optimum route to the destination node based on the link status between nodes, and sends the packet over that route. Nodes neighboring the destination node overhear the sent packet and hold the packet for a specific time. A neighboring node and destination node exchange control messages to trigger retransmission of the packet if necessary; this improves the success ratio of communication.

[57] also confirms the route to the destination node based on the link status between the nodes. Fig. 23 shows an example of communication from A to F. The neighboring node overhears the packet. It bypasses the route to relay the packet if a communication failure occurs in the communication route. These methods improved the success ratio, but are not so useful if the radio wave environment fluctuates rapidly since neighboring nodes hold the packet within specific period.

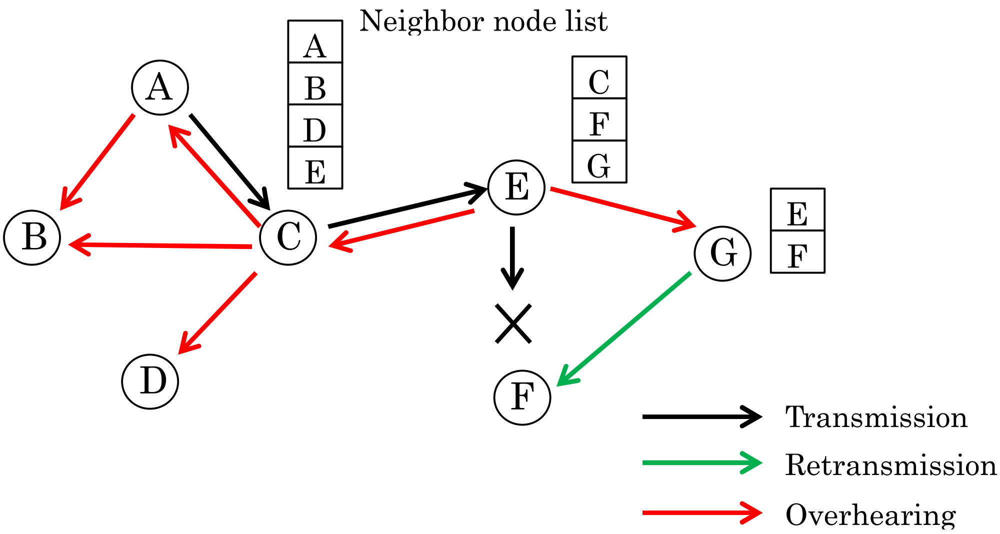


Fig. 23 Routing based on the link status between the nodes.

Opportunistic routing (OR) has been proposed as a method suitable for high mobility environments [58] [59]. OR can handle fluctuations in radio wave propagation as it does not depend on specific routes when relaying packets. OR regularly acquires the communication success ratio, reception power, etc., to select the suitable route at that time. In this way, it responds to changes in the topology and the radio wave environment. An example of packet forwarding using opportunistic routing is shown in Fig. 24. Unfortunately, it assumes there is no delay constraint. [60] uses the distance between nodes in suppressing the unnecessary transmission of neighboring nodes. However, the spatial distance between nodes does not correspond to the changes in the radio wave environment inside the vehicle.

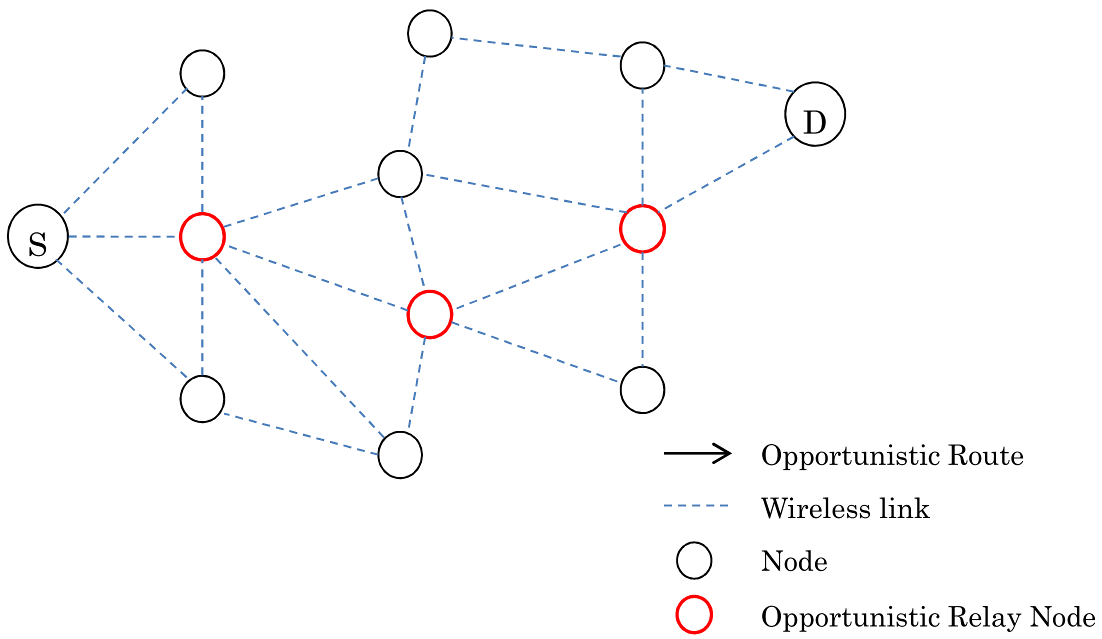


Fig. 24 Packet forwarding using Opportunistic Routing.

Table 5 summarizes the characteristics of network control method used in the wireless multi-hop network described above.

Table 5 Characteristic of Network control method.

Method	Overview	Effect	Unconsidered
OLSR [43]	Proactive-routing	Low delay	Influence of radio wave environment
AODV [44]-[46]	Reactive-routing	Drastic changes of the environment	Communication delay
DMHS [47]	Adjusts the average number of hops	Reduction of delay time	Influence of radio wave environment
EDIT [48]	Routing by distance and hop-count	Reduction of delay time	Delay time by routing
NC [49]	Combining information at relay node	Improves the throughput	Delay time by encoding/decoding
TSCH [50]	Allocates frequency and routes	Success ratio	Delay time in information gathering
DBP [51]	Reduce packets by predicting data trends	Reduce application message	Application not changing linearly
UWB-IR [52]	Utilize UWB-IR radio characteristics	Ideal arrangement of wireless devices	Actual position of devices
Gossip protocol [53] [54]	based on the distance, and the number of surrounding terminals	Improving packet delivery ratio	Influence of radio wave environment

Distributed retransmission method without reconstruction [55]-[57]	Routing based on link status	Success ratio	Influence of radio wave environment
OR [58]-[60]	Broadcast data packets according to routing	High mobility environments	Influence of radio wave environment

2.5. Summary

We measured the radio wave propagation characteristic in the vehicle and clarified that the distance between nodes is not related to the changes.

Also, even if there is a shielding object, even if it is out of line of sight, radio waves are received by multi-path. However, it was confirmed that the radio wave propagation loss changes due to the influence of the shielding object.

Furthermore, we confirmed existing research on wireless communication. These methods are thought to function effectively if there are a large number of neighboring nodes in a wide area with a target area of several tens of meters or more. However, it does not consider the fluctuation of propagation loss in a short time in a narrow space of about several m as in the vehicle.

In this thesis, on the assumption that several sensors detection are used in a vehicle, we propose a new method to provide reliable communications in a vehicle by sending overheard packet without selecting the most suitable route. In addition, the performance of the proposed method is evaluated by computer simulation and experimental implementation. The proposed method achieves that 99.999% of packets are received within 20 ms.

Chapter 3

Reliable Wireless Communication Method with Low Delay

3.1. Introduction

As shown in Chapter 2, there are several methods for achieving the success ratio. However, neither method takes into consideration the fluctuation of the radio wave propagation characteristic and very low delay.

One reason for the delay occurrence is processing such as routing setup before starting communication. Shortening this route creation is effective for low delay. However, if it does not check the status between nodes before starting communication, it will not be able to cope with fluctuations in the radio wave environment.

In order to keep the delay below a certain level, it is considered to use TDMA by centralized control, but it is difficult to set up a centralized control node that can communicate with all other nodes from the radio wave environment in the vehicle clarified in Chapter 2.

Therefore, in this thesis, we assumed applications and proposed a method to reduce the packet loss ratio using overheard. Furthermore, we propose data aggregation to reduce the packet transmission.

Section 3.2 describes AP that is expected to be used in a vehicle. Section 3.3 proposes a method to reduce the packet loss ratio within delay constraint by overhearing. Furthermore, we propose to enhance proposed method with data aggregation to shorten the transmission time in section 3.4, Section 3.5 draws some conclusions.

3.2. Assumed Application

Reliable wireless communication in the vehicle should be considered with reference to real applications. It seems that the importance of sensors in vehicles will increase in the future since many sensors are installed in the vehicle. In particular, it can be assumed that EV penetration will increase in the future. EV will need to sense many batteries and the number of sensors will increase. Therefore, this thesis focuses on a seat sensor system and the Battery Management System (BMS) of EV [35] which has more nodes than considered in the basic performance evaluation in section 2.3.

This thesis assumes that the BMS and crew sensor network system are working in EV. There are so many battery cells in EVs. The Leaf 14s, one of the most famous EVs, has 192 battery cells [61] [62]. To determine the upper-limit charge voltage must consider the internal resistance and charging current for the battery, and a protection circuit is installed to prevent the upper limit voltage from being exceeded. Standard Li-ion batteries have good performance within 4.2V. The internal resistance of the INR-18650C battery [63] is 0.02 Ω, and the maximum current to the battery is more than several amperes of regeneration which is an electric current from inverter. Thus a voltage of 3.7V shall be measured in 1 second that assumed as battery measurement time.

On the other hand, generally, a quick charger can charge 80% of the battery module in 30 minutes. This means that 192.2kwh was charged in 1800 seconds since the capacity of Leaf's battery pack is 24kwh [62]. That is, its charge rate for 1 second is 10wh. For the Leaf vehicle, this capacity will drive the vehicle 100m.

In the following, we assumed the measurement time of the battery to 1 second.

A standard EV contains several battery management ICs. In the case of BQ76PL455A-Q1, 16 battery cells can be monitored at the same time [64] [65]. In order to monitor 192 battery cells, 12 (=192/16) battery management ICs are required, so we assume 12 monitoring ICs will need to transmit battery cell data. As a result, a packet is sent to the sink at intervals of 83.3 (=1000/12) ms all over the

BMS. In addition, other sensor node will send data at random intervals.

There are many sensors detecting the battery voltage and the state of passengers in a vehicle as shown in Fig. 25. BS01 to BS12 in Fig. 25 are battery cell sensors. These 12 battery cell sensors are installed under a baggage space at a tail. The battery management controller (BMC) is located under the glove box. BMC collects all battery cell voltage information and controls a charge voltage.

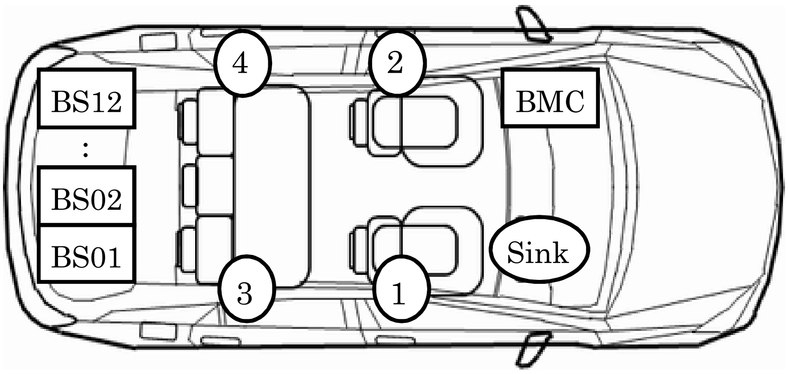


Fig. 25 Node arrangements of BMS and seat sensors.

In addition, 4 crew sensors are installed with each seat. Each seat sensor detects passenger occupancy and sends a packet to the sink at the constant interval of 400 ms but with different timing, since the reaction time of humans is about 400 ms [66]. Note that the activation timings of sensor nodes must be assumed to be unsynchronized since the start timing of the power supply of the sensors in a vehicle will differ [67]. The sink which collects all messages from crew sensor nodes is located under the meter. All nodes have the relay function. Each crew sensor node or sink may relay the packets of the battery cell sensor nodes as well as those of other crew sensor nodes. Battery cell sensor nodes or BMC also may relay the transmission of each crew sensor node. Of course, the crew sensor node relays the transmission of other crew sensor nodes, and the battery cell sensor node relays the other battery cell sensor nodes. Communications between battery cell sensors and crew sensors and BMC and sink must be reliable regardless of passenger state. The type of the assumed vehicle is PRIUS, which is one of the most famous vehicles in Japan [68]. Its cabin size is 1,470 mm × 2,690 mm.

Since the transmission between these sensors requires high reliability equivalent to conventional wire harness, target success ratio is 99.999%. In addition, required delay constraint is 20 ms.

In this thesis, we assumed 12 battery sensors, but it is thought that data from several sensing systems will be bundled in the future sensor communication. It is expected that communication nodes will be kept to an appropriate amount in the future.

Equipment brought into the vehicle may occupy the channel if it uses a streaming service. However, these services will utilize infrastructure communication using 4G or next 5G. In addition, short-term streaming by Wi-Fi hotspots in downtown while driving a vehicle were not considered as problem in the communication area and communication time. This is another issue of this thesis.

3.3. Reliable Wireless Communication based on Substitute Forwarding

All sensor nodes in a vehicle are able to communicate directory (via 1 hop) each other in a good condition. As described in Chapter 2, however, a packet loss may occur in a fluctuate condition. Generally, it should be recovered by retransmission. However, our assumed applications require very low delay time. Therefore, a traditional retransmission is not effective.

On the other hand, TDMA is effective in satisfying the delay constraints, it is difficult to realize in the radio wave environment inside the vehicle as shown in section 2.2 since it needs a centralized control node that communicates with all other nodes in the vehicle. In this scenario, a routing method is generally adopted. However, we consider the communication method without routing in order to apply a lot of time for communication since the delay constraint in vehicles is 20 ms.

It is better to use common equipments for early development. Consequently, we try to achieve the required reliable communications using standard devices with Wi-Fi or ZigBee.

We used the overhearing technique to create a reliable in-vehicle wireless communication protocol that offers low packet loss ratios [69]. When a source node sends a packet to a destination node, neighboring nodes overhear the packet. If the destination node receives it successfully and replies an acknowledgement, this communication is completed. Otherwise, if the destination node does not receive the packet successfully, one of the neighboring nodes sends the overheard packet to the destination node in the CSMA/CA manner. We call this "substitute forwarding (SF)".

If the destination node does not receive the packet by the substitute forwarding, another neighboring node also conducts substitute forwarding. If the destination node receives the packet by the substitute forwarding, the neighboring node sends a message indicating the success of substitute forwarding to the source node. We call this “confirmation message”. It is also delivered by substitute forwarding. If the destination node does not receive the packet by the substitute forwarding, another neighboring node misses the confirmation message and also makes substitute forwarding.

In this method, a source node makes retransmission in the same manner of 802.15 if a source node does not receive an acknowledgement packet from the destination node or the confirmation message from neighboring node. To the contrary, a neighboring node never makes retransmission even if it does not receive the acknowledgement from the destination node. In addition, even if it misses a confirmation message, it never retransmits. Once it has made substitute forwarding, it discards the overheard packet. However, this node makes substitute forwarding when it overhears the substitute forwarding of another node. In other words, it makes “substitute forwarding of substitute forwarding”. We name this method RWCSF (Reliable Wireless Communication based on Substitute Forwarding).

This thesis assumes a delay constraint, so each packet has a TTL (Time to Live) and is discarded when its TTL expires.

RWCSF is based on the CSMA manner. A packet from source node sets CWmin=2, and a packet by substitute forwarding sets CWmin=1. This means that the priority of packet by substitute forwarding is higher than that of packet by retransmission from source node for back-off time. A packet from source node increases CW size depending on the number of retransmissions. The maximum size is CWmax=32. CW is expressed in Appendix A.

Fig. 26 demonstrates how the proposed method works for communication between node A and node F.

(1) The source node (node A) sends a packet to the destination node (node F) directly.

(2) Neighboring nodes of node A (nodes B and C) overhear the sent packet at the same time.

(3) As the sent packet from node A is not received by node F, the neighboring node (node B) cannot overhear the acknowledgement from destination node. Therefore, node B recognizes the fail of the communication and sends the overheard packet to the destination node in place of the source node as substitute forwarding.

(4) Node B which has made the substitute forwarding does not receive the acknowledgement from the destination node. It means that the substitute forwarding has failed. But nodes C, D and E overhear the substitute forwarding from node B and cannot overhear the acknowledgement from destination node. Therefore, they can recognize the fail of the substitute forwarding. Here node C had already received the original packet from node A. In such a case, node C discards the overheard packet from node B. Note here that the order of sendings is randomly decided based on CSMA/CA.

(5) Node E has had the first opportunity to send by CSMA/CA and sends the packet as a substitute forwarding to the destination node. Node F receives it successfully and replies its acknowledgement.

(6) Node D cancels its substitute forwarding, since it can confirm the completion by overhearing both the substitute forwarding of node E and the acknowledgement from node F.

(7) Node E sends a confirmation message to the source node since the substitute forwarding of node E yielded successful reception by the destination node. This message notifies that node E made the substitute forwarding successfully.

(8) Nodes B and C overheard the confirmation message from node E. Then node C discards the packet sent by the substitute forwarding.

(9) Node B sends an overheard confirmation message from node E. Node A receives it and sends the acknowledgment to node B.

Here, we define a flow as an end-to-end communication event. Note that, in this method, while a packet may reach at its destination via two or more routes, it is treated as one flow.

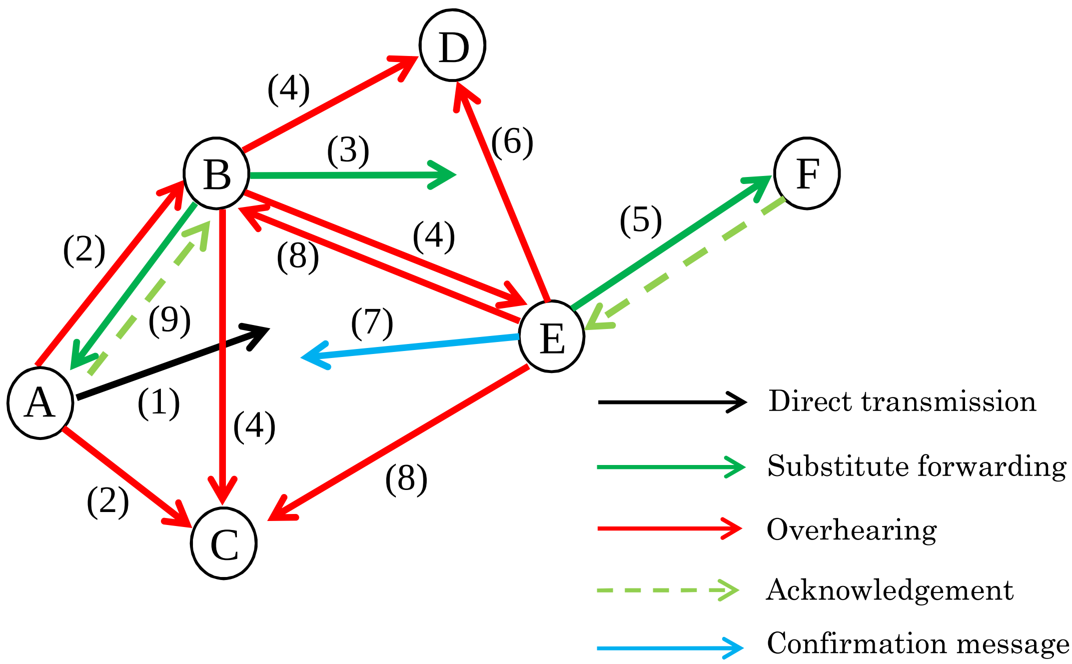


Fig. 26 Execution example of RWCSF.

3.4. Data Aggregation with Substitute Forwarding

In RWCSF, the more packets a node overhears, the longer it takes to forward them and the delay constraint is broken.

Therefore, we propose RWCSF with data aggregation (SFwDA). The process of SF aggregates data that has the same destination.

Data aggregation contributes to reliable communications but usually increases the delay. For example, a data aggregation scheme based on attributes decision tree (DABA) was proposed as a reliable and secure communication method [70]. DABA uses data aggregation scheme based on decision tree with encryption algorithm and pseudonym algorithm. However, the delay constraint was not considered since the aims were high data integrity and data privacy.

To the contrary, [71] showed that choosing an appropriate packetization interval can minimize the average end-to-end delay. However, this method is optimized for the conditions that the channel condition varies slowly over time with respect to symbol arrival rate. Therefore, it does not work well with the significant fluctuations expected in the vehicle applications assumed in this thesis.

In the assumed model, each sensor sends its data periodically, so that data aggregation possibly works effectively to be a practical solution. In addition, the battery status and seat sensor information are sent to the same control device. Consequently, we propose to aggregate the payload part of overheard packets to reduce the number of packet transmission events.

Specifically, an overheard packet is not forwarded until the number of queuing packets with the same destination reaches aggregate size (x) or aggregation time (xt) elapses from when the head packet was enqueued. Here, the aggregate size (x) is a tunable parameter and t is one frame time. In addition, for more effective aggregation, we propose that when a sensor node detects a failure of a previous transmission around it, it sends its own sensed data immediately.

Fig. 27 shows demonstrates the proposed method aggregating packets from node A1 and node A2 to node D1. Suppose that Node B sends a packet to D2. Node A2 sends its one after node A1. The proposed method works as follows. Parameter x is set to 3.

(1) Node A1 sends a packet to its destination node (node D1) directly. The sent packet is assumed to be dropped.

(2) Neighboring nodes of node A1 (nodes A2 and R) overhear the sent packet at the same time. Node A2 and R did not overhear the acknowledgement from the destination node.

(3) Node A2 takes sensor information and sends the packet immediately after node A1 transmission since the direct communication of node A1 failed.

(4) Neighboring nodes of node A2 (node R) overhear the sent packet at the same time. Node R aggregates packets from node A1 and A2 as they have the same destination.

(5) Node B sends a packet to destination node (node D2) directly.

(6) A neighboring node of node B (node R) overhears the sent packet. Node R does not aggregate this packet since the destination does not match those of any other packet in the queue.

(7) After time *xt* has elapsed, node R sends the aggregated packet in substitute forwarding to node D1. Node D1 receives it and replies with acknowledgement.

(8) Node R sends the confirmation message to source nodes.

(9) Node R sends the overheard packet from node B in substitute forwarding to node D2. Node D2 receives it and replies an acknowledgement.

(10) Node R sends a confirmation message to source node B. Node B receives it and sends an acknowledgment.

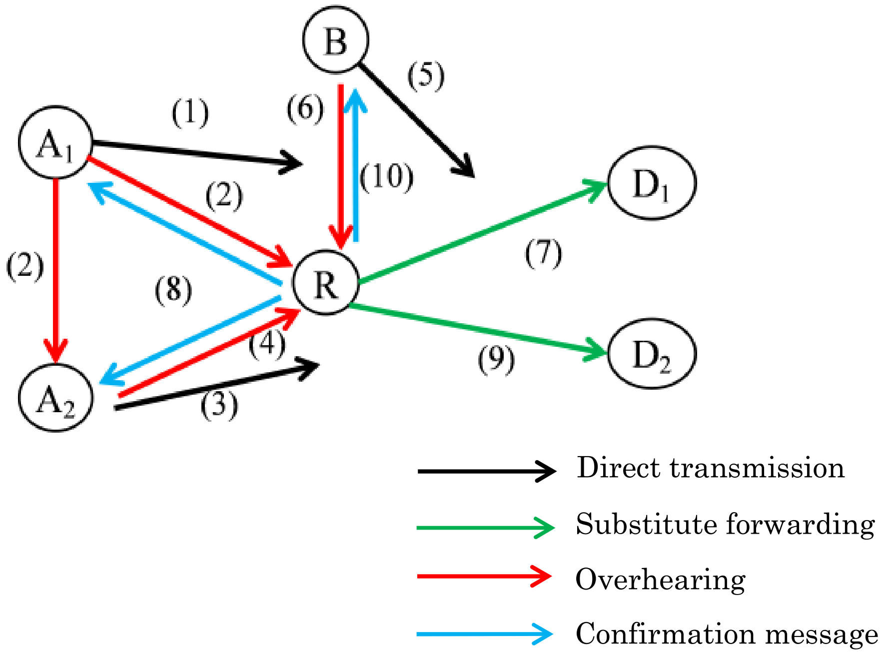


Fig. 27 Execution example of data aggregation.

3.5. Summary

In considering highly reliable wireless communication in the vehicle, we revealed the seat sensor system and BMS (Battery Management System) of EV [35]. The measurement time of the battery cell and the seat sensor were assumed.

We proposed RWCSF which is used the overhearing technique to create a reliable in-vehicle wireless communication protocol that offers low packet loss ratios [69]. When a source node sends a packet to a destination node, neighboring nodes overhear the packet. If the destination node does not receive the packet successfully, one of the neighboring nodes sends the overheard packet to the destination node.

Further, the more packets a node overhears, the longer it takes to forward them and the delay constraint is broken. Therefore, we proposed RWCSF with data aggregation (SFwDA). SFwDA aggregates data that has the same destination at neighboring node and retransmits the aggregated packet.

This thesis confirms the effect of the proposed method in the assumed application. Also, we evaluate its performance assuming a real environment and achieve that 99.999% of packets are received within 20 ms.

Chapter 4

Evaluation

4.1. Introduction

Chapter 2 clarified the radio wave propagation characteristic in the vehicle. Chapter 3 described the Battery Management System and the seat sensors that were assumed to be future vehicle applications, and proposed a reliable wireless communication method that uses fewer prior processes while satisfying the reliability and delay constraints.

Also, we proposed an enhancement this method to reduce the traffic expected with further advances in the multi-flow.

Section 4.2 shows the simulation conditions, and Section 4.3 confirms the effect of each method proposed in Chapter 3 under the radio wave environment shown in Chapter 2. The evaluation starts by confirming the basic performance of the proposed method. Next, we apply it to the assumed applications and evaluate its effectiveness. The results achieved with the enhancement of the proposed method are shown. We evaluate it in the noise environments expected, finally showed the effect of the proposed method.

4.2. Simulation Conditions

We evaluated the performance of the proposed method using own event-driven simulator with the experimental data shown in Chapter 2.

8 nodes were placed in 1470 mm × 2690 mm area. Its topology was shown in Fig. 13. There are four passengers in the driver's seat, passenger's seat, and back seat. The driver operated the steering. The passenger operated the navigation and audio system. Two people on the back seat sat down with talking.

And we simulated in the method based on IEEE802.15. RWCSF shown in section 3.3 has a simple structure as shown in Fig. 28 and the necessary elements as shown in Table 6. SRC2 is the original source node where a transmission data is generated at first. It is never changed by the relay nodes. DST2 means final destination and also is held constant. HD2 is header with data size and TTL. SRC1 is the source node address of the data link layer transmission. DST1 is the destination node address of the data link layer transmission. In original source node, SRC2 and DST2 are copied into SRC1 and DST1, respectively. On the other hand, for substitute forwarding by an intermediate node, SRC1 is overwritten by the address of the node. In addition, for confirmation message, DST1 is overwritten by SRC2. HD1 is a header including frame length, sequence number and data identifier of direct transmission, substitute forwarding or confirmation message. A transmission node sent 400bits data frame with 20 ms interval as a single flow. Its delay constraint was 20 ms. In other words, its TTL was also 20 ms. The destination node replied 176bits ACK frame immediately upon it received the data frame. The retransmission timer was set to 1 ms. DIFS (Distributed Inter Frame Space) and SIFS (Short Inter Frame Space) were 0.08 ms and 0.05 ms, respectively, from the setting value of the equipment.

SFwDA shown in section 3.4 also has the frame format as shown in Fig. 28 and the information of frame elements as shown in Table 6. Packets with the same destination have the same data type and same data size since they are data generated by the same type of sensor. In addition, in SFwDA, the TTL of each packet is considered to be the same value since the transmission timing of the sensor is changed within one frame time from the previous sensor communication event. Fig. 29 shows the format of the aggregated packet.

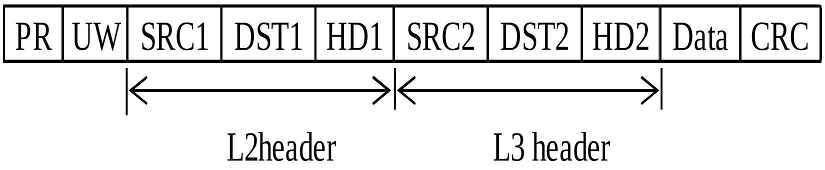


Fig. 28 Frame format.

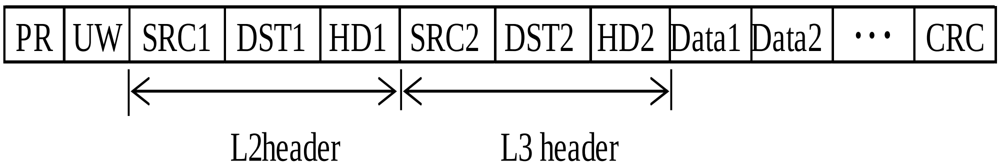


Fig. 29 Aggregated frame format.

Table 6 Frame elements.

Parameter	Type
SRC1	Source address of wireless link
DST1	Destination address of wireless link
HD1	Header information frame length, data type, sequence number
SRC2	Source address of data
DST2	Destination address of data
HD2	Header information data length, TTL
Data	Payload
CRC	Cyclic Redundancy Check code

4.3. Evaluation

4.3.1. Substitute Forwarding Characteristic

In this section, we evaluate the fundamental performance of RWCSF for all topology configurations shown in Fig. 13.

High transmission power can lower the loss ratio. However, it is undesirable from the viewpoint of radio wave interference of the outside the vehicle. Therefore, in this thesis, the maximum transmission power was selected as that rendering the influence to the outside of the vehicle could be made sufficiently small. The distance from node A to node H shown in Fig. 13 is the longest at 2944 mm. The corresponding theoretical propagation loss is 49 dB from equation (1). The minimum sensitivity of the module used is −95 dBm. Given the radio wave fluctuation distribution of Fig. 13, the transmission power was set to −36 dBm.

Table 7 shows the success ratio of each path with transmission power −36 dBm. Bitrate was 1Mbps. It achieved that 100% of packets were received except between node F and node H.

Next, transmission power was changed from −30 dBm to −42 dBm. Therefore, it needs just a little more transmission power.

Table 7 Success ratio for each path in RWCSF.

Node / Node	B	C	D	E	F	G	H
A	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
B		1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
C			1.00000	1.00000	1.00000	1.00000	1.00000
D				1.00000	1.00000	1.00000	1.00000
E					1.00000	1.00000	1.00000
F						1.00000	0.99827
G							1.00000

Fig. 30 shows the success ratio as a function of transmission power. It indicates that 100% of packets were successfully received with transmission power more than −33 dBm. However, some packet losses occurred with smaller transmission power.

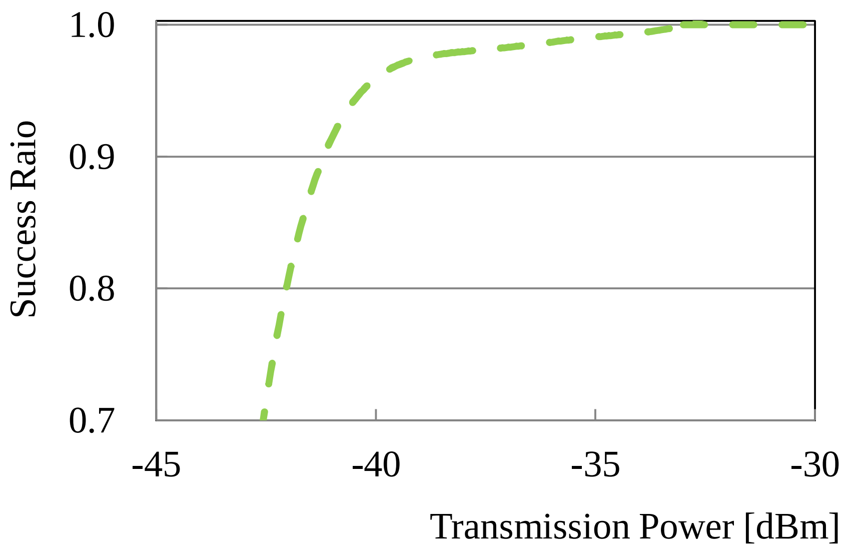


Fig. 30 Success ratio as fluctuation of transmission power in simulation.

We also evaluated the performance of the proposed method by experimental implementation. We adopted a general module, a model number ADF7242, made by Analog Devices, Inc. [72]. This module has a capability to add an original function in addition to standard Bluetooth. Then we implemented the proposed method in the same manner of simulation experiments. The operating frequency is 2.4GHz. Frequency-modulation is GFSK. Bitrate is 1Mbps. Receiving sensitivity for loss factor is −86 dBm.

Packets were sent from the driver's position (node A). Experiments were conducted with changing transmission power from −32 dBm to −44 dBm.

Fig. 31 shows the success ratio as a function of transmission power. It was confirmed that the high success ratio and low delay were achieved by substitute forwarding. Furthermore, an approximate curve between success ratio and transmission power was also plotted in Fig. 31. It was derived that calculated by high dimension polynomial. It shows the success ratio of more than 99.999% can be achieved by transmission power over −36 dBm. This result comes into line with the simulation result for large transmission power (more than −40 dBm).

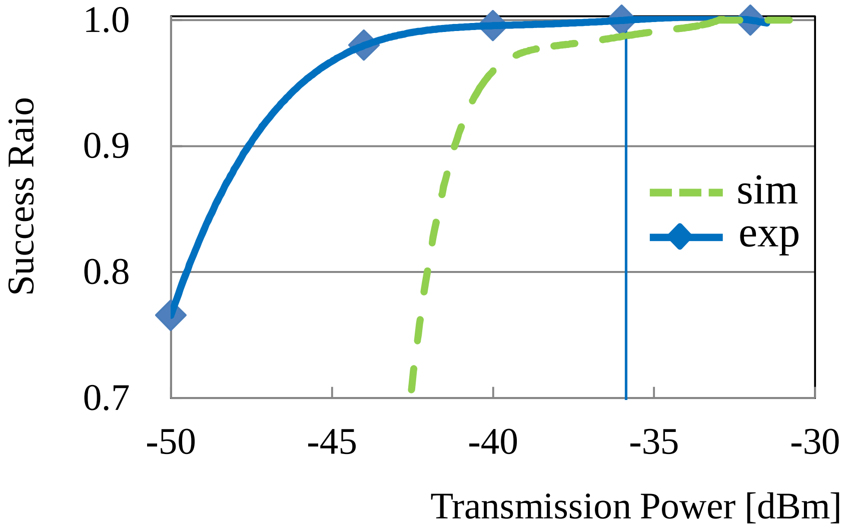


Fig. 31 Success ratio as fluctuation transmission power in implementation.

Fig. 32 shows the CDF (cumulative distribution function) of the end-to-end delay with the −36 dBm transmission power. It shows that almost all transmissions were completed within 5 ms in spite of the delay constraint 20 ms.

Fig. 33 shows the CDF of the number of hops with the −36 dBm transmission power. It confirms that more than 70% of communications made substitute forwarding. Although more than 95% of communications were within 3 hops, a few communications were delivered by virtue of 4 times or more substitute forwarding. Specifically, 3 trials used 6 hops and just one trial used 7 hops.

Table 8 shows the retransmission ratio by substitute forwarding at each node. It is found that node B and node C were often used with first substitute forwarding. They were near the source node. After that, node F was often used with second and third substitute forwarding.

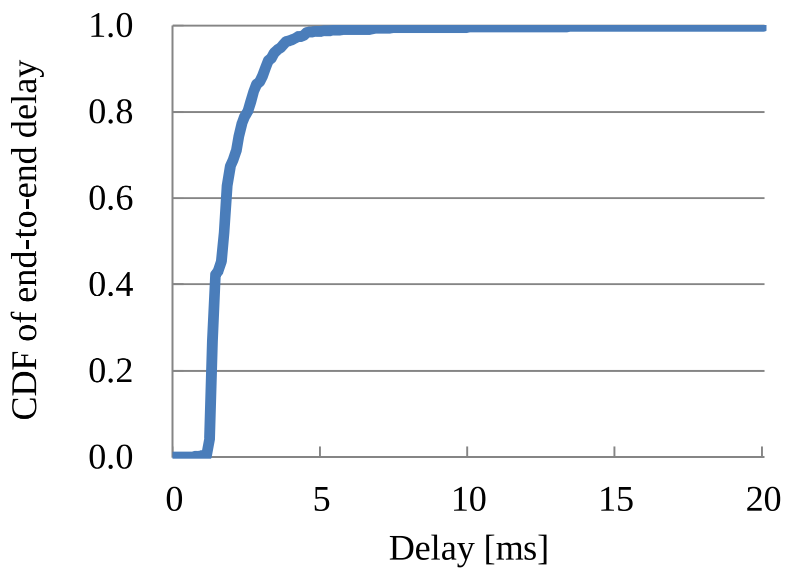


Fig. 32 CDF of End-to-end delay.

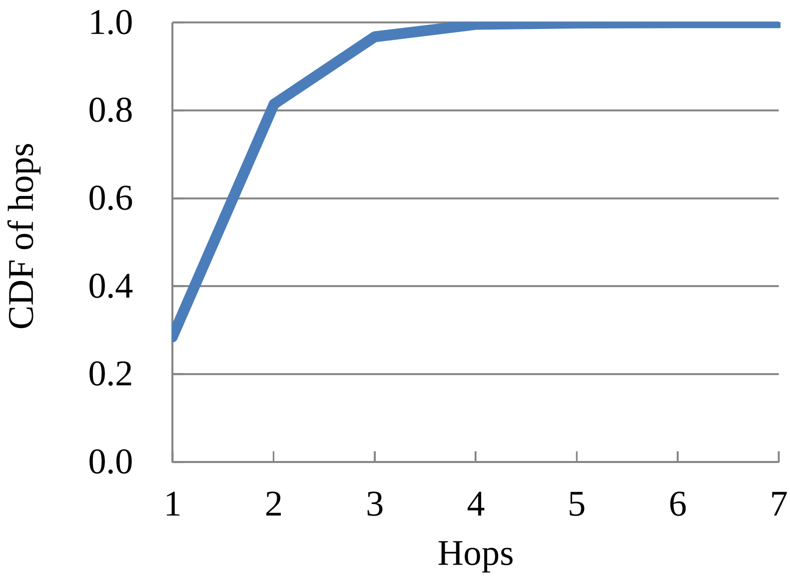


Fig. 33 CDF of the number of hops.

Table 8 Retransmission ratio by substitute forwarding at each node.

Hops / Node	2	3	4	5	6	7
B	0.21490	0.01585	0.01053	0.00314	0.00000	0.00025
C	0.27592	0.00720	0.00376	0.00000	0.00000	0.00000
D	0.00177	0.06701	0.00226	0.00000	0.00050	0.00000
E	0.08755	0.06052	0.01504	0.00209	0.00025	0.00000
F	0.10745	0.11888	0.03985	0.00000	0.00000	0.00000
G	0.00265	0.09438	0.01354	0.00523	0.00000	0.00000
H	0.00000	0.08790	0.01053	0.00105	0.00000	0.00000

Some neighboring nodes overhear the packet from source node. Therefore, we expected that relay nodes were distributed all over the network due to randomized back off in CSMA/CA. Although this is an unexpected result, the proposed method achieves the requirements that 99.999% of packets are successfully received within 20 ms.

For a single flow, the target success ratio of 99.999% was achieved. Of particular importance, the communication success ratio was significantly improved within the delay constraint for the communication route with low success ratio in Table 4. Ratios of almost 100% were achieved.

Multi-flow increased the likelihood of failure exponentially to the number of flows, but the success ratio improved in all routes.

The communication success ratio for double, triple, and quad flow are shown in Table 9, Table 10 and Table 11, respectively.

Table 9 Success ratio with double flows for each path.

Node / Node	B	C	D	E	F	G	H
A	1.000	1.000	1.000	1.000	1.000	1.000	0.954
B		1.000	1.000	1.000	1.000	1.000	0.967
C			1.000	1.000	1.000	1.000	0.937
D				1.000	1.000	0.999	0.899
E					0.999	1.000	0.937
F						1.000	0.924
G							1.000

Table 10 Success ratio with triple flows for each path.

Node / Node	B	C	D	E	F	G	H
A	1.000	0.999	0.993	0.944	0.946	0.931	0.801
B		0.999	0.997	0.997	0.974	0.997	0.885
C			0.997	0.997	0.998	0.982	0.872
D				0.990	0.998	0.932	0.827
E					0.992	0.997	0.914
F						0.994	0.881
G							0.994

Table 11 Success ratio with quad flows for each path.

Node / Node	B	C	D	E	F	G	H
A	0.952	0.952	0.945	0.899	0.901	0.887	0.763
B		0.952	0.949	0.950	0.927	0.949	0.843
C			0.950	0.950	0.950	0.935	0.830
D				0.943	0.950	0.887	0.787
E					0.945	0.949	0.871
F						0.947	0.838
G							0.947

In RWCSF, neighboring nodes retransmit the overheard packet if the destination node does not receive the packet from source node. In many cases, a node that recognized that the first packet sent by substitute forwarding (corresponds to the second hop) failed, could transmit the packets by substitute forwarding (the third hop).

Meanwhile, another node performs packet transmission by substitute forwarding of the second hop. While the second hop communication is repeated, the third hop communication is executed.

RWCSF is effective for improving the success ratio. However, it is thought that its advantage will turn negative if the number of hops exceeds a certain number. The benefit falls as the number of flows simultaneously generated increases.

In other words, as the number of flows increases, the number of nodes that overhear and hold packets by substitute forwarding increases, which increases the probability of communication collisions.

We investigated the average number of communications that occurred in the network, the average transmission waiting times, and the transmission waiting ratio. Table 12 shows the result. It is not related to the flow number. The results show the effect of terminating packet transmission by substitute forwarding if the communication of a neighboring node is confirmed to have succeeded by the overhearing function.

Table 12 Transmission queuing ratio.

Flows	Average number of communications [hops]	Average transmission waiting	Transmission waiting ratio [%]
1	4.12	1.05	25.6
2	4.94	1.48	58.0
3	7.17	1.26	64.4
4	7.84	1.28	64.9

4.3.2. Effect of Substitute Forwarding in Assumed Application

In this section, we evaluate assuming applications. That is BMS and seat sensors shown in section 3.2.

We placed 18 nodes in 1470 mm × 2690 mm area. Its topology was shown in Fig. 25. The transmission power was −36 dBm obtained in section 4.3.2. Bitrate was 1Mbps.

As a radio propagation model, the observed path loss described in section 2.2 was used with the addition of a standard white noise component.

We evaluated in the following 4 scenarios.

In the first scenario, only BCs shown in Fig. 25 send packets. In the second scenario, in addition to BMS, each sensor node sends a packet in constant interval. In the third scenario, each sensor node sends a packet following a Poisson arrival (PA) process. The last scenario has just two sensor nodes send a packet. One of the two was constant interval, and the other was the intervals of 160 ms.

Table 13 shows the simulation results. In the scenario 1 and 2, all communications were successfully finished within 20 ms. In scenario 3 and 4, sometimes 2 or more flows were active simultaneously and a few flows failed to finish within 20 ms.

Table 13 Success ratio for BMS and sensor.

		Scenario 1 Only BMS	Scenario 2 BMS+ 1 sensor	Scenario 3 BMS+PA	Scenario 4 BMS+ 2 sensors
Success Ratio within 20 ms	BMS	1.00000	1.00000	0.99994	0.99980
	Sensors	-	1.00000	0.98973	0.99986
	Total	1.00000	1.00000	0.99484	0.99983

Fig. 34 shows the CDF (cumulative distribution function) of the end-to-end delay. It shows that applications succeed more rapidly. On the other hand, BMS tends to take longer time to complete. This means that the distance between nodes is related to the delay time.

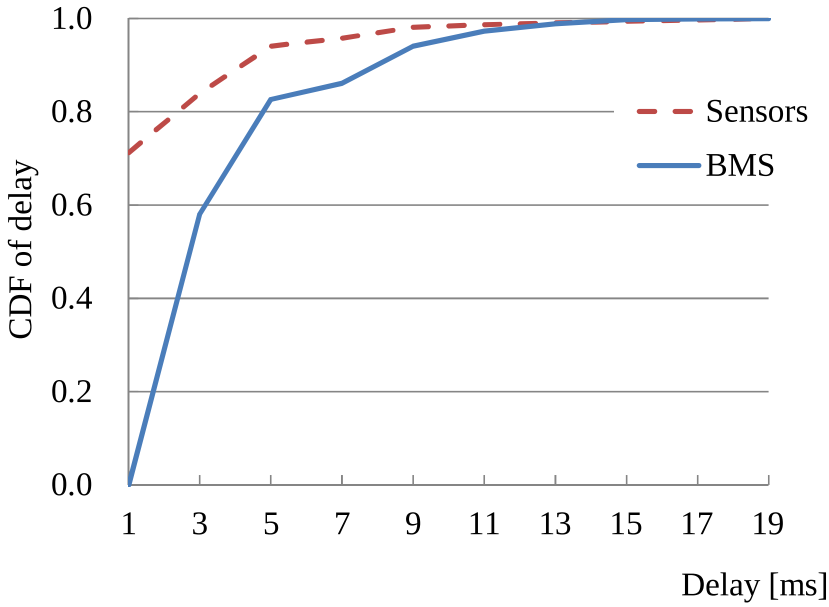


Fig. 34 End-to-end delay for BMS and sensors.

In this method, neighboring nodes overhears the packet if the destination node does not receive the packet successfully. Therefore, several nodes hold the same packet. These nodes try to start transmission at the same time, but transmission nodes detect by CSMA/CA.

In a case where 2 nodes send a packet simultaneously, the transmission node is detected by CSMA/CA since each source node also tries to start transmission at the same time. Neighboring nodes overhears the packet if one of two source node fails. The other node may hold the overheard packet and own sent packet. The overheard packet is sent first if the overheard packet and the sent packet are hold. Therefore, the own packet of the second source node is delayed. Moreover, in multi flow, the packet is sent at different timing from that of the single flow. With that timing, it does not complete the communication within the remaining delay constraint since radio wave propagation characteristics have changed.

Fig. 35 shows a typical sequence of single flow with substitute forwarding. The source node is BC01 node. The destination node is BMC node. The source node sends a packet to the destination node. The destination node does not receive the packet. Neighboring nodes overhear the sent packet and node 1 sends the overheard packet to the sink node. This communication is completed.

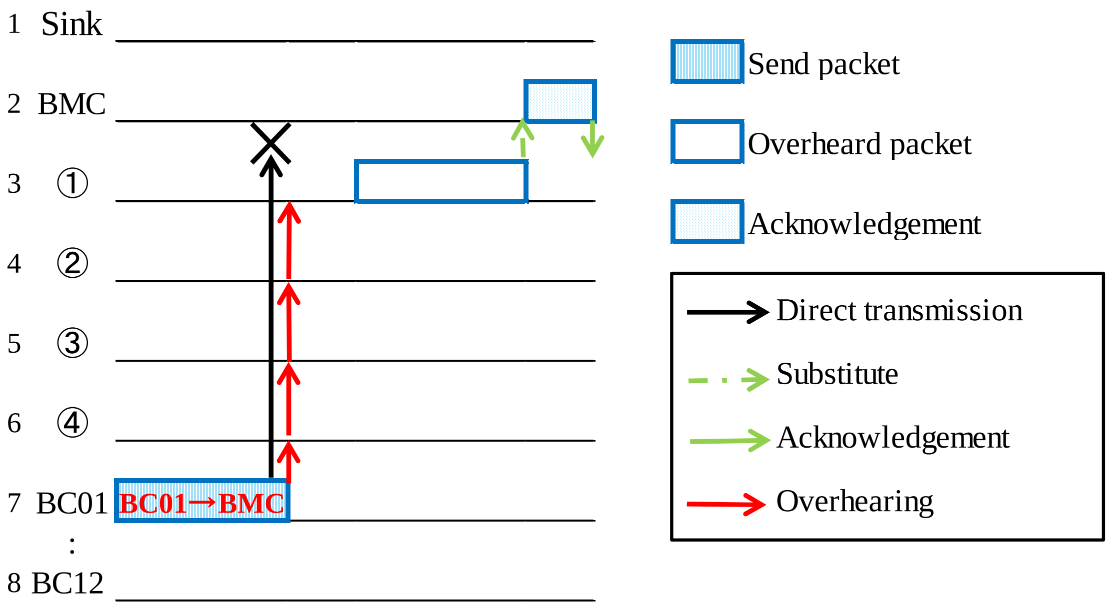


Fig. 35 The sequence of single flow.

Fig. 35 shows an example sequence with 2 flows. One of two source nodes is also BC01 node and its destination node is BMC node. The other source node is node 1 and its destination node is Sink node.

BC01 node sends its packet but the BMC node does not receive it. Neighboring nodes overhear the sent packet. Here, node 1 has two packets. One is sent packet to sink node. The other is overheard packet to BMC node. Then, the overheard packet was not forwarded immediately since the sent packet is enqueued first. Therefore, node 2 sends the overheard packet. Next, node 3 sends the overheard packet. After that, node 4 sends the overheard packet. Thus, the transmissions are repeated. Then, node 1 sends the packet to destination node. The destination node receives it and sends the acknowledgment packet. Next, node 1 sends the packet as substitute forwarding. However, the destination node receives none of the packets due to the bad condition of wireless link. Finally, it cannot satisfy the delay constraint.

In another case, the neighboring nodes may hold two overheard packet when two different nodes send overheard packet. In this case, one of two packets is randomly sent. The other overheard packet is also delayed as shown in Fig. 35.

Consequently, when two or more flows occur simultaneously, one of them may not satisfy the delay constraint with small probability.

Our method had a good performance under the only BMS. However, one of communications may not satisfy the delay constraint with small probability if two or more flows occur simultaneously.

The reason for this is increased the number of packet transmission events in network.

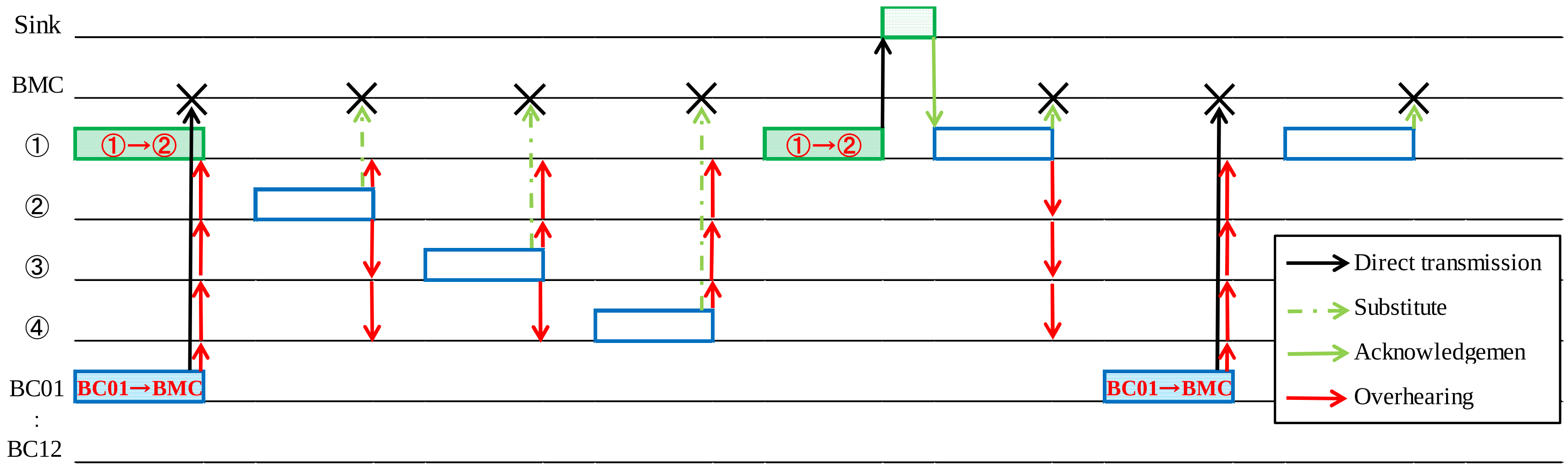


Fig. 36 The sequence of two flows.

4.3.3. Effect of Aggregation

We evaluated the performance of the SFwDA method, which is the purpose of reducing the number of packet transmission events in the network, using our own event-driven simulator based on the assumed model described in section 3.1.

The number of battery sensors was fixed at 12. On the other hand, the number of active seat sensors was changed from 1 to 4 corresponding to the number of passengers. The transmission order of each sensor followed the numerical order shown in Fig. 25. The timing of packet sending was decided randomly following a uniform distribution. In addition, parameter x was changed from 1 to 4. 1×10 ˆ 7 flows were observed under each condition. Note, *t* defined in section 3.4 was set to 1 ms.

Table 14 and Table 15 show the results. Any flow that did not satisfy the delay constraint of 20 ms was regarded as a failure. As shown in the tables, the proposed method with aggregate size (*x*=2) achieves the target success ratio even if all 4 seats are occupied.

Table 14 Simulation results of seat sensor in wagon type vehicle.

Number of aggregated packets / Active seat sensors	1	2	3	4
1	1.00000	1.00000	1.00000	1.00000
2	1.00000	1.00000	0.99999	0.99999
3	0.99998	0.99999	0.99996	0.99929
4	0.99997	0.99999	0.99972	0.99824

Table 15 Simulation results of battery sensor in wagon type vehicle.

Number of aggregated packets / Active seat sensors	1	2	3	4
1	1.00000	1.00000	1.00000	1.00000
2	1.00000	1.00000	0.99999	0.99999
3	0.99998	0.99999	0.99995	0.99924
4	0.99996	0.99999	0.99922	0.99781

Further, we discuss on the optimal parameter setting.

In each aggregate size of 1 to 4, we show the total number of frame transmissions. As shown in Fig. 37, the total number of transmissions was decreased by aggregation compared with the case of aggregate size (x=1).

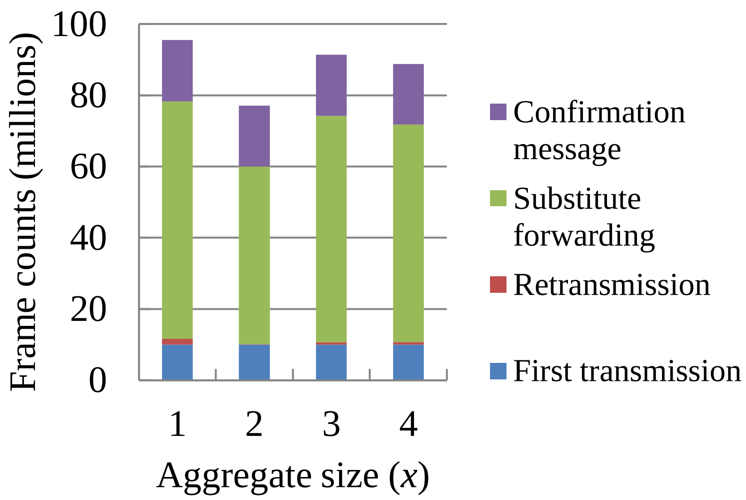


Fig. 37 Total frame counts.

Next, we analyzed the retransmission ratio. The aggregate size (x=2) achieved the smallest as shown in Fig. 38. Note that if a retransmission occurred before an aggregated packet including the original packet arrived at the destination node, additional substitute forwarding would be invoked. Therefore, as shown in Fig. 37, the number of transmissions by substitute forwarding increased significantly even if that by retransmission itself was negligibly small.

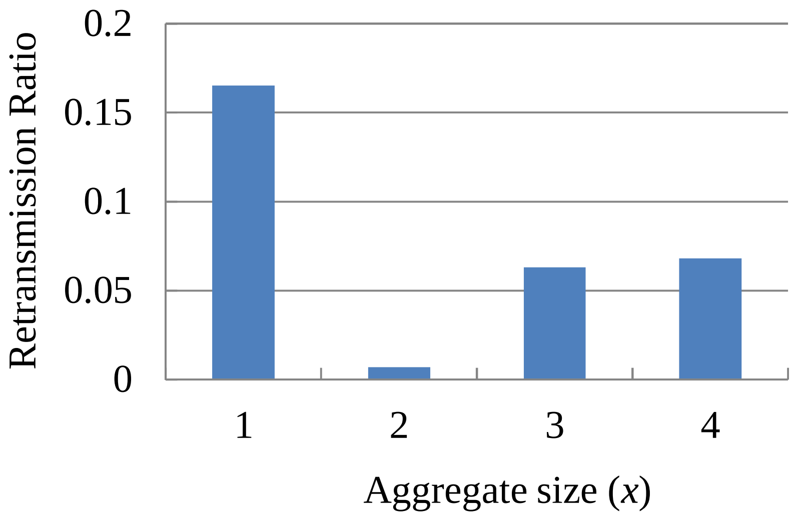


Fig. 38 Retransmission ratio.

Then, Fig. 39 shows the CDF of elapsed time from data generation to communication success. About 30% of flows were successfully finished right after data generation. It means that they were done by direct (single hop) communications. After that, in the case of aggregate size (x=2), more flows finished earlier by virtue of aggregation than in other cases of aggregate sizes (x=3, 4). On the other hand, in the case of aggregate size (x=1), the large total number of frame transmissions as shown in Fig. 37 led traffic congestion because of no aggregation. As a result, as shown in Fig. 40 which is an enlargement of Fig. 39, more packets easily met the deadline with aggregate size (x=2).

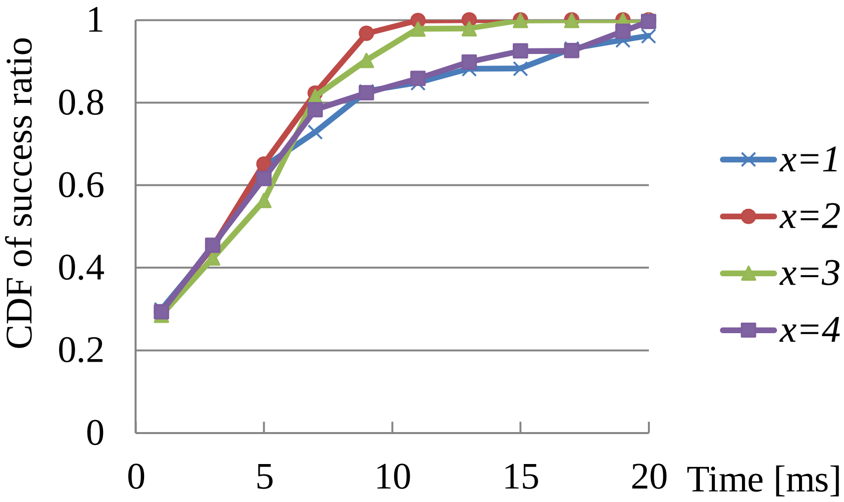


Fig. 39 Success ratio for the elapsed time.

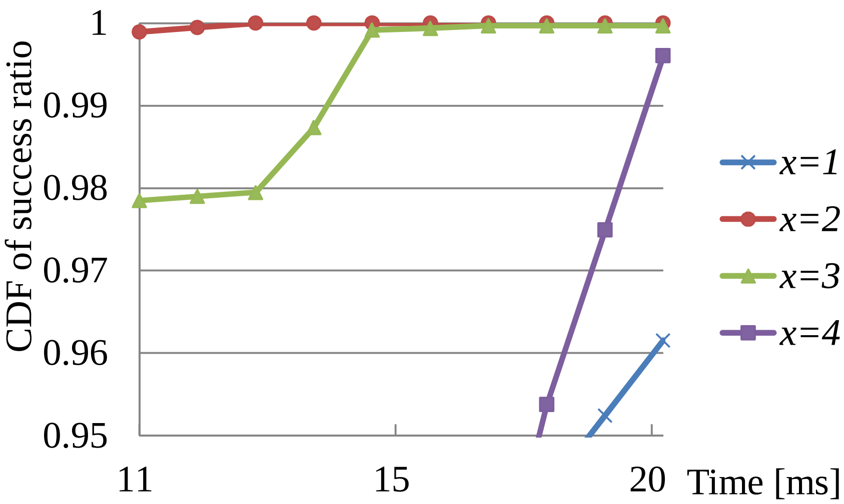


Fig. 40 Success ratio after elapsed time 11 ms.

Here, the result of aggregate size (*x*=2) in Table 14 and Table 15 were tested by statistics.

Total 1×10＾7 samples, which were independent, were divided into 10 sets, and an average error rate was obtained for each set. Table 16 shows the average error rates with 95% confidence interval derived from t distribution with 9 degrees of freedom. It was confirmed that the width of the confidence interval was sufficiently small relative to the average value in each cases.

From the above discussion, we conclude that the aggregate size (*x*=2) is the optimal.

Table 16 95% confidence interval in aggregate size (*x*=2).

Active seat sensors	Seat sensor		Battery sensor	
	Average	Width of confidence interval	Average	Width of confidence interval
1	1.00000	0	1.00000	0
2	1.00000	0	1.00000	0
3	0.999990	2.29 × 10 ＾ -6	0.9999942	0.83 × 10 ＾ -6
4	0.999988	2.37 × 10 ＾ -6	0.9999938	0.89 × 10 ＾ -6

4.3.4. Affect of Internal Noise

In this section, we consider the influence of internal artificial noise. First, we evaluated the effect of the noise by simulations. We assumed Gaussian noise at levels from 0 to 30 dBm.

Table 17 and Table 18 show the results with the RWCSF method and the SFwDA method with aggregate size (*x*=2), respectively. The SFwDA method obtains higher success ratios than the RWCSF method and achieves the target ratio even if −90 dBm of noise was added. This is because the apparent number of flows is decreased by SFwDA.

Next, we observed the real noise in a vehicle. Specifically, we measured the level of noise generated by operating the window, windshield wipers, and accessories.

Fig. 41 shows that any one operation invoked noise of −90 dBm or less. It means that the SFwDA method works well even with such noises as shown in Table 18. Consequently, the SFwDA method is practical.

Table 17 Noise added to RWCSF.

Number of seat sensors active / Noise level [dBm]	1	2	3	4
< -92	1.00000	1.00000	0.99998	0.99997
-91	0.99999	0.99999	0.99998	0.99997
-90	0.99999	0.99999	0.99998	0.99997
-89	0.99999	0.99999	0.99998	0.99997
-84	0.99997	0.99998	0.99998	0.99997
-82	0.99980	0.99998	0.99998	0.99997
-77	0.99961	0.99998	0.99998	0.99994
-72	0.99921	0.99976	0.99976	0.99970
-62	0.99055	0.99222	0.99225	0.99170

Table 18 Noise added to SFwDA with aggregate size (x=2).

Number of seat sensors active / Noise level [dBm]	1	2	3	4
< -92	1.00000	1,00000	0.99999	0.99999
-91	0.99999	0.99999	0.99999	0.99999
-90	0.99999	0.99999	0.99999	0.99999
-89	0.99999	0.99999	0.99999	0.99996
-84	0.99999	0.99999	0.99996	0.99996
-82	0.99999	0.99999	0.99990	0.99986
-77	0.99998	0.99996	0.99988	0.99962
-72	0.99976	0.99952	0.99961	0.99911
-62	0.99237	0.98459	0.99172	0.98342

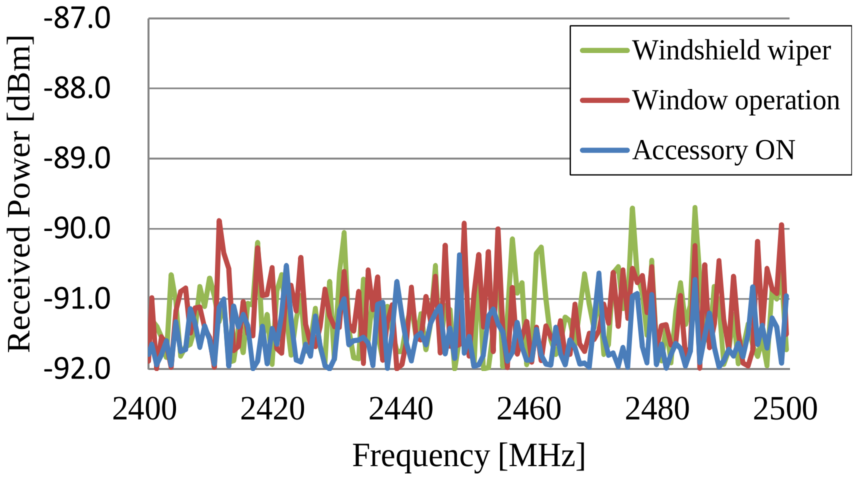


Fig. 41 Artificial noise in vehicle.

4.3.5. External Noise

This section considers external noise sources such as Wi-Fi access points. The radio waves from the external noise source are attenuated by the vehicle body. In order to measure this attenuation, we observed the reception at 360 degrees around the transmitting node in 10 degree steps. The left side of the vehicle was 0 degrees. The transmitter was installed in the vehicle and reception intensity was measured at 5 m. We measured the maximum radiation power using the MAX HOLD function of the measuring device. Fig. 42 shows the reception intensity. The position of the radio wave source was near the door switch. The reception intensity was plotted around the transmission source.

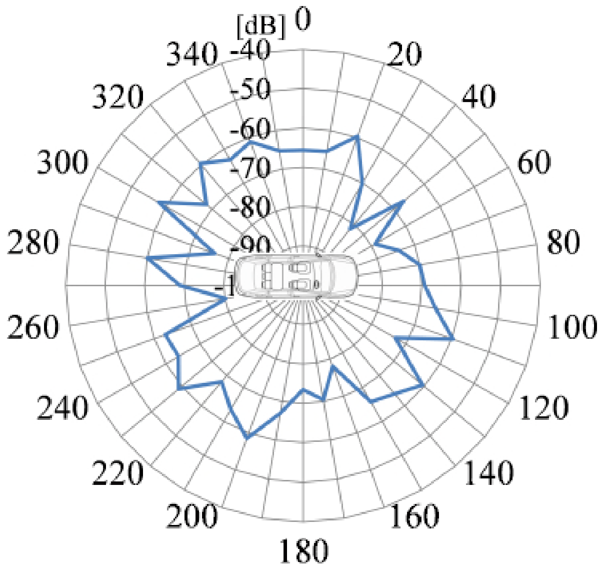


Fig. 42 Reception intensity at 5 m from vehicle.

Path losses were affected by air if the wireless terminal was directly visible. Path losses were affected by air and the vehicle body if the wireless terminal was hidden by the vehicle body. According to equation (1) in section 2.1.1, the path loss is about 54 dB at the distance of 5 m in air attenuation. Therefore, the attenuation by the vehicle body was 6 dB or more.

Note that in radio wave propagation, the reciprocity theorem makes it possible to switch between transmission and reception, for that reason, this result is the same for external incidence [73].

There are various radio wave sources in urban areas, and the reception intensity in such areas is known to be −55 dBm or less [74]. From the result in Fig. 42, radio waves radiated into the vehicle with attenuation in the vehicle body are less than −60 dBm.

Next, we evaluate the communication quality when radiation noise from the outside of the vehicle is received. These noise intensities vary depending on the position of the radio wave source and the surrounding environment, so we assumed random noise of less than −60 dBm. We assumed that the terminal devices were installed around the vehicle. When each node sent a packet, noise was randomly added with the possibility *p*.

Table 19 and Table 20 show the results for the previous method and the proposed method with aggregate size (*x*=2), respectively. The other conditions are the same as in other sections. The radiation noise affects the reliability of wireless communication within the vehicle. However, the results confirm that the proposed method is more effective in combatting radiation noise from outside the vehicle than the conventional method.

Table 19 Success ratio in RWCSF.

Number of seat sensors / Possibility *p* [%]	1	2	3	4
0	1.00000	1.00000	0.99998	0.99997
3	0.99961	0.93962	0.93960	0.93912
5	0.93727	0.93727	0.93726	0.93676
10	0.93382	0.93381	0.93279	0.92833
20	0.92641	0.92642	0.92141	0.91590
30	0.91628	0.91630	0.90625	0.79578
40	0.85688	0.85692	0.83627	0.78641
50	0.79390	0.79385	0.75380	0.68934

Table 20 Success ratio when aggregate size (*x*) is 2.

Number of seat sensors / Possibility *p* [%]	1	2	3	4
0	1.00000	1.00000	0.99999	0.99999
3	1.00000	0.99999	0.99999	0.99999
5	0.99999	0.99999	0.99999	0.99999
10	0.99999	0.99999	0.99999	0.99999
20	0.99999	0.99999	0.99999	0.99999
30	0.99999	0.99999	0.99999	0.99999
40	0.99716	0.97166	0.95667	0.91766
50	0.90563	0.88563	0.85863	0.79853

This means that SFwDA reduces the traffic while satisfying the delay constraint and each packet can be successfully transmitted as the influence of radiated noise is suppressed.

In other words, the proposed method provides reliable wireless communications if the radio source outside the vehicle operates at utilization ratios of less than 30%.

4.4. Summary

We evaluated the performance of RWCSF and SFwDA which were proposed in Chapter 3.

First, we simulated the basic characteristic of RWCSF which is the basic method proposed in this thesis. We then evaluated the proposed method in an environment that mirrored the real world, and clarified that −36 dBm is the required minimum transmission power.

We also evaluated the performance of SFwDA, which is the enhanced variant of RWCSF. The proposed method with aggregate size (x=2) achieves the target success ratio even if all 4 seats are occupied.

Next, we evaluated SFwDA under aggregated multiple flows, in a variety of vehicle types with artificial noises. Another evaluation considered external noises. Each noise type (internal and external) had much smaller impact than passenger number, which confirms that the assumed environment used in the performance evaluation is severe enough. Therefore, we conclude that the proposed method is practical for regular private vehicles.

Consequently, the evaluation results confirmed that the proposed method achieves the required quality, 99.999% of success ratio and 20 ms of delay, equivalent to wired links, with multiple simultaneous transmissions.

Chapter 5

Conclusion

Chapter 1 summarizes the background and contributions of this dissertation. Wireless communications is the fastest growing segment of the communications industry [1]. We expect that the use of wireless links will become popular as a simple and reliable method for connecting devices in the future. Also, IoT (Internet of Things) which attach sensors to various things existing in the real world such as furniture and home appliances and connect them to the Internet is researched [9].

We investigated to apply our method to battery management system in addition to a vehicle sensor network since wireless communication for ICT equipment and as a wiring substitute for vehicles is an undeveloped area. And more, we considered how to achieve high reliability by using general radio module and controlling the LLC of the data link layer and the network layer without changing the modulation method or using the codec.

Chapter 2 measured the radio wave characteristics and clarified that the radio wave environment in a vehicle does not depend on link distance. The environment within the vehicle's body can be considered as a kind of wireless multi-hop network. All nodes can communicate directly (via 1 hop) with each other if radio wave environment is not so drastic. Unfortunately, the convention approach of direct communication does not consider the severe and rapid fluctuation in the propagation loss due the short link distances, just a few meters at most. Therefore, we confirmed existing research on wireless communication. However, the application assumed in this thesis requires reliable communications with very low delay even though the radio propagation environment is very unstable. Therefore, most existing methods cannot be applied.

Chapter 3 examined the target applications of BMS and seat sensor network, and proposed RWCSF with substitute forwarding; it can handle the rapid fluctuations in propagation loss expected. In RWCSF, neighboring nodes overhear packets. And relay the packets if original transmission fails. We proposed RWCSF with data aggregation (SFwDA) to reduce the traffic increased expected due the use of relay nodes.

Chapter 4 evaluated the basic performance of the proposed method by computer simulation, its performance in an actual vehicle was confirmed, and the required minimum transmission power was clarified to -36 dBm. Further, SFwDA was also evaluated in the same environment, and it was confirmed that the optimal aggregate number was 2. Moreover, we evaluated it in a variety of vehicle types with artificial noises and observed the real noise. The noises used in the simulation were found to have much smaller effect than the number of passengers, so the environment assumed in the performance evaluation was verified to be severe enough. The evaluation results showed that the proposed method could achieve the quality requirements, success ratio of 99.999% and delay of less than 20 ms, equivalent to wired links, with multiple simultaneous transmissions.

By avoiding wiring, ICT equipment should reduce metal consumption and improve assembly and maintenance efficiency [75]. In a satellite system, launch costs are reduced by using light-weight wireless links [76]. A manufacturing field is able to design a layout-free manufacturing which enables smooth rearrange of assembly line. Therefore, it is considered that the proposed method is effective even in application areas other than automobiles such as ICT equipment, satellite system and IoT equipments.

In the future, we will implement the proposed method and confirm its feasibility in the real world. In addition, we will consider to apply the proposed method to larger special-purpose vehicles such as buses and trains. Furthermore, it is expected that the automobile technologies will be more fully developed and real-time communication must be supported in the trillion sensor era.

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Appendix A: Optimal Size of Contention Window

CSMA / CA generally increases delay time if CW is large. On the other hand, the possibility of collision increases if it is small. It is also necessary to set an appropriate backoff time by substitute forwarding. Therefore, we conducted a preliminary experiment to obtain the optimal size of the CW by using the success ratio over delay time as the evaluation index.

We selected two routes in the node arrangement shown in Fig. 13. One is the communication from node C to node D which can be communicated directly and have a line of sight. The other is the communication from node A to node E which crosses other route. As the CW size was changed, the evaluation index with direct communication in the passenger compartment was confirmed. The evaluation value was the highest when CW=32 as shown in Fig. 43. And more, other communications without line of sight which were node D to node E and node C to node D, were also similar result. Therefore, CWmax=32 was set for the confirmation of this thesis.

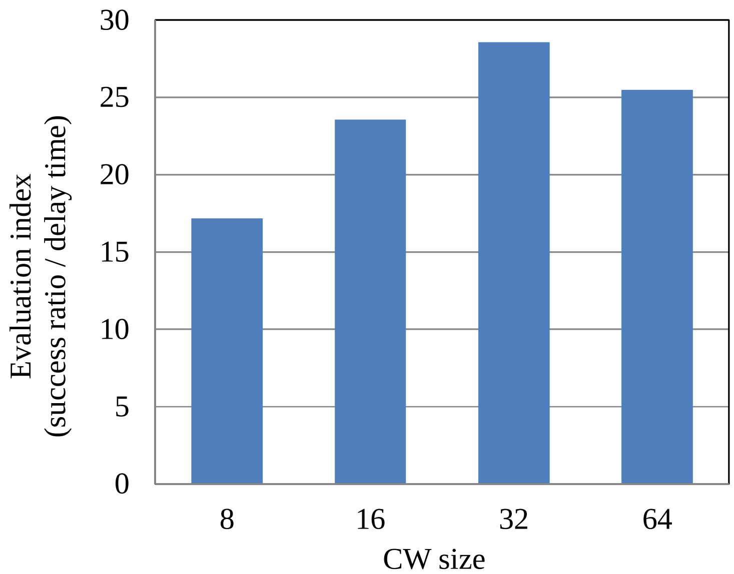

Fig. 43 Optimal size of contention window.

Note, RWCSF send packet the packet by substitute forwarding faster than retransmission from source node due to the backoff time. Therefore, direct communication has CWmax=2, substitute forwarding has CWmax=1. In addition, CW size is increased according to the number of retransmission since direct communication can retransmit. This maximum size is CWmax=32.

Here, the shortest backoff time is from 0 ms to 0.48 ms since the length of one CW size which was calculated from the transmission / reception switching time of the wireless module is 0.0015. As a result, the communication frame time was 0.721 to 1.186 ms.