Technology Reports

R&D Densoku-car | Mobile Radio Field Experiment | Special Vehicle

# History of "Densoku-cars" for Research and Development Supporting the Evolution of Mobile Communications

## —Unique Vehicles Used in 1G – 5G Mobile Radio Field Experiments—

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Mobile radio field (outdoor) experiments are an important and indispensable process at the research and development stage of a mobile communication system that aims to provide stable communications under mobile conditions in a variety of environments. For conducting these field experiments, NTT DOCOMO has introduced mobile radio field experiment vehicles (called "Densoku-cars" for short) for research and development purposes having unique and original specifications tailored to each generation from 1G to 5G. Through experiments involving extensive driving over great distances, these Densoku-cars have come to support the evolution of mobile communications.

This article describes the features of Densoku-cars for research and development purposes in each generation and makes extensive use of photos to introduce main Densoku-cars, associated mobile radio field experiments, and auxiliary equipment.

## 1. Introduction

Radio system engineers in Japan usually call radio wave measurement ("denpa sokutei" in Japanese) or electric field strength measurement ("denkai kyodo sokutei" in Japanese) "densoku" for short in Japanese. Furthermore, vehicles whose purpose is to measure the received state of radio waves for a wide range of areas in a variety of radio systems including mobile communication system and broadcast system are called "Densoku-cars." However, Densoku-cars for research and development (R&D) of mobile communications systems (hereinafter referred to as "R&D Densoku-cars" or "[class name]

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Densoku-cars*") described in this article are special vehicles whose purposes are not only to conduct radio wave measurement and electric field strength measurement but also to conduct outdoor mobile radio field experiments such as radio communication/transmission experiments, communication connection tests with commercial equipment, etc. while moving. Their specifications and functions are basically common to those of broadcast relay vehicles used by broadcasters and mobile base station vehicles used by mobile network operators.

Mobile terminals (or mobile stations) used in mobile radio field experiments in the research stage are usually prototype equipment, and in addition to being large in size with high power consumption, they are extremely delicate pieces of equipment. Careful and diverse measures are therefore needed for loading such equipment onto a vehicle. Over the years, NTT DOCOMO's R&D department (including the mobile-communication R&D departments of the Nippon Telegraph and Telephone Public Corporation and NTT eras) have introduced special vehicles to meet the requirements of each generation as R&D Densoku-cars taking the above points into account. The experiences gained from experiments by running Densoku-cars in a variety of environments have driven the evolution of vehicle specifications tailored to the times and have built up extensive know-how in holding field experiments.

Making extensive use of photos, this article describes the features of R&D Densoku-cars, introduces main Densoku-cars and associated mobile radio field experiments that played an active role in each generation of the mobile communication system, and describes auxiliary equipment.

## 2. Features of R&D Densoku-cars

**Photo 1** shows R&D Densoku-cars assembled in the parking lot of the NTT DOCOMO R&D Center (photo taken in October 2007). Against the background of progressively higher frequencies and functionality in each generation of the radio access system, mobile station equipment and measurement equipment for experimental use have become increasingly larger in size. In step with this trend, Densoku-cars have become increasingly larger as reflected by the transition from 3-to-4-ton-class vehicles (small trucks or small buses) to 8-ton-class vehicles (medium trucks) as base vehicles. In addition, measures for making it easier to load large experimental equipment have been taken such as the installation of support rails, movable loading mechanisms, and specialized doors in Densoku-cars. At the same time, the power consumption of experimental equipment has been escalating upward, and to deal with this issue, a large-capacity (maximum 20 kVA*1 class) engine-driven generator*2 (hereinafter referred to as "E/G") that can provide a stable and sufficient amount of power has come to be installed in Densoku-cars. Special measures have also been taken to reduce generator noise and vibration. Furthermore, equipment mounts have been equipped with anti-vibration mechanisms to alleviate the vibration of experimental equipment while the Densoku-car is moving in addition to the adoption of air suspension in the vehicle itself.

Additionally, a variety of measures have been

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* Densoku-car class: This article considers vehicle size and scale of equipment to be loaded and divides R&D Densoku-cars into 3 classes (having the class names of small, medium, and large).

*1 VA: Symbol for volt-ampere. This is the unit representing apparent power when supplying an AC power supply to various types of equipment and devices taking into account the active power used by the load and reactive power not used by the load. It is used to rate the capacity of generators, transformers, etc.

*2 Engine-driven generator: An electrical power generator or power generating equipment driven by an engine as a power source that serves to supply power mainly in environments in which commercial power cannot be supplied. Gasoline, gas oil, gas cartridges, etc. may be used as fuel. Called "E/G" for short. When applying generators to R&D Densoku-cars, a variety of methods have been adopted taking into account their use in mobile radio field experiments (see Section 5).


**Photo 1 Densoku-cars assembled in the parking lot of the NTT DOCOMO R&D Center**

adopted for verification experiments of new radio access technologies and measurement experiments of mobile radio wave propagation characteristics*3 depending on the vehicle. These include the use of detachable specialized mounts that can mount antennas of various shapes according to the experimental items and the use of roof wiring mechanisms for handling antenna cable with low loss. Moreover, to measure and evaluate communication performance and propagation characteristics that depend on antenna ground height, antenna installation position, and other factors, R&D Densoku-cars have been equipped with moveable antenna mounts using extendable poles, folding arms, turntables, etc.

R&D Densoku-cars for conducting special experiments were also introduced. These included Densoku-cars capable of radio communication experiments during high-speed movement up to a maximum of 300 km/h. The idea here was to conduct simulation experiments with the aim of improving communication performance and stabilizing communication quality when using mobile phones or smartphones while riding high-speed trains. They also included Densoku-cars equipped with high extendable antenna poles for conducting radio wave propagation experiments that reproduce the installation conditions of actual base station antennas.

Some R&D Densoku-cars, moreover, have been registered as special purpose vehicles in accordance with the Road Transport Vehicle Act in Japan, that is, as automobiles whose main purpose of use is special in nature. These vehicles are called "number 8 vehicles" because the numbers identifying the type of vehicle on the automobile's license plate (class number) begin with the number 8.

*3 Mobile radio wave propagation characteristics: In mobile communication systems, characteristics such as propagation loss, power delay profile, and angle profile in the propagation of radio waves from a transmission point (base station or mobile terminal) to a receive point (mobile terminal or base station). In land movement, obstacles and reflective objects such as buildings, trees, and undulating terrain are constantly affecting radio wave propagation so that the receive level is always fluctuating according to movement with the possibility of momentary drop offs.

## 3. R&D Densoku-cars by Mobile Communication System Generation

This section describes the main Densoku-cars that played an active role in R&D in each generation of the mobile communication system.

### 3.1 1G

On setting out to achieve the first-generation mobile communications system (1G) using a cellular system[*4], it was first necessary to clarify and model the mobile radio wave propagation characteristics of the 800 MHz band—a new radio frequency candidate—in the system study. In 1962, researchers at the Electrical Communications Laboratories of Nippon Telegraph and Telephone Public Corporation (Musashino City, Tokyo) clarified the radio wave propagation characteristics between a base station and mobile terminal, the basis of mobile radio link design, through radio wave propagation measurement experiments while actually driving around in an automobile. Then, on the basis of the results obtained, they began studies with the aim of generalizing a method for estimating received electric field strength and service area. Additionally, to obtain actual mobile radio wave propagation data in the Very High Frequency (VHF) band[*5] and Ultra High Frequency (UHF) band[*6], a large-scale experiment by running Densoku-cars was conducted throughout the Kanto region (which includes the Tokyo metropolitan area) from 1962 to 1965 [1]. The idea here was to conduct mobile radio wave propagation experiments in both urban and suburban areas throughout this region. Transmit equipment was installed at five locations, one of which was the high-reaching Tokyo Tower (Minato ward, Tokyo) in central Tokyo. This location was used as the base point for conducting experiments for propagation distances in the range of 1 – 100 km. The Densoku-car used in these experiments is shown in **Photo 2**. Using the Mitsubishi Jupiter truck as the base vehicle, this vehicle (medium Densoku-car) was equipped with receiving antennas for measuring the reception of

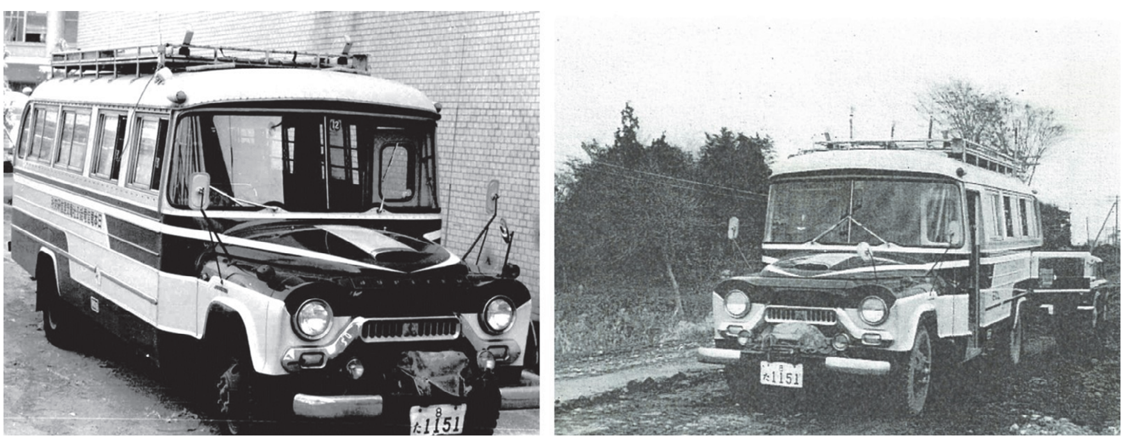


**Photo 2 Densoku-car and experimental scene in large-scale radio wave propagation experiments**

*4 Cellular system: In mobile communications, a system that divides the service area into many small areas called cells and installs a base station in each cell so that users (mobile terminals) can connect with a neighborhood base station and make calls. If a user (mobile terminal) in the middle of a call should cross over into another cell, the current base station will be automatically switched to the base station in the new cell through handover control without interrupting the call. Giving cells a hexagonal shape can make spectrum utilization even more efficient.

*5 VHF band: Frequency band in the range of 30 – 300 MHz with wavelengths of 1 – 10 m. Also called the meter-wave or ultra-short-wave band.

*6 UHF band: Frequency band in the range of 300 MHz – 3 GHz with wavelengths of 10 cm – 1 m. Also called the decimeter-wave or super-ultra-short-wave band.

radio waves emitted from transmit equipment, received-electric-field-strength measurement equipment, and an E/G for supplying power. The measurement equipment at that time used vacuum tubes in the transmitter and receiver, and if operated continuously throughout the day, measurement values would vary over a range of approximately 10 dB, which required that the equipment be used while performing a level calibration every 30 minutes. The running distance of this experiment conducted twice throughout the Kanto region came to approximately 2,500 km in total.

Next, based on the results of these large-scale mobile radio wave propagation experiments, development of a commercial 800 MHz band land mobile telephone system (metropolitan system) [2] began in 1972 at the Yokosuka Electrical Communication Laboratory (Yokosuka City, Kanagawa Prefecture) of Nippon Telegraph and Telephone Public Corporation. Based on a cellular system, this development work involved the establishment of technologies as a foundation for this system. These included frequency effective utilization technology that adopted Frequency Division Multiple Access (FDMA)*7 in a frequency reuse system*8 and multiple access scheme*9 as well as radio link control technology, mobile telephone switching technology, etc. As part of this development effort, system tests were conducted in the field from 1973 to 1976.

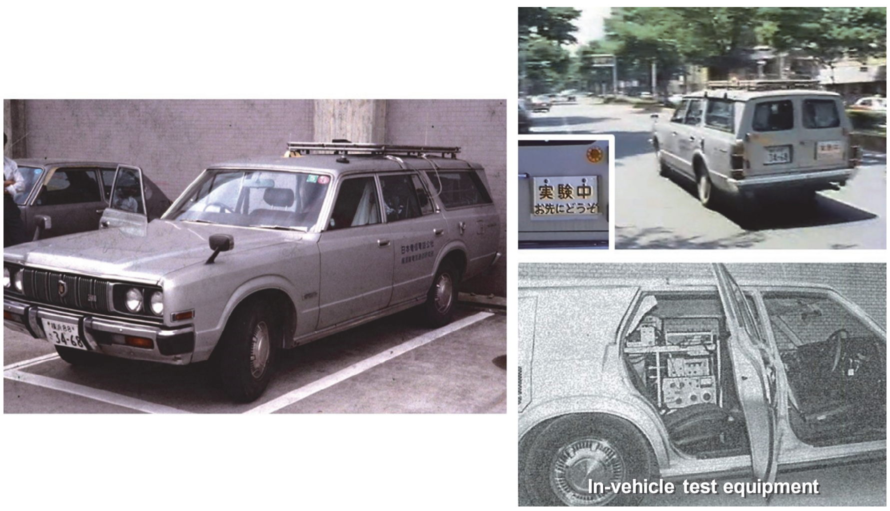
The R&D Densoku-cars used in these tests are shown in **Photo 3**. A variety of tests were conducted using a microbus vehicle (medium Densoku-car, Photo 3 (a)) that could seat seven using the Toyota Massy Dyna (medical examination car model that could carry X-ray equipment; 4-ton vehicle) as the base vehicle and a station-wagon vehicle (small Densoku-car, Photo 3 (b)) with extended space in the rear for equipment using the Toyota Crown Van as the base vehicle. The microbus vehicle was equipped with communications experimental equipment and various types of measurement equipment as well as a computer (equipment installed on the left side in the lower-right vehicle-interior photo of Photo 3 (a)) for analyzing and plotting experimental data. Power was supplied to all of this equipment from a 6 kVA E/G. The station-wagon vehicle, meanwhile, was introduced to reproduce the mounting of a mobile terminal in an ordinary passenger vehicle with the same antenna height and to evaluate the effects of noise when using the car phone (noise in both the high-frequency band and voice band). This type of vehicle was also used in system tests of a small and medium-sized urban system such as for regional cities with a small subscriber base.

On completion of development, the metropolitan system began commercial services in Tokyo's 23 wards in December 1979 as a car phone service (voice call service), and the small and medium-sized urban system began service in Hiroshima, Gifu, and Sendai in March 1983. Following this, portable shoulder phones and hand-held mobile phones were commercially introduced in 1985 and 1987, respectively. Continuing on, a practical large capacity system [3] that could accommodate five times as many subscribers as the previous system was developed to meet increasing demand with commercial services launched in 1988. Then, in 1991, the super-compact portable telephone "Mova" [4] having a terminal size

*7 FDMA: A multiple access scheme in the frequency domain that divides a wide frequency band allocated to a system into multiple narrow band radio channels each of which can be used independently by a different user as a communication channel.

*8 Frequency reuse system: A system for making effective use of limited radio frequency resources in a cellular system by repeating and reusing the frequency used by a certain base station (cell) in another cell located at a certain distance away to avoid inter-cell interference. This scheme divides the entire frequency band allocated to the system into a single group of $N$ frequency bands and repeats those frequency bands across the entire system in such a way that cells using the same frequency band are not adjacent. (As a typical example, $N = 7$ corresponds to 7 reused frequencies.)


(a) Microbus Densoku-car and test scene




(b) Station-wagon Densoku-car and test scene

**Photo 3 Densoku-cars used in R&D of 1G (metropolitan system and small and medium-sized urban system)**

of only 150 cc was commercially introduced.

## 3.2 2G

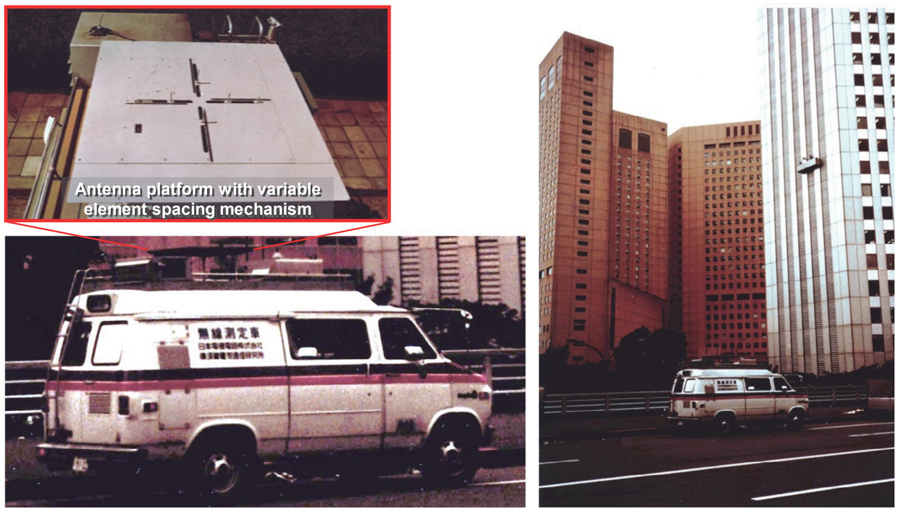
Around the time that 1G was introduced, initial studies on the next-generation system began. In 1987, with the aim of increasing system capacity and improving voice quality beyond 1G and achieving new services such as facsimile and data communications in addition to voice call services, R&D of the second-generation mobile communications system (2G), namely, the Personal Digital Cellular (PDC) system*10 [5] using Time Division Multiple Access

*9 Multiple access scheme: In a mobile communications system, a system that enables a base station to accommodate multiple users (mobile terminals) and that enables each terminal to correctly send/receive information without mutual interference when those terminals are simultaneously performing radio communications with that base station. Methods exist for allocating radio resources to each user by dividing them into time, frequency, and other domains, and various schemes have been adopted in each generation's system to accommodate even more terminals using limited radio frequency resources such as methods that combine multiple domains.

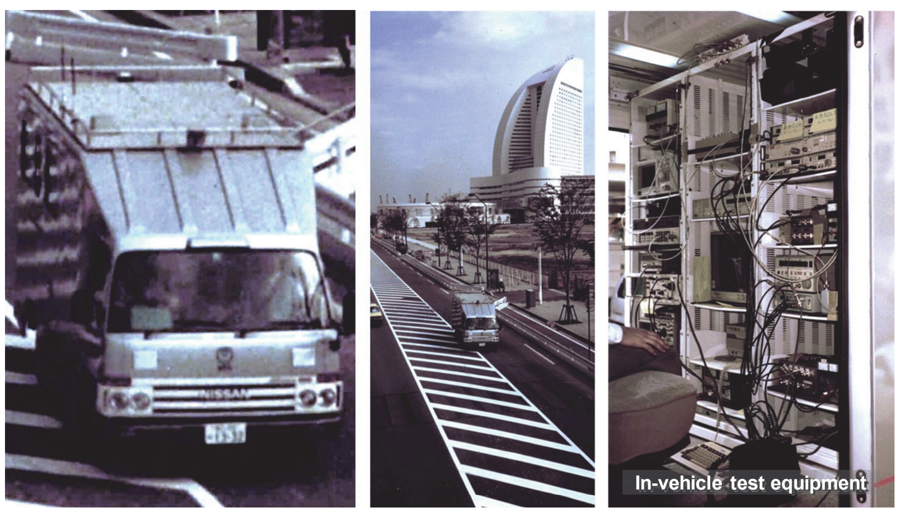
*10 PDC system: A second-generation mobile communications system widely used in Japan adopted by NTT DOCOMO and others.

(TDMA)*11, began in earnest and a variety of mobile radio field experiments were conducted the same as in 1G.

**Photo 4** (a) shows a view of an experiment conducted in 1989 in the vicinity of Shinjuku ward, Tokyo on achieving high-quality transmission by combining Quaternary Differential Phase-Shift Keying (QDPSK)*12, a digital transmission system, and selective receive diversity*13. The base vehicle for the R&D Densoku-car used here was the General Motors (GM) Chevy Van (Chevrolet brand) from the United States. This vehicle (small Densoku-car)




(a) Small Densoku-car and QDPSK digital transmission experiment




(b) Medium Densoku-car and system test

**Photo 4 Densoku-cars used in R&D of 2G (PDC system)**

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*11 TDMA: A multiple access scheme in the time domain that divides a single radio channel having a prescribed frequency band into multiple fixed time intervals (time slots) each of which can be used independently by a different user as a communication channel.

*12 QDPSK: As a phase-shift keying (phase modulation) system that modulates transmission digital data in the phase domain of the radio signal, a system that uses four phase states per symbol and that reflects data in the phase difference between symbols. In communications via a mobile radio wave propagation path in which amplitude and phase fluctuate greatly due to the fading phenomenon, QDPSK can improve communications quality compared with systems using absolute phase.

incorporated an E/G and a roof-mounted platform for installing antennas equipped with a mechanism for varying the spacing between multiple antenna elements. The reason for using an American vehicle as the base vehicle was that there was no suitable Japanese vehicle at that time that could install prototype equipment for such a communication experiment and an E/G to provide the power supply capacity required for operating that equipment, and that could also drive smoothly considering road conditions in a downtown district.

On approaching the last phase of 2G R&D, a series of mobile radio field experiments were conducted from 1990 to 1992 in Yokohama City, Kanagawa Prefecture near Yokohama Station and in the Minatomirai district. The base vehicle for the main R&D Densoku-car used in these experiments was the Nissan Atlas (4-ton truck) shown in Photo 4 (b). This vehicle (medium Densoku-car) was equipped with a box-shaped measurement room, experimental/measurement equipment racks, E/G, etc. The experimental/measurement equipment racks (Photo 4 (b), right) consisted of three standard racks for electronic equipment forming an integrated unit. The vehicle was equipped with a mechanism for moving this integrated rack unit back and forth on rails embedded in the floor or keeping it fixed depending on the types of equipment accommodated and the target experimental/measurement items.

Commercial services for 2G (PDC system) began in March 1993. Then, in March 1997, commercial services [6] began for the PDC packet system (maximum 28.8 kbps) achieving three times the digital data bit rate of PDC system, and in February 1999, "i-mode" services [7] enabling Web access, mail, etc. began using the same system.

## 3.3 3G

Research into the third-generation mobile communications system (3G) got under way at about the same time as the completion of 2G development. After comparing and studying multiple candidates, the multiple access scheme chosen for 3G was one based on Code Division Multiple Access (CDMA)*14. It was the wideband coherent Direct Sequence-CDMA (DS-CDMA) [8] featuring wideband radio transmission using the newly allocated 2 GHz band (system employing this scheme, came to be called "Wideband-CDMA (W-CDMA) system*15" later). This system widens the radio frequency bandwidth up to a maximum of 5 – 10 MHz, which makes it easy to separate/combine the paths generated by radio wave propagation in an urban setting (multipath*16 phenomenon) and to achieve high-speed and high quality data transmission. A series of mobile radio field experiments were conducted in Funabashi City, Chiba Prefecture starting in 1994 to check the effect of bandwidth widening in a real environment, evaluate video transmission by maximum bit rates of 384 kbps – 2 Mbps, and test newly adopted technologies such as fast power control and soft handover*17.

**Photo 5** (a) shows the R&D Densoku-car used in the initial mobile radio field experiments of the wideband coherent DS-CDMA system featuring the new NTT DOCOMO logo. The base vehicle for this Densoku-car was the Nissan Atlas used in

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*13 Diversity: Technology for suppressing the fading phenomenon (a significant drop off in the received signal level) during terminal movement in a multipath environment by combining or selectively using different fluctuating components obtained by giving the transmit/receive signal redundancy thereby reducing the probability of a drop off in the received signal level and improving radio transmission quality. There are various types of diversity such as space diversity, frequency diversity, and time diversity depending on the domain used to give redundancy.

*14 CDMA: A multiple access scheme in the code domain that enables simultaneous communication by multiple users on a radio channel of the same frequency band and time slot by multiplexing a spread spectrum communication channel using different orthogonal code streams for each user.

*15 W-CDMA system: The name given to the third-generation mobile communications system (3G) that was made into international standardized specifications at 3GPP.


(a) Medium Densoku-car and wideband coherent DS-CDMA experiment


(b) Newly deployed medium Densoku-car and 384 kbps – 2 Mbps transmission experiment

Photo 5 Densoku-cars used in R&D of 3G (W-CDMA system)

*16 Multipath: The phenomenon in which a radio signal emitted from a transmission point arrives at the reception point over multiple paths due to its reflection and diffraction off of obstacles such as buildings and topographical features.

*17 Soft handover: In handover control that automatically switches a user (mobile terminal) in the middle of a call to the base station of a different cell that the user has crossed into, a method of moving between cells with no momentary interruption by simultaneously connecting to multiple base stations in the area near cell borders and combining and receiving the signals from those base stations. In contrast, the method that performs only cell switching without simultaneous connections near cell borders is called "hard handover."

the 2G system tests described above. This vehicle was later replaced by a new type of Densoku-car as shown in Photo 5 (b) for use in transmission experiments up to 2 Mbps considering the need for loading large experimental equipment and conducting long-term experiments by running the Densoku-car. This new vehicle (medium Densoku-car) used the Isuzu Elf (3.5-ton truck) as its base vehicle and came equipped with a measurement room in the vehicle's rear body molded with safety (strength), insulation, and attractive design in mind, a low-noise E/G, and air conditioning equipment as well as air suspension to lessen vibration during vehicle running. This vehicle also added dedicated doors for loading/unloading large experimental equipment and introduced for the first time an equipment-fixing base with rails so that equipment could be slid in from the side of the vehicle using a dedicated lift, a mechanism for directly connecting various types of experimental antennas installed outside the vehicle to experimental equipment, and other auxiliary equipment (described later). This new type of Densoku-car continued to be used or additionally deployed across system generations and the seventh version of this vehicle is currently seeing active use in field experiments.

Commercial services [9] for the 3G (W-CDMA) system began in October 2001 (maximum bit rate at the time of service launch was 384 kbps). This was followed by the launch of commercial services for the High-Speed Downlink Packet Access (HSDPA)*18 system [10] in August 2006 (maximum bit rate on the downlink at the time of service launch was 3.6 Mbps; this was successively increased and the provision of a bit rate of 14 Mbps began in June 2011) and for the High-Speed Uplink Packet Access (HSUPA)*19 system in June 2009 (maximum uplink bit rate of 5.7 Mbps).

### 3.4 4G

Prototyping of radio access experimental equipment toward the fourth-generation mobile communications system (4G) began in 2002, the year following 3G commercialization [11]. Here, to expand the radio frequency bandwidth to achieve high-speed packet communications in the downlink of 100 Mbps and to eliminate the effects of multipath mutual interference and frequency selective fading*20 that tend to increase due to band widening, NTT DOCOMO adopted Orthogonal Frequency Division Multiple Access (OFDMA) as the base radio access system for 4G. This system divides the downlink signal into multiple narrow-band signals to perform multicarrier transmission*21. Using prototype equipment developed for the purpose of verifying the system, 100 Mbps transmission experiments were conducted in mobile radio field experiments from May 2003.

**Photo 6** (a) shows the medium Densoku-car (Isuzu Elf) used in these experiments conducted in Yokosuka City. Using the previously described mechanism for sliding in experimental equipment from the side of the vehicle, these experiments were conducted by reloading multiple types of mobile station experimental equipment.

In May 2005, a real-time packet-signal transmission experiment [12] achieving a maximum downlink bit rate of 1 Gbps with a 100 MHz bandwidth was

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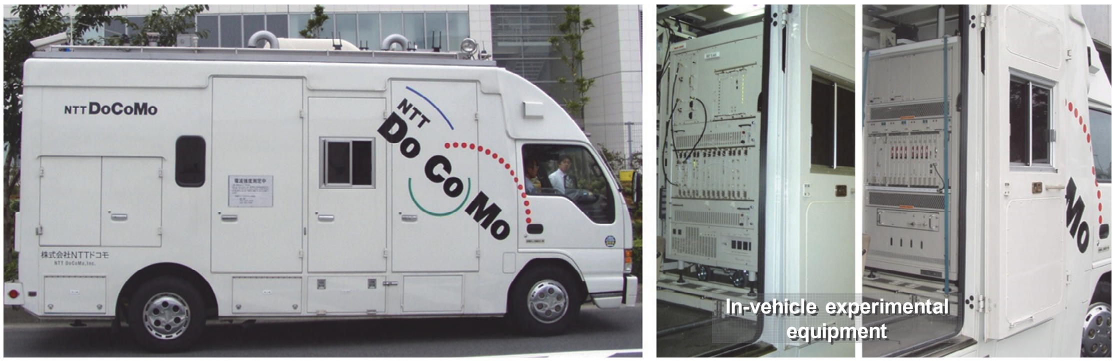
*18 **HSDPA**: A high-speed packet transmission system on the downlink based on W-CDMA. The maximum downlink bit rate in the 3GPP standard is approximately 14 Mbps. It optimizes the modulation system and code rate according to the signal reception conditions of the mobile terminal.

*19 **HSUPA**: A high-speed packet transmission system on the uplink based on W-CDMA. The maximum uplink bit rate in the 3GPP standard is 5.7 Mbps. It optimizes code rate, spreading factor, and transmission power according to the signal reception conditions at the base station.

*20 **Frequency selective fading**: Refers to the state of a radio propagation path having multipath characteristics in which the power level on the frequency axis of the received signal is not uniform.

*21 **Multicarrier transmission**: A method for transmitting digital data in parallel using multiple carriers (carrier waves). Orthogonal Frequency Division Multiplexing (OFDM) is a typical example of a system using multicarrier transmission, which has come to be used in many recent radio systems including mobile communication systems from LTE on as well as wireless LAN, digital TV, etc.




(a) Medium Densoku-car and 100 Mbps transmission experiment


(b) Newly deployed large Densoku-car and 1 Gbps transmission experiment


(c) Medium Densoku-car and Super 3G system experiment

Photo 6 Densoku-cars used in R&D toward 4G successfully conducted. The experimental equipment used here applied a system that combined 4 × 4 Multiple-Input-Multiple-Output (MIMO) multiplexing technology*22 and 16 Quadrature Amplitude Modulation (QAM) higher-order modulation technology*23 with the base OFDMA radio access system. Then, in December of the same year, a packet-signal transmission experiment achieving a maximum downlink bit rate of 2.5 Gbps was successfully conducted by extending the radio access system to 6 × 6 MIMO multiplexing and 64QAM, and in December 2006, a subsequent transmission experiment [13] achieving a maximum downlink bit rate of 5 Gbps was successfully conducted by applying 12 × 12 MIMO multiplexing.

Next, to deal with the further increase in equipment size in this series of Gbps-class transmission experiments, a new vehicle (large Densoku-car) based on the Isuzu Forward (8-ton truck) was deployed and used in mobile radio field experiments as shown in Photo 6 (b). This vehicle could install two rows (front-and-rear) of experimental equipment in the measurement room. In terms of vehicles used for communication experiments, this vehicle was the largest yet. It was also equipped with a 20 kVA-class large-capacity E/G and an Uninterruptible Power Supply (UPS) to provide a stable supply of power to radio access equipment performing high-speed and advanced signal processing and to various types of equipment for demonstrating parallel transmission of multiple video streams using high-speed transmission.

In addition to the above, NTT DOCOMO proposed the Super 3G concept [14] to the world in November 2004. The idea behind this concept was to enable a smooth transition to 4G while maintaining a long-term competitive edge in 3G technology. The development of an experimental system for testing Super 3G began in 2006, and after conducting basic indoor experiments, mobile radio field experiments in the vicinity of Yokosuka City and Kofu City, Yamanashi Prefecture began in February 2008 using a medium Densoku-car (Isuzu Elf) as shown in Photo 6 (c). A maximum bit rate of approximately 250 Mbps on the downlink was confirmed by these field experiments. The same experimental system assessed the utility and effectiveness of Super 3G toward commercialization using a variety of applications such as voice/image transmission and games.

Super 3G was standardized as Long Term Evolution (LTE) in 3rd Generation Partnership Project (3GPP) specifications in March 2009 and commercial services in Japan [15] began in December 2010 (maximum bit rate on the downlink at the time of service launch was 75 Mbps; this was successively increased doubling to 150 Mbps by October 2013). Then, in March 2015, the PREMIUM 4G [16] commercial service was launched using LTE-Advanced, a further development of LTE, that applied new high-speed, large-capacity technologies such as carrier aggregation*24 and Advanced Centralized Radio Access Network (C-RAN)*25 (maximum bit rate on the downlink at the time of service launch was 225 Mbps; this was successively increased reaching 1.7 Gbps by March 2020).

## 3.5 5G

R&D on the fifth-generation mobile communications

*22 **MIMO multiplexing technology:** Signal transmission technology that simultaneously transmits different information signals from multiple antennas using the same frequency and receives the signals by multiple antennas through spatial multiplexing on the radio wave propagation path.

*23 **QAM higher-order modulation technology:** One example of a technology that converts digital data to a radio transmission signal with high efficiency. A 16QAM conversion, which represents the signal after conversion by 16 combinations of different phases and amplitudes, can transmit 4 bits of information in one transmission symbol.

*24 **Carrier aggregation:** A key radio access technology in LTE-Advanced that enables high-speed communication by bundling multiple frequency bands (carriers).

*25 **C-RAN:** Network architecture that centralizes the control functions of multiple base stations.

system (5G) began in 2010, the year of LTE commercialization, with the aim of achieving a system having features such as high-speed and large-capacity transmission, low latency, and massive connectivity. In December 2012, a basic experiment in packet signal transmission achieved a maximum bit rate of approximately 10 Gbps using experimental equipment that increased bandwidth in the 11 GHz band to 400 MHz (four times that of LTE-Advanced) while applying 8 × 16 MIMO multiplexing technology [17].

A mobile radio field experiment conducted in Ishigaki City, Okinawa Prefecture using this experimental equipment showed that the target of ultra-high-speed communication exceeding 10 Gbps by 5G could be achieved. This was accomplished by loading a mobile station (transmission equipment and antennas) onto a vehicle (small Densoku-car) based on the Toyota Estima (hybrid car) as shown in **Photo 7** and conducting broadband radio transmission using high frequencies above 6 GHz that had so far been considered difficult to use considering radio wave propagation characteristics in prior mobile communication systems. In addition, the equipment used in this experiment was supplied power through a configuration that used a 1.5 kVA power supply output from the hybrid-car battery and power from an additionally mounted battery to make up for any deficiencies in power. This configuration made it possible to avoid the noise caused by loading an E/G when driving the Densoku-car through residential streets on the test course.

The full-scale R&D stage for 5G got under way in 2014. At this time, a number of frequency bands were being considered as candidates for 5G frequencies including those from the low Super High Frequency (SHF) band*26 such as 3.7 GHz and 4.5 GHz—which were slightly higher than the current 4G frequencies—to the high SHF band such as 15 GHz and 28 GHz and the even higher Extremely High Frequency (EHF) band*27 such as 39 GHz and 70 GHz. Parallel experiments on radio access technologies in each of these frequency bands were conducted in collaboration with leading vendors from around the world [18].

The low SHF experiments included a transmission field experiment of a distributed antenna system*28 using the 4.5 GHz band and a mobile radio field experiment of a Massive MIMO system*29 in



**Photo 7 Small Densoku-car and 10 Gbps transmission experiment**

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*26 **SHF band:** Frequency band in the range of 3 – 30 GHz with wavelengths of 1-10 cm. Also called the centimeter-wave band.

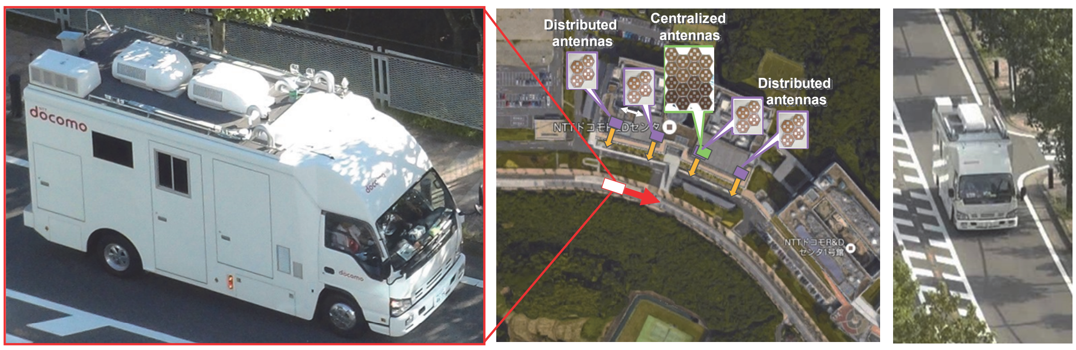
*27 **EHF band:** Frequency band in the range of 30 – 300 GHz with wavelengths of 1-10 mm. Also called the millimeter-wave band (or mmWave as a popular name).

*28 **Distributed antenna system:** A system that can increase communication performance and capacity by connecting multiple geographically distributed antenna units to central-processing (concentrated-processing) equipment via optical fiber and performing integrated signal processing at that equipment.

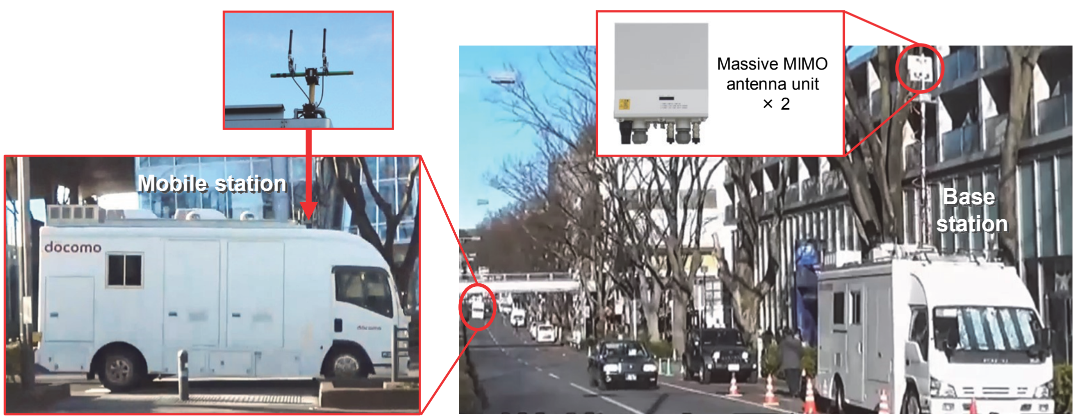
*29 **Massive MIMO system:** A system using large-scale MIMO configured with an ultra-large number of antenna elements. Antenna-element size can be made small in a high-frequency band, so the deployment of this system is being promoted in 5G that uses even higher frequency bands (SHF band – EHF band) than past generations. Corresponds to a centralized antenna system in contrast to a distributed antenna system.

the same 4.5 GHz band with digital beam forming[*30] and beam tracking[*31]. Specifically, in experiments conducted in Yokosuka City and Tokyo in 2016 and 2018, mobile station equipment was loaded onto the medium Densoku-cars (Isuzu Elf) shown in **Photos 8** (a) and 8 (b) to conduct mobile experiments. The beam-tracking field trial was conducted using a medium Densoku-car (Isuzu Elf) parked with permission on the side of the road. This vehicle was equipped with a Massive MIMO base station in which the main unit of the base station was installed inside the vehicle and a Massive MIMO antenna unit[*32] (64 elements × 2) was mounted on an extendable pole.

The high SHF band experiments included high-speed mobile 5G beam-forming communication experiments using the 28 GHz band and a communication experiment using vehicle-mounted 5G glass antennas. First, in an ultra-high-mobility experiment conducted on a racing course (Shizuoka Prefecture) in 2016, the main unit of 28 GHz band mobile station equipment equipped with analog beam forming[*33] was installed inside the small Densoku-car (Toyota Estima) shown in **Photo 9** (a) while the antenna unit




(a) Medium Densoku-car and 4.5 GHz distributed antenna system experiment




(b) Multiple medium Densoku-cars and 4.5 GHz digital beam forming transmission experiment

**Photo 8 Densoku-cars used in R&D of 5G, (1)**

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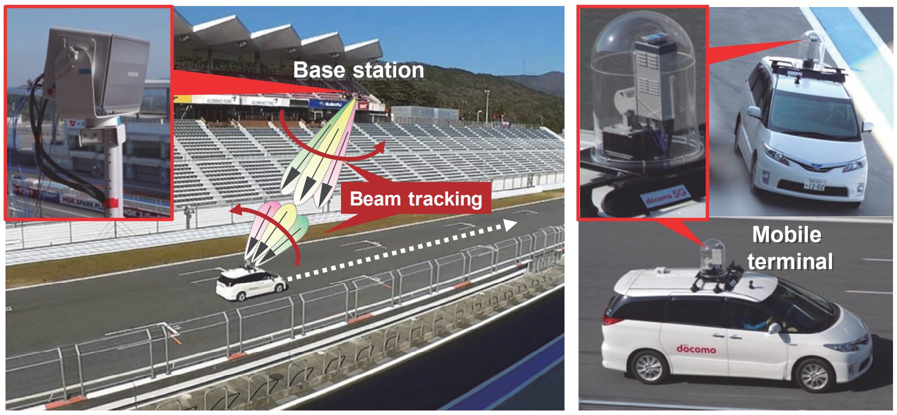
*30 Digital beam forming: A system that uses digital signal processing to achieve a function for concentrating signal radiation in a specific direction (beam forming) using an antenna configured with an ultra-large number of elements.

*31 Beam tracking: A function for following and controlling the radiated direction of a signal subjected to beam forming so that it matches the direction of a moving terminal.

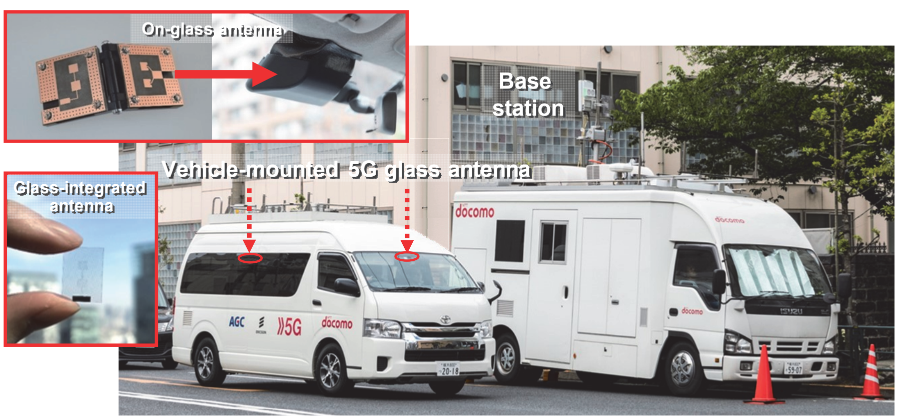
*32 Antenna unit: One piece of equipment for configuring a base station. It integrates the functions for converting the digital signal to be transmitted/received to a radio signal, amplifies the radio signal, and transmits/receives radio signals via the antenna elements.

*33 Analog beam forming: A system that uses analog signal processing to achieve a function for concentrating signal radiation in a specific direction (beam forming) using an antenna configured with an ultra-large number of elements.




(a) Small Densoku-car and 28 GHz band analog-beam-forming ultra-high-mobility experiment


(b) Small Densoku-car and 28 GHz band digital-beam-forming ultra-high-mobility experiment




(c) Small/medium Densoku-cars and 28 GHz band vehicle-mounted glass-antenna communication experiment

Photo 9 Densoku-cars used in R&D of 5G, (2) for the mobile station was installed inside a transparent dome (windproof structure) attached to the roof of the vehicle. In this way, a beam tracking experiment was conducted at speeds of up to 150 km/h envisioning calls while riding high-speed express trains. Next, in an experiment conducted on a test track (Ibaraki Prefecture) in 2020 as part of a millimeter-wave R&D project*34, the mobile station of a 28 GHz band communication-experiment system was installed in the small Densoku-car (Toyota Alphard) shown in Photo 9 (b). This mobile station was equipped with digital beam forming capable of even more accurate beam tracking plus an inter-base station coordination function. In short, an experiment was conducted of a new system that could achieve stable and high-quality communication while overlapping multiple base stations even for automobiles driving on an expressway. In addition, the 28 GHz band communication experiment using vehicle-mounted 5G glass antennas was conducted in an urban area (Sumida Ward, Tokyo) in 2019. In this experiment, the main unit of 28 GHz band mobile station equipment was installed inside the small Densoku-car (Toyota HiAce) shown in Photo 9 (c) while vehicle-mounted 5G glass antennas (two types: glass-integrated antenna*35 and on-glass antenna) were installed on vehicle windows in four places. This mobile radio field experiment conducted at speeds of approximately 30 km/h successfully achieved high-speed radio data transmission at maximum bit rates on the downlink of 3.8 Gbps (400 MHz bandwidth) and 7.5 Gbps (800 MHz bandwidth) [19]. Here, in addition to this mobile station, the main unit of base station equipment was installed inside a medium Densoku-car (Isuzu Elf) parked with permission on the side of the road and a Massive MIMO antenna unit (128 elements × 2 polarization*36 directions) was mounted on an extendable pole (Photo 9 (c)).

In 2017, NTT DOCOMO began its participation in "5G Comprehensive Demonstration Tests (5G Field Trials)*37" of the Ministry of Internal Affairs and Communications (MIC) to test the feasibility of new mobile solutions using 5G in diverse usage fields. This involved the loading of application-oriented equipment such as experimental 5G mobile terminals and high-definition video equipment onto R&D Densoku-cars. For example, in 2018, in the smart workplace field, a test was conducted in Kamiyama Town, Tokushima Prefecture of a "mobile satellite office" (using a small Densoku-car) for performing video editing work while sharing large-capacity content data using 5G [21]. Then, in 2020, in the regional healthcare field, a test was conducted in Wakayama Prefecture of a "mobile health clinic" (using a large Densoku-car) that supports remote medical care while sharing multiple diagnosis video streams [22] (**Photo 10**).

Additionally, from 2019 on, after accelerating the development of mobile terminals and base station equipment toward 5G commercialization and conducting indoor tests, NTT DOCOMO conducted a series of mobile radio field experiments in a variety of communication environments from urban to suburban areas. Then, after the launch of the 5G Pre-commercial Service [23] in September 2019, the 5G commercial service [24] was launched in March 2020 (providing a maximum bit rate on

*34 Millimeter-wave R&D project: "R&D for Expansion of Radio Wave Resources (JPJ00024)" conducted by NTT DOCOMO from FY2018 – FY2020 on consignment from the Ministry of Internal Affairs and Communications (MIC).

*35 Glass-integrated antenna: A compact, thin, and transparent glass antenna installed in vehicle windows without obstructing the driver's field of vision or detracting from the vehicle design.

*36 Polarization: Direction of electric-field oscillation when a radio wave propagates through space. A frequently used configuration when transmitting and receiving radio waves from base station antennas consists of both vertical polarization and horizontal polarization in which the electric field vibrates in a plane vertical to the ground and horizontal to the ground, respectively.

the downlink of 3.4 Gbps using the 3.7/4.5 GHz band). After this, an increasing number of models of 5G-compatible mobile terminals began to appear, and in September 2020, services providing a maximum bit rate on the downlink of 4.1 Gbps began using the 28 GHz band for the first time.

Then, in parallel with the spread of the COVID-19 infectious disease from April 2020 on, communication connection tests performed in the field using an R&D Densoku-car as part of the development process for new 5G terminal models were modified so that the collection and analysis of test data (that had previously been performed by a number of measurement personnel within a Densoku-car) could be done from a remote site (**Photo 11**). These tests continue in this form to mitigate the risk of infection.

## 4. R&D Densoku-cars for Special Experiments

This section introduces R&D Densoku-cars for ultra-high-mobility communication experiments and radio wave propagation experiments as Densoku-cars equipped with the functions needed to conduct special experiments and measurements.

### 4.1 R&D Densoku-cars for Ultra-high-mobility Communication Experiments

In April 2018, NTT DOCOMO conducted simulation experiments with a running vehicle on the


**Photo 10　5G Field Trials by small/large Densoku-cars**


**Photo 11　Remote testing of 5G commercial mobile terminals by small Densoku-cars**

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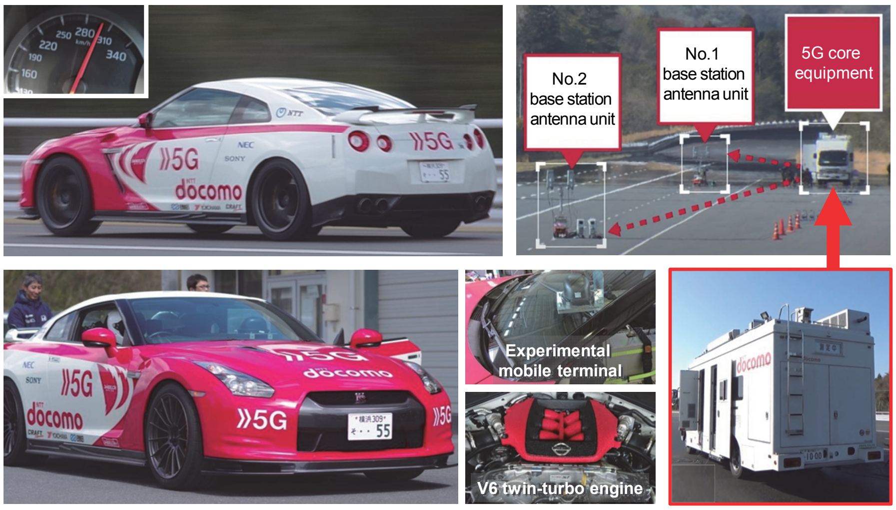
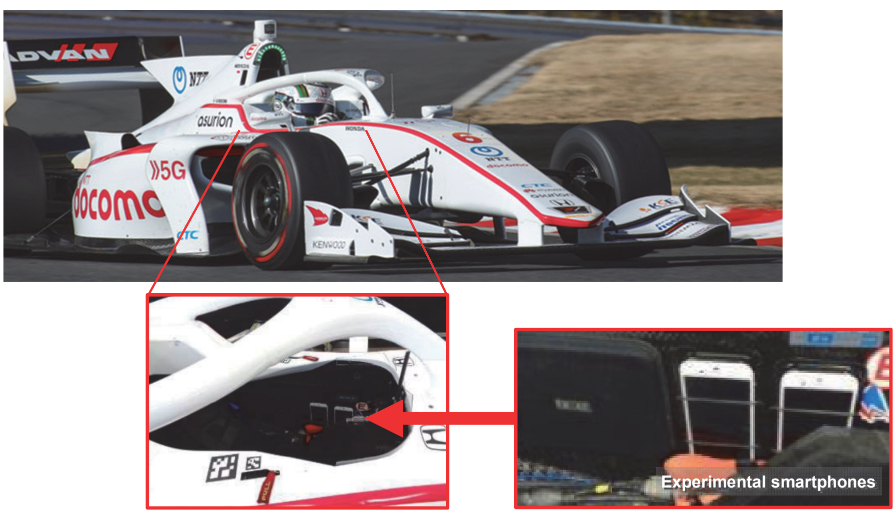
*37 **5G Comprehensive Demonstration Tests (5G Field Trials):** Tests led by MIC from FY2017 – FY2019 with the participation of mobile network operators and concerned parties in a variety of usage fields with the aim of creating new markets and new services/applications through 5G. The Fifth Generation Mobile Communications Promotion Forum (5GMF) that came to promote and support these tests has published and released reports (in English) on test results [20].

high-speed oval track of the Japan Automobile Research Institute (JARI) in Ibaraki Prefecture to emulate the provision of 5G services in an ultra-high-mobility environment such as high-speed trains moving at speeds in excess of 200 km/h [25]. In these experiments, 5G communications using the 28 GHz band were conducted between experimental mobile terminal equipment loaded on a small Densoku-car capable of running at high speeds and two experimental base stations set up beside the track (Photo 12 (a)). The base vehicle for this small Densoku-car was a specially tuned NISSAN GT-R sports car




(a) 5G communication experiments using a small Densoku-car capable of high speeds and a large Densoku-car




(b) 5G communication experiments using a formula racing car

Photo 12　Densoku-cars for ultra-high-mobility communication experiment (mounting a V6 twin-turbo engine) chosen to enable running speeds in excess of 300 km/h while carrying experimental equipment and materials having a total weight of nearly 200 kg. It was equipped with dedicated racks to hold experimental equipment safely and firmly inside the car and mounted a dedicated battery in the trunk to power equipment. These experiments also used a large Densoku-car (Isuzu Forward) to set up quasi-5G core network*38 equipment for controlling handover between the two base stations during communications.

In these experiments, 5G communications were successfully achieved between a base station and mobile station moving at a maximum speed of 305 km/h. In addition, ultra-high-mobility 5G radio data transmission with a downlink bit rate of 1.1 Gbps was successfully achieved while moving at 293 km/h, and handover, that is, switching to another base station while maintaining a radio communication link between the 5G mobile station moving at 290 km/h and a 5G base station, was likewise achieved. A 5G radio live relay of video from a car-window camera was also achieved through 4K High Frame Rate (HFR) video*39 from a 5G mobile station moving at 200 km/h.

NTT DOCOMO has worked to improve the quality of mobile communication services in ultra-high-mobility environments such as high-speed trains in each system generation. To simulate such ultra-high-mobility environments, NTT DOCOMO continues to conduct a variety of communication experiments including handover tests between small mobile terminals (mobile phones and smartphones) mounted on a formula racing car of the type that competes in Super Formula*40 open-wheel car racing (Photo 12 (b)) and peripheral base stations. These communication experiments using a formula racing car are also conducted on a race track, but here, to obtain conditions in which the car running speed, that is, the terminal moving speed, abruptly changes in a short period, the car is first made to accelerate up to 300 km/h on the straight portion of the race course, and then, when entering a curve, to decelerate suddenly to about 50 km/h. In this way, a race track facilitates the efficient collection of test data by circling the same course any number of times. It can also be used to compare and evaluate experimental data such as when adjusting parameters with the aim of improving communication performance.

## 4.2 R&D Densoku-cars for Radio Wave Propagation Experiments

**Photo 13** shows an R&D Densoku-car specialized for conducting radio wave propagation measurement experiments assuming diverse communication environments from urban to suburban. This special Densoku-car (Isuzu Elf) is equipped with two extendable poles with maximum lengths of 14 m and 24 m to enable experimental antennas to be mounted at arbitrary heights above the ground. These maximum lengths are about 2 to 3 times those of antenna-mounting extendable poles mounted on some medium Densoku-cars, which makes it possible to conduct radio wave propagation experiments for a broad range of conditions with respect to base station antenna height. While moving, the 24 m extendable pole can be horizontally

*38 Core network: A network comprising switching equipment, subscriber information management equipment, etc. A mobile terminal communicates with the core network via a Radio Access Network (RAN).

*39 4K HFR video: High-definition video with a frame rate of 120 fps double that of 4K standard frame rate video. Using a real-time 4K HFR HEVC codec [26], the experiment achieved smooth and high-presence camera video transmission even for a fast-moving scenario in an ultra-high-mobility environment.

*40 Super Formula: The top car race in Japan using formula racing cars having a structure in which tires and the cockpit are not covered by the car body. Its official name is Japanese SUPER FORMULA Championship (formerly Japanese Championship Formula Nippon). NTT DOCOMO has been conducting communication experiments since 1999 using the formula racing cars of DOCOMO TEAM DANDELION RACING [27] that competes in this race.


**Photo 13 Densoku-car for radio wave propagation experiments mounting high extendable poles**

stowed on the roof of the Densoku-car in its shortest contracted state (Photo 13, left). Additionally, when extending an extendable pole near its maximum length, experiments can be conducted while supporting the pole with auxiliary wires at the experiment site.

## 5. Auxiliary Equipment of R&D Densoku-cars

### 5.1 Power Supplies for Experimental Equipment

As a major facility in an R&D Densoku-car, the E/G supplies power to various types of experimental and measurement equipment used inside the vehicle. The Densoku-cars of successive system generations (mainly medium and large Densoku-cars) have come to be loaded with E/Gs having a wide range of power supply capacities from several kVA to 20 kVA depending on the power consumption of the equipment and devices used in the experiments. In any case, anti-vibration measures during vehicle travel, soundproofing and anti-heat measures while operating the E/G, and measures for reducing exhaust gas from the E/G were taken reflecting the concern given for tests involving the running of Densoku-cars in urban area, residential districts, etc. (Photo 14 (a)). Incidentally, for the 1G Densoku-car introduced at the beginning of this article (Photo 2), no domestically made E/G that could be used as a power supply (about 1 kVA) for loaded measurement equipment could be found at that time, so two military surplus products were obtained from the United States military. However, problems in starting up those E/Gs with a starter rope*41 and variations in output voltage made their use difficult, and it was necessary to put aside one unit for repair and inspection while loading the other unit onto the Densoku-car for use in the current experiment. Consequently, if the E/G in use should become

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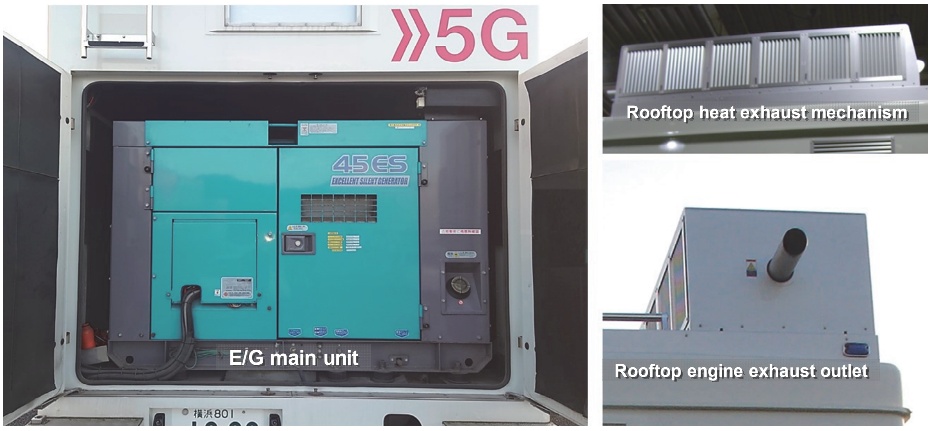
*41 Starter rope: A pull chord used in a recoil starter (manual starter) for manually starting an engine such as an engine-generator. Pulling strongly on this rope rotates the engine's crankshaft and starts the engine. Current engine-generators commonly use a system that starts the engine using a cell motor (see *42).




(a) Low-noise E/G

(b) Power-supply-system central operation panel (top), vehicle-mounted battery (bottom left), UPS and regulated power supply (bottom right)

Photo 14 Power supplies for experimental equipment

unstable, the only way to continue the experiment was to return immediately to Electrical Communications Laboratories and switch that unit with the one whose repair and inspection had been completed. The present E/G is turned over by a cell motor*42 similar to that in vehicle engines and features an automatic voltage regulation function. It is also durable enough for long-term experiments.

Furthermore, as shown in Photo 14 (b), medium and large Densoku-cars loading E/Gs from 3G on are equipped with a panel for centralized operation of the power supply system including start-up of the E/G from within the measurement room. In addition, the introduction of a vehicle-mounted battery system linked to the E/G makes it possible to deal with battery discharging. A large-capacity UPS and stabilizing power supply are also installed for vehicle-mounted equipment. Meanwhile, for small Densoku-cars, the hybrid car*43 is being actively introduced since it mounts a large-capacity battery

*42 Cell motor: A specialized motor for applying torque when starting up an engine. Also called a “starter.” The electric power for moving the motor is supplied by a battery but engine startup cannot be performed if the battery is dead.

*43 Hybrid car: A vehicle that has two sources of power: a combustion engine and electric motor. It can improve fuel efficiency by controlling the use of the engine and motor in an optimal manner depending on driving conditions. It is equipped with a dedicated battery for driving the motor that, in some models, can be used as a general-purpose on-vehicle power supply (power supply capacity of about 1.5 kVA). A model that uses a large-capacity battery and enables charging from an external power supply is called a “plug-in hybrid car,” which can significantly extend the distance that can be driven with only the motor.

that enables the vehicle itself to supply power to the equipment. By not loading an E/G in this way, NTT DOCOMO is contributing to reduced emission of $CO_2$, a greenhouse gas. Going forward, the use of electric cars and Plug-in Hybrid vehicles (PHVs) that can reduce emissions even further is desirable.

## 5.2 Mechanisms for Loading Experimental Equipment

Along with the progress made in R&D in every generation since 3G, the functionality and performance of experimental equipment has dramatically risen and equipment size has become increasingly larger. Newly deployed medium and large Densoku-cars that assume the loading of such large-scale equipment for mobile field experiments have added dedicated doors to the measurement room for loading/unloading experimental equipment and have adopted for the first time an equipment-fixing base with rails so that equipment can be slid in from the side of the vehicle using a dedicated lift (**Photo 15**). The conventional method for mounting various types of experimental equipment in a Densoku-car was to install standard racks for electronic equipment (19-inch rack[*44]) or general-purpose shelves in the measurement room beforehand, place the experimental equipment or measurement equipment on those racks or shelves, and perform the necessary wiring to assemble the experimental system. The new loading style in new Densoku-cars represents a major change over this conventional method. Instead of breaking down integrated experimental equipment in which many circuit cards or modules are incorporated in a large-scale rack (a rack wider than the 19-inch rack or two or three connected 19-inch racks), the new method loads that experimental equipment directly in its existing form. (Subsequent medium and large Densoku-cars have inherited this new style of loading equipment.)

Another adopted measure was the insertion of

**Photo 15　Equipment-fixing base with rails**

*44　19-inch rack: A rack for accommodating various types of electronic equipment with the width of each unit of equipment standardized to 19 inches (482.6 mm) (EIA standard in the U.S. and other standards). The JIS standard in Japan has adopted an equipment width of 480.0 mm but the spacing between holes for equipment mounting is common with the EIA standard (465.0 mm).

vibration-absorption rubber between the equipment-fixing base and the movable platform on the side of the vehicle to counter vibration in prototype experimental equipment requiring careful handling. Air suspension in the vehicle itself was also adopted. These measures make it possible to reduce the effects of vibration having a wide range of frequency components that arise when running the vehicle.

## 5.3 Mounting Mechanisms for Experimental Antennas

Antennas are a characteristic and important element of experiments targeting radio communication systems using radio waves, and R&D Densoku-cars are equipped with special mechanisms for mounting and using a variety of experimental antennas.

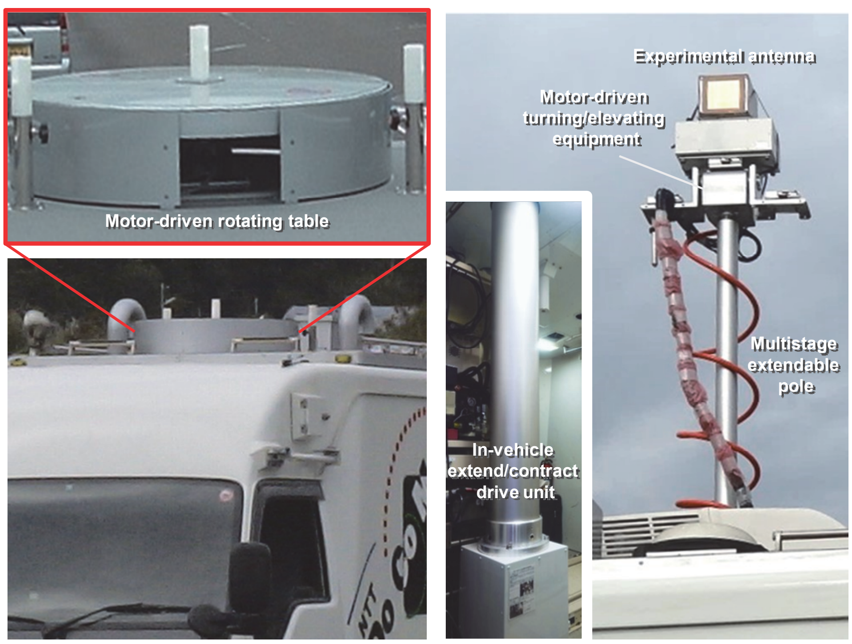
In old-model small Densoku-cars and current medium and large Densoku-cars, experimental antennas have usually been fixed to the deck installed on the roof of the vehicle (roof deck) using specialized fixtures such as magnetic bases or clamps. However, to reduce electromagnetic effects of the metallic vehicle body (including the roof section), some vehicles have been installing antennas using collapsible/projecting pipe bases or fixed projecting rail bases as shown on the left side of **Photo 16** (a) to maintain sufficient separation from the vehicle body.

Additionally, newly deployed medium and large Densoku-cars in 3G and later R&D have come to be used in experiments involving 2 GHz and higher frequencies for the first time given the trend toward higher system frequencies. These vehicles are equipped with roof pass-through pipes (inverted U-shaped pipes) for the wiring of antenna-connection cables as shown at the upper right of Photo 16 (a). These pipes enable direct connection with a relatively short cable length. They negate the need for relay connectors of high-frequency coaxial cable connecting experimental antennas outside the Densoku-car and experimental equipment inside the Densoku-car. They also make for low loss on the cable interval. Here, the reason for using an inverted-U shape is to prevent water penetration by rain or other sources while making the pipe radius large at the pass-through section on the vehicle roof.

On the other hand, small Densoku-cars (excluding some special vehicles and old-model vehicles) are equipped with a general-purpose antenna base as shown at the lower right of Photo 16 (a). For use in mobile radio field experiments, this base adopts a plug & socket attachment that makes it easy to switch antennas of different frequencies for each experiment and to compare and evaluate multiple types of antennas in the same experiment.

There are situations in which antenna installation conditions must be finely adjusted and experimented with depending on the type and content of tests targeting a radio access technology based on a new principle or scheme. Some R&D Densoku-cars are equipped with a variety of antenna-moving mechanisms to meet this need. The photos on the left side of Photo 16 (b) show a low-speed motor-driven rotating table installed on the roof of a medium Densoku-car. This mechanism can move antenna elements in a form that draws a circle on a plane surface and enables antenna interval to be varied in combination with a stationary antenna. The


(a) Various antenna mounting mechanisms




(b) Various antenna moving mechanisms

Photo 16 Mounting mechanisms for experimental antennas photo on the right side of Photo 16 (b) shows a multistage extendable pole with motor-driven turning/elevating equipment (angle adjustment mechanism) that can move and adjust the position of antenna elements or antenna unit in an up/down direction and adjust the direction of radio-wave emission from an antenna (azimuth and elevation).

In the mobile radio field experiments shown in Photos 9 and 10 using high-frequency bands in 5G R&D, antenna units integrated with the high-frequency circuit section came to be installed outside the R&D Densoku-car instead of installing antennas alone and new mechanisms (including a wind-resistant mechanism) for installing such units came to be used.

## 6. Conclusion

This article introduced with photos the R&D Densoku-cars that have supported the R&D of the mobile communication system from 1G to 5G. At present, NTT DOCOMO is promoting 5G evolution to expand upon initial 5G system technologies and drive R&D toward the sixth-generation mobile communications system (6G). Going forward, we seek to achieve a mobile communication network that can meet user expectations and gain their trust by continuing to operate vehicles of all types and sizes in the field as Densoku-cars in support of these R&D efforts while deploying both existing and upgraded vehicles. From 4G on, NTT DOCOMO has been actively involved in promoting and demonstrating new user applications and services that leverage the improved system capabilities of each generation. In addition, it has recently deployed a new category of R&D vehicles oriented to those new applications and services, but I would like to introduce those vehicles at another opportunity.

Finally, I would like to extend my gratitude to those veterans of Nippon Telegraph and Telephone Public Corporation, NTT, and NTT DOCOMO who graciously provided valuable photos of R&D Densoku-cars for this article including those used in the early R&D of the mobile communication system. In addition, I would like to use this opportunity to express my deep gratitude to all concerned at Shoden Communications Inc., Customized Vehicles Business Department (Kanazawa Ward, Yokohama City, formerly Asuka Electronics Co., Ltd), which has supported the manufacturing and maintenance of R&D Densoku-cars over many years.

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