PAPER Special Issue on Historical Review of Antenna Systems in Japan

Land Vehicle Antennas

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SUMMARY Information services for drivers and passengers in land vehicles have been drastically increasing in recent years. Frequency spectra used in vehicle communications cover an extremely wide band ranging from the LF band to the millimeter-wave band. Today, a variety of properties are required of antennas depending on the types of radio systems; more than ten kinds of antennas are installed in land vehicles. Advances in such land vehicle antennas developed in Japan are reviewed in reference to antennas for broadcasting reception and mobile communication systems. Typical antennas are introduced for each system, and the technology and performance are described.

key words: *Vehicle Antennas, Mobile Communication, ITS, Broadcasting, Train communication*

1. Introduction

Broadcasting and mobile communication systems today are indispensable not only for business activities but also personal life, and have become an important infrastructure. In the 1950s, only AM radio broadcasting was available for personal use in cars, while land vehicle radio communications were restricted to government and commercial use. However, now even FM radio and television programs can be received in cars, in addition to the AM radio. Furthermore, various mobile radio communication systems, such as mobile telephone systems, mobile satellite communication systems and so on, can be personally utilized in land vehicles. The number of mobile radio terminals has explosively increased since the middle of the 1990s; it will reach more than 70 million sets this year, while it was 4.7 million sets in 1990. The new services of Intelligent Transport Systems (ITS) using radio systems were introduced one after another, and contribute to a safer and more comfortable drive. The rise in car navigation systems using Global Positioning System (GPS) is also remarkable, and cumulative number of the navigation systems reaches nearly 10 million sets.

Recently, equipment not only for communication systems but also for sensing systems using the millimeter-wave frequency for ITS applications, such as Adaptive Cruise Control System and Collision Warning System, is being installed in cars. Consequently, frequency spectra used in the land vehicles cover an extremely wide band ranging from the LF band to the millimeter-wave band. In the early days of broadcasting and mobile communication services, only a monopole antenna was commonly used for land vehicles. However, a variety of radio communication systems are in use today and more than ten kinds of antennas not only for broadcasting and communication but also for radio control and sensing are installed in vehicles.

The antenna is a critical device which significantly affects system performance. Antennas for vehicles need to satisfy various stringent requirements. Consequently, vehicle antennas have been designed with particular attention to both radio systems and environmental conditions. Numerical analysis is very useful for this purpose, and Computer Aided Design by computer simulation is widely used in conjunction with experiments today.

Antenna systems for vehicles were reviewed in many previous references [1]–[7], and these references will be helpful to understand past development well. This paper reviews advances in vehicle mount antennas developed in Japan. In particular, technical description focuses on antenna systems for land vehicles, such as passenger cars, buses and trains. Firstly, advances in antenna systems since 1950 are summarized for each system of terrestrial broadcasting, land mobile communication, vehicle satellite communication, intelligent transport systems and train communication systems. Next, typical antennas are introduced for each system, and then the technology and performance are described, but without detail for brevity.

2. Features of Land Vehicle Antennas and Overview of Past Development in Japan

2.1 Features of Vehicle Mount Antennas

The initial consideration in the design of land vehicle mount antennas is how to maintain sufficient sensitivity of reception on the occasion of high-speed travel and rapid changes of orientation. Vehicle mount antennas are designed so that sensitivity may be kept constant. Omnidirectional antennas are generally required in radio systems for vehicles. Since high-gain antennas with a narrow beam are used for most satellite communication systems, it is necessary to track the satellite as the vehicle changes orientation.

Vehicle mount antennas are not used in isolation

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Table 1 Advances of antenna systems used in land vehicles.

		1950–1979	1980–1989	1990–
Terrestrial broadcasting (AM,FM,TV)	System (Frequency)	AM (526.5–1606.5 kHz), FM (76–90 MHz)	TV (90–108, 170–222 MHz, 470–770 MHz)	2003– Digital TV(UHF)
	Antenna [Reference]	Monopole antenna (Pole antenna)	Window glass antenna with amplifier, FM-diversity [8,9], TV-diversity [10,11]	Digital TV-Adaptive array [12]
Land mobile communication	System (Frequency)	Taxi, BusAVM (60, 150, 450MHz), Mobile telephone (800MHz)	MCA, Personal radio (800MHz)	Digital mobile telephone (800MHz, 1.5GHz), IMT-2000 (2GHz)
	Antenna [Reference]	Monopole antenna	Siersity-Sleeve dipole [13], On-glass Pole antenna [15,16], Flat plate antenna [18,19,20], Printed dipole [23]	Sleeve dipole [14], Window glass antenna [17], Flat plate antenna [21,22], Cabin antenna [24,25]
Mobile satellite communication	System (Frequency)		ETS (L-band), INMARSAT (L-band)	N-STAR (S-band), COMETS (21–47 GHz)
	Antenna [Reference]		8 elements spiral array [33], Phased array [37,38], Switched-element spherical array [36]	Quadrifilar-helix [26], Annular ring MSA [27], Dipole & Helix combination antenna [29], Bifilar-helix [28,30], 5 elements spiral array [31], 4 elements cross dipole array [32], 9 elements MSA array [34,35], Wave guide slot array [39], Torus reflector[39], Cylindrical slot array [40]
Satellite broadcasting	System (Frequency)		BS (11.7–12.2 GHz)	BS Digital
	Antenna [Reference]		MSA array [41,43], Crank line [42]	Wave guide slot array [44,47], MSA array [45], Radial waveguide + MSA array [46,48,49]
ITS communication and navigation	System (Frequency)	CACS (96 kHz)	RACS, AMTICS (800MHz), GPS (1.6GHz)	ASV, AHS, VICS (2.5GHz), ETC (5.8GHz)
	Antenna [Reference]	Loop antenna, Ferrite antenna	Quadrifilar-helix, MSA (for GPS)	MSA [50–54], IFA
ITS radar	System (Frequency)			Automotive radar (60,76 GHz)
	Antenna [Reference]			V-shape waveguide slot [6], Tri-plate antenna [55], Parallel plate slot antenna [57], NRD Guide antenna [58], Dielectric slab leaky wave antenna [59], Lens [60], MSA array [61,63], Waveguide slot [56,62]
Train communication	System (Frequency)	Inductive communication system (200kHz), Space wave radio system (150, 400MHz)	LCX communication system (400MHz)	
	Antenna [Reference]	Loop antenna, Inverted L antenna [67], Beam switching monopole array antenna [68]	Phased array antenna with 6 capacitor elements [69], Slot array antenna [70,71]	

AVM: Automatic Vehicle Monitoring, MCA: Multi Channel Access, CACS: Comprehensive Automotive Control Systems, RACS: Road Automobile Communication System, AMTICS: Advanced Mobile Traffic Communication Systems, ASV: Advanced Safety Vehicle, AHS: Advanced cruise assist Highway System.

in free space, but in complex environment with multipath and some adjacent objects. Therefore, even if an antenna has an omnidirectional radiation pattern, fluctuation of the received voltage by multipath propagation arises. Thus it is necessary to design an antenna in consideration of mitigating the fluctuation of the field strength and consequent degradation of communication quality.

Various antenna types, such as a wire type, a patch type and a slot type and arrays of those, are used on land vehicles. Since vehicle mount antennas are mostly installed in confined spaces, small size and lightweight are natural requirements. For example, a low-profile antenna or a flush-mount antenna is desirable. Further structural requirements are for robustness, temperature variation tolerance, no handicap with respect to vehicle styling, and no wind noise.

Another major problem of the vehicle environment is the influence of the adjacent objects. If the antenna element resides on or near the vehicle body, radiation current will be induced on the body near the antenna element, and the body will also work as a radiator. In most cases of vehicle mount antennas, radiation patterns and impedance characteristics are considerably changed from the isolated free space case condition for this reason. When a low profile or build-in antenna element is used inside the vehicle, the influence of the surrounding body becomes larger. The influence on the antenna element can cause both improvement and degradation in the performance. Generally, since the influence of the vehicle body causes antenna performance degradation, designs which suppress degradation as much as possible are needed.

2.2 Overview of Past Development in Japan

Advances of antenna systems used in land vehicles for each radio system are shown in Table 1 with the relevant references. It is surprising that a very wide frequency range from the LF band to 76GHz is used in radio systems for land vehicles. Next, a brief history of land vehicle antenna systems for each radio system is given.

2.2.1 Antennas for Terrestrial Broadcasting Reception

The AM radio and FM radio bands cover the frequency range of 526.5-1,606.5 kHz and 76-90 MHz, respectively, in Japan. The TV band is located within 90-108 MHz for VHF Low-channels, 170-222 MHz for VHF High-channels and 470-770 MHz for UHF channels. Polarization of radio waves in the AM band is vertical, but most of FM radio and TV stations are horizontally polarized in Japan.

Since the early 1950s, an electrically small monopole antenna (often called a "whip antenna" or "pole antenna") has been in use for AM reception. The best place to mount such antennas is considered to be the rear fender to avoid reception of electrical noise generated by the engine. However, almost all cars in Japan had a front fender antenna until around 1975 because of easiness to extend or retract the antenna from driver's seat. Although the pole antenna has very simple structure, it has the disadvantages of wind noise, durability and exterior design.

In the early 1970s, new types of antennas different from the pole antenna were introduced in the Japanese market, which overcame the above disadvantages. One was the trunk-lid antenna which uses a trunk-lid floated electrically from the car body as an antenna. Another was the wire antenna printed on a glass window (called a "window glass antenna"). The advantages of these new antennas are no need for cleaning, no danger of breaking, no handicap with respect to styling, and no wind noise. Slant pole antennas fixed to the front driver side pillar have been used for the cars without the window glass antenna since 1980, because these can be operated from the driver's seat and low cost.

Since the demand for high-fidelity audio became strong with the spread of the FM radio, diversity reception technology was introduced for reception of the FM radio in the middle of 1980s [8],[9]. The combination of two wire antenna elements printed on the rear window glass, or the combination of the rear pole antenna and the rear window glass antenna was adopted as the antenna system for FM diversity reception.

The diversity reception system for the terrestrial television was on the market in the middle of the 1980s [10],[11]. Two V-shaped pole elements were first used for TV reception. A new antenna system consisting of four antenna elements printed on the rear quarter window glass was developed in 1986. In recent years, an adaptive array antenna for terrestrial digital TV broadcasting has been developed, and high quality digital TV programs will be able to be enjoyed in cars in the near future [12].

2.2.2 Antennas for Land Mobile Communication

Since antenna systems for land mobile communication systems are to be reviewed in another paper of this special issue, only a brief history is given here. Frequency used from the 1950s to the 1970s was mainly 150MHz or 450MHz, and most antennas used on cars were a quarter wave-length monopole antenna. As the system capacity reached its limit with the rapid increase in mobile system users, the 800MHz band was allocated to mobile communication systems such as Mobile Telephone, Personal Radio and MCA systems.

Cellular mobile telephone systems in the 800MHz band started in 1979, and digital mobile telephone systems started in 1993. Currently, frequencies from the 800MHz band to the 2GHz band are assigned for mobile telephones. Diversity reception systems have been adopted to solve the multipath fading problem, which is very serious in urban areas. A variety of car mount antennas were developed in the 1980s and 1990s. Antennas used for these systems are a sleeve dipole antenna, a quarter-wavelength monopole antenna and an on-glass pole antenna, etc [13]–[16]. Further, to avoid the disadvantages of the pole antenna, low profile flat antennas, window glass antennas and cabin mount antennas have been developed [17]–[25].

2.2.3 Antennas for Vehicle Satellite Communication and Satellite Broadcasting Reception

(1) Communication

Research and development activities such as ETS and COMETS programs on mobile satellite communications have been ongoing since the middle of the 1970s in Japan. Since the early 1980s, the INMARSAT system has provided international maritime satellite communication services in the L-band (1.6/1.5GHz), and has been expanding their services to aircraft and land vehicles. Domestic mobile telephone services using the N-STAR satellite started in 1996.

Bifilar or quadrifilar helical antennas and microstrip antennas (MSA) are widely used as land vehicle antennas because of light weight and good circular polarization properties [26]–[30]. In the 1980s and the 1990s, various kinds of antennas with a mechanical tracking mechanism were developed one after another for the ETS-V program and the INMARSAT system [31]–[35]. In order to realize low profile and high speed tracking, phased array antennas for land vehicles were also developed [37],[38]. Details of the phased-array antenna are to be described in another paper in this special issue.

Several types of antennas have been developed for advanced mobile satellite communication experiments in the Ka and mm-wave bands using the COMETS satellite. One is an active phased array antenna, another is the mechanically steered waveguide slot array antenna, and the third is the mechanically steered torus reflector antenna [39],[40].

(2) Broadcasting

Direct broadcasting satellite services (BS) began in 1989. In addition, BS digital television broadcasting started in 2001. With the spread of BS broadcasting reception in homes, the demand for BS reception in land vehicles has increased. Since an antenna with high gain of approximately 30dBi is necessary, a mechanism to precisely track the BS satellite is indispensable.

The BS reception system for land vehicles was unveiled in 1988, and was mounted on buses and trains [41]. Since the dimensions and weight were still excessive for mounting on a passenger car, various planar array antennas with high efficiency and a tilted beam were studied aggressively in the 1990s. Also the noise figure of Low Noise Amplifier (LNA) was improved considerably. As a result, sufficient C/N was obtained by using an antenna with gain of approximately 21dBi to 25dBi, and the miniaturization of the vehicle mount antenna system progressed rapidly. Many sophisticated antennas have been on the market from the middle to the end of the 1990s [42]–[49].

2.2.4 Antennas for Intelligent Transport Systems (ITS)

(1) Communication and Navigation
Radio communication systems in ITS applications deal mainly with data, not voice. History of traffic information and management systems can be traced from the early 1960s when inductive communication systems were used. Although traffic information and management systems had been planned since the 1970s, radio communication means were not sufficient. For this reason, a higher frequency band (5.8 GHz) was allocated to dedicated short-range communication systems (DSRC) for ITS applications [50].

The largest market in relation to ITS applications is car navigation. In the beginning of the 1990s, car navigation systems using Global Positioning System (GPS) was introduced onto the market, and the total number shipped exceeds 9,600,000 units to date. The present car navigation system is equipped with not only GPS but also Vehicle Information and Communication System (VICS) and DSRC, etc. A helical antenna was mainly used at the beginning of the GPS service, but it has gradually been changed to a MSA [51]. The MSA using ceramic materials with a high dielectric constant is widely used today [52].

The VICS service, which started in the middle of the 1990s, provides real-time road and traffic information to drivers using three media; the radio beacon, the infrared beacon and the FM multiple broadcasting system. The 2.4GHz band is used for the radio beacon.

Electronic Toll Collection system (ETC) enables vehicles to pass through a toll gate without stopping to pay the road toll by means of the radio communication between vehicles and the toll gate facilities.

It started in 2001. This communication system is an application of the DSRC system at 5.8GHz.

Antennas for ETC or VICS are usually put on the narrow dashboard of the car. Consequently, low profile antennas such as MSA are commonly used [52],[53]; especially a high permittivity substrate is used for the VICS antenna.

(2) Automotive Radar
The system which detects obstacles or preceding vehicles in the road environment and prevents accidents due to a driver's carelessness and misjudgment is an important ITS application. Automotive radars are an indispensable key sensor in realization of important ITS applications, such as Collision Avoidance System, Obstacle Warning System and Adaptive Cruise Control, and have been actively developed since the early 1970s. In the Advanced Safety Vehicle (ASV) project, an automatic braking system using the radar to detect any danger of collision has been developed in Japan. Automotive radar development in the USA and Europe has focused on the 76GHz band, while efforts in Japan mainly focused on the 60GHz band. Today, however, the 76GHz band is used as the global standard frequency for automotive radars.

The radar sensor should be as compact and light as possible so that it may not affect the car design. Moreover, the lateral resolution ability of the radar should be less than a lane width at the maximum detection distance. For example, the beam width which illuminates one lane width (3.5m) at 100m to the front is approximately 2 degrees. An antenna aperture requires at least 9cm width at 76GHz to obtain the 2-degrees beam width, thus dimensions of the radar are mostly determined by the size of the antenna. Therefore, a flat shape array antenna with high radiation efficiency is desirable for automotive radars. Polarization diversity is used to mitigate interference by the radar signals emitted by any oncoming cars in the opposite lane. For example, 45degrees inclined linear polarization is used in many cases.

The first millimeter-wave automotive radar was developed in 1992, and was composed of a mechanical steering mechanism and a V-shaped waveguide antenna [6]. Subsequently the tri-plate planar array antenna, the waveguide slot array antenna, the NRD guide antenna and the dielectric slab leaky wave antenna, etc. have been developed for mechanical beam scanning radars [55]–[60]. Electrical beam scanning radars were proposed in the latter half of the 1990s. Antennas used in these radars are the waveguide slot array antenna and the serial fed MSA array antenna, etc. [61]–[63].

2.2.5 Antennas for Train Communication Systems

Inductive communication systems using a loop coil in the 200kHz band was used in the early communication system for trains. Similar systems are presently used as a communication system for the subway. A full-fledged train communication system started in 1965 for Tokaido and Sanyo Shinkansen (Japan Railways new bullet trains). It was a communication service by using a radio wave (Space wave radio system), which covered the whole line with the 59 base stations. An inverted L plate antenna and a directional beam switching antenna were first used for this system as antennas in the 150MHz and 400MHz bands, respectively [67],[68]. In addition, the three beam switching type using a phased array antenna with 6 capacitor antenna elements was adopted in 1985 as a new antenna system [69].

Another communication system using leaky coaxial cables (LCX system) has been used in the whole line of Tohoku and Joetsu Shinkansen since 1982 [70],[71]. It was first developed for train communication systems in a tunnel for Tokaido and Sanyo Shinkansen. The communication system of Tokaido Shinkansen also shifted to the LCX system in 1989. An advantage us-

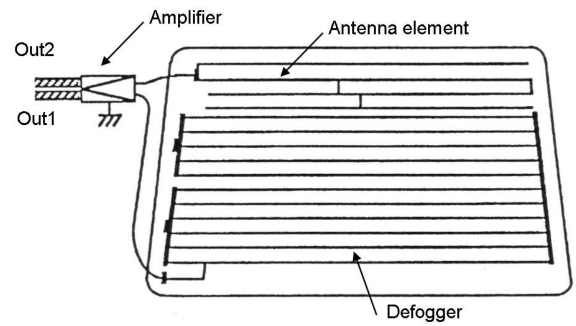


Fig. 1 Window glass antenna.

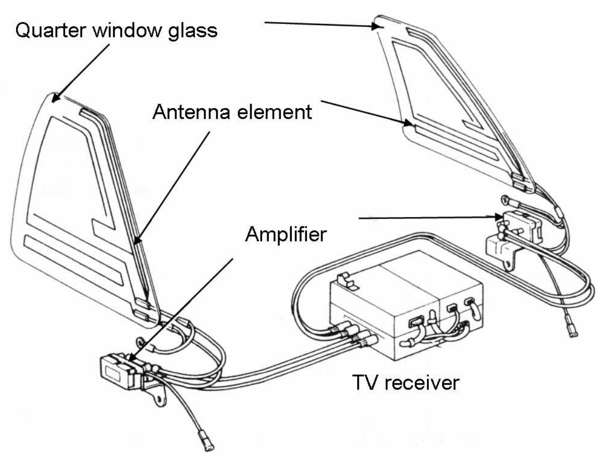


Fig. 2 Diversity antenna system for TV.

ing LCX cables can prevent unnecessary propagation compared with radio communication systems. That is, the LCX system is suitable for the special service area, such as a tunnel and an area along the railroad line. LCX cables have a slot array on its outer-conductor and radiate weak electromagnetic energy. Folded slot array antennas are used as a train mount antenna for the LCX system.

3. Land Vehicle Antennas and Technologies Developed in Japan

3.1 Antennas for Terrestrial Broadcasting Reception

The typical problems in the design of the car radio and TV antennas are to match the antenna to the receiver over the wide operating frequency range, reduction of multipath fading and to avoid the reception of noise. In the AM radio band, exact matching is impossible, since the commonly used antennas are electrically very small and thus have extremely small radiation resistance and very large reactance. As a result, matching the antenna impedance with the nominal impedance of the cable is not attempted in the AM range.

Window glass antennas have been developed to solve the pole antenna's disadvantages with respect to wind noise, durability and exterior design. Figure 1 illustrates one example of window glass antennas having AM and FM diversity reception antenna elements, and came on the market in the middle of the 1980s. Antenna elements are printed on the rear window glass, and one of the antenna elements is directly connected to a defogger (heater) element for improving its sensitivity in the AM radio band. It was difficult for the early window glass antenna to obtain sufficient sensitivity across the wide frequency band of FM radio. In the early 1980s, this problem was solved by using an amplifier as an impedance matching device.

In order to mitigate the fading distortion in reception of FM radio, window glass antennas for diversity reception system were studied and introduced into the Japanese market in the middle of 1980s [8],[9]. The combination of two wire antenna elements on the window glass and the combination of the rear pole antenna and a rear window glass antenna were used as the diversity antennas.

Vertically oriented pole antennas are not suitable for the horizontally polarized FM radio and TV signals in Japan. In the case of a pole antenna vertically mounted on a car roof, it was clear from an analysis by the wire-grid model that sensitivity to horizontal polarization was only due to the currents excited on the car body [65]. Particularly for the pole antenna mounted at a symmetrical location on the car (for example, the center of roof or trunk), remarkable degradation appears in its radiation patterns. As a result, it is obvious that the omnidirectional radiation patterns in the horizontal plane cannot be expected for FM radio and TV signals. Therefore, selection of the optimal antenna location and adoption of diversity reception are very important for reception of FM radio and TV waves.

The wavelength of the frequency band of FM radio or the Low-channel TV is close to the length of a car body. The antenna performance changes considerably due to the resonance phenomenon of the car body. Consequently, not only an antenna element but also the car body should be taken into consideration in order to design an antenna with a desired performance, especially in these bands. The Method of Moments (MOM) using the wire grid model of a car body is highly useful for the design of car radio antennas [65],[66].

Figure 2 illustrates the diversity reception antenna system for TV [10],[11]. The antenna elements are printed symmetrically on the left and right rear quarter windows of the car. The antenna consists of two parts; the slanted element consisting of three thin lines located close to rear pillars and a horizontal element printed at the center of the quarter glass. A switching diversity system was adopted because the synthetic diversity system was not so effective to suppress the multipath distortion. The switching diversity system can effectively follow changes in field strength by se-

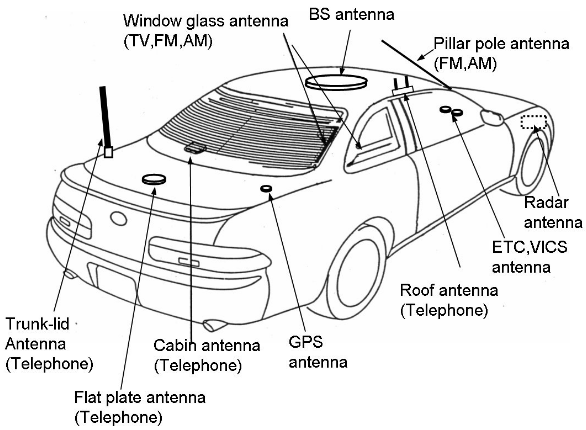


Fig. 3 Car mount antennas.

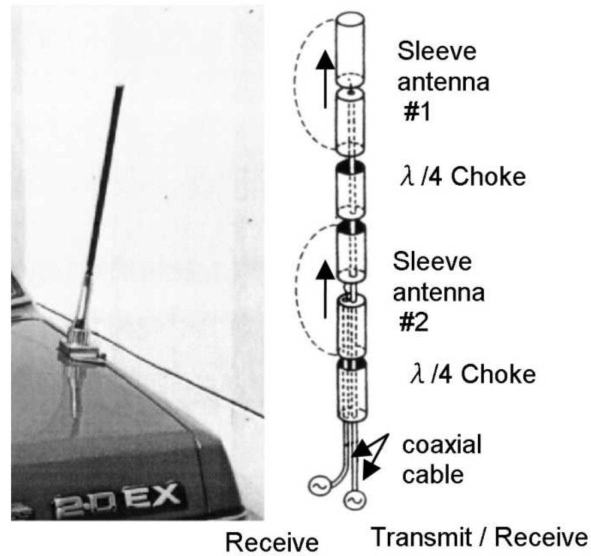


Fig. 4 Trunk mount antenna for car telephone.

lecting appropriate antennas for better reception. The antenna switching is performed during every vertical blanking period in the TV video signals.

3.2 Antennas for Land Mobile Communication

Vertical polarization is usually used in most mobile communication systems because it makes broadband omnidirectional antennas very easy to develop and mobile terminals are very near the ground. Figure 3 illustrates the typical antennas developed for mobile telephone and other communication systems. In order to cope with the problem of the multipath fading, diversity reception technology is used on car mount antennas for mobile telephone systems. Conventional 1/4-wavelength monopole antenna elements are used as a roof mounted diversity antenna. The most commonly used antenna is the trunk mount antenna which consists of two sleeve dipole antennas as shown in Fig. 4 [13],[14]. These antenna elements are arranged one on top of the other, and the feeder for the upper antenna element exists in the core of the lower antenna element. This antenna acts as a space diversity reception composition in the vertical plane, and a small correlation coefficient of less than 0.6 is achieved.

Figures 5(a) and (b) show two types of cabin mount antennas [23]–[25]. One consists of two directive antenna elements put on the front and the rear positions in the car cabin. Each antenna element has directivity in the front or the rear direction. The front side antenna element is shown in the Fig. 5(a). Radiation pattern diversity reception is performed by use of these two antenna elements and the hybrid circuit. As for the correlation coefficient, less than 0.3 is attained. The other antenna on the market is the space diversity antenna which consists of two omnidirectional antenna elements, and is put on a rear tray of the car cabin. The antenna element is a post-added monopole antenna shown in Fig. 5(b). Although the element spacing is less than 0.3-wavelength, a small correlation coefficient of less than 0.5 is obtained, and sufficient diversity reception effectiveness is realized.

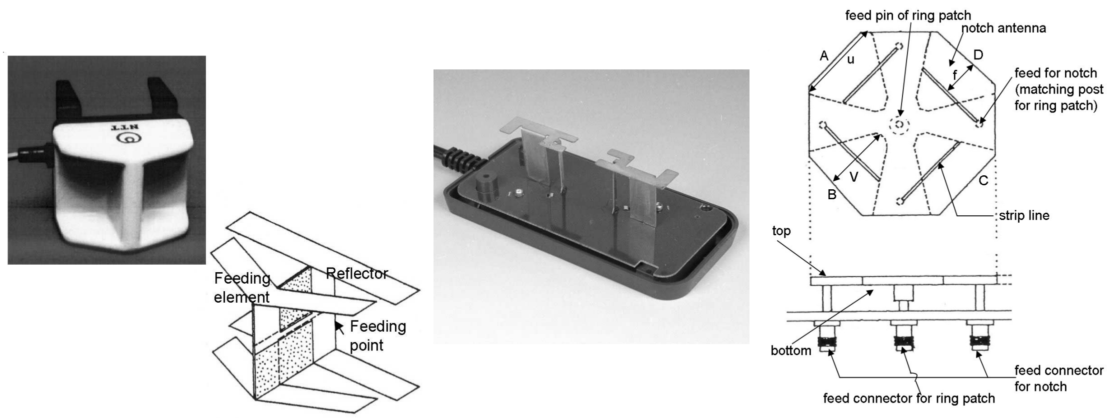
Another notable antenna is the low profile energy density antenna [21],[22]. The antenna shown in Fig. 5(c) consists of a disk loaded monopole antenna (a ring patch antenna) and four notch antennas forming a crossed slot antenna in the disk [21]. The electric field is received by the ring patch antenna, while the magnetic field is received by the notch array; as a result, the energy density reception is realized. The ring patch antenna is fed by a center probe and has four matching posts to have the same pattern as that of the monopole antenna over a wide frequency range. The notch antenna has a Fig. 8 radiation pattern shape, but an omnidirectional pattern can be realized by the four notch antenna elements and the 90 degrees phase difference excitation circuit.

3.3 Antennas for Vehicle Satellite Communication and Satellite Broadcasting Reception

(1) Communication

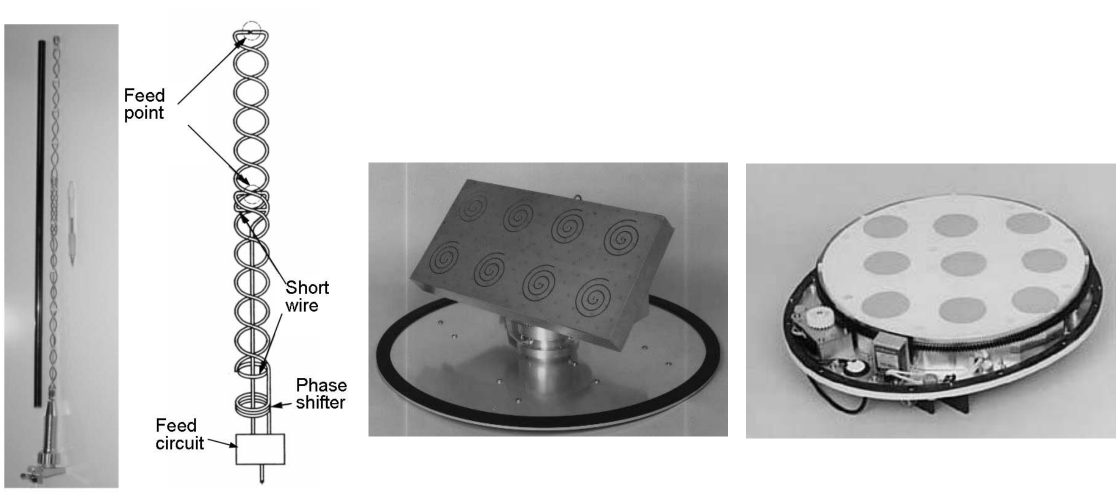
Since an axial mode helical antenna has good circular polarization characteristics over a wide frequency range, the quadrifilar helical antenna (QHA) with four two-turn helical elements is commonly used for satellite communication [26]. A high order mode microstrip antenna features a conical radiation pattern and low profile structure. It is also used as a vehicle mount antenna for satellite communication systems [27].

The maximum gain of these antennas, however, is usually less than 4dBic. In order to obtain a conical radiation pattern over the elevation range from 30 to 60 degrees, the pole-shaped antenna using the quadrifilar helix array or the bifilar helix array was developed. These antennas have the maximum gain of more than



(a) (b) (c)

Fig. 5 Antennas for car telephone. (a) and (b) Cabin mount antenna, (c) Flat energy density antenna.



(a) (b) (c)

Fig. 6 Antennas for Land vehicle satellite communication systems. (a) Bifilar helical antenna, (b) 8 elements spiral array, (c) 9 elements MSA array.

5dBic, and are utilized for the satellite telephone services of the INMARSAT and N-STAR systems [28]–[30]. Figure 6(a) shows the bifilar helical antenna for the N-STAR system. A conical radiation pattern with the wide elevation angle coverage is realized by helical elements arranged to overlap each other [30].

In order to obtain the maximum gain from 10dBic to 15dBic, mechanical beam steering antennas are considered to be the best candidates for land vehicles from a cost standpoint. Many notable beam steering antennas have been developed for vehicle satellite communication systems [31]–[35]. MSA elements and spiral elements, etc. were adopted for these systems. Figures 6(b) and (c) show two types of the mechanical tracking antennas. One is an 8 spiral elements array for the ETS-V program [33], and the other is a 9 MSA elements array for the N-STAR system [34]. These antennas have maximum gains of 15dBic and 12.5dBic, respectively. Another interesting antenna is a switched-element array antenna of 6 MSA elements [36]. It has no mechanical mechanism, and has the maximum gain of approximately 10dBic.

(2) Broadcasting

The first BS reception system developed in Japan in 1988 is shown in Fig. 7(a), and is composed of the two tilted MSA planar array antennas arranged in front and rear positions [41]. Each planar array consists of two sub-arrays (left and right). In order to track the satellite, the phase mono-pulse technique was adopted together with a gyroscope. The dimensions were 862mm in diameter, 350mm in height and 50kg in weight, and the maximum gain was 34dBic.

Required antenna gain and dimensions strongly depend on the noise figure (NF) of the front-end amplifier and antenna efficiency. In the 1990s, the miniaturization of the vehicle mount antenna system progressed as NF and antenna efficiency improved gradually, and various antenna systems were developed for train, ship, and car [42]–[49].

The following BS reception antenna systems on the market are suitable for compact cars. The antenna system shown in Fig. 7(b) has a leaky waveguide slot array antenna with beam tilt of 50.5 degrees [47]. Since this thin array antenna is installed horizontally, it is possible to make the antenna system low profile. The beam width in the vertical plane is wider than the horizontal one. The antenna section mechanically rotates only in the horizontal plane to track the satellite. The maximum gain of the array antenna within the BS band is 26.7dBic and the antenna efficiency is more than 70%. The dimensions are 550mmX450mm in width, 90mm in height and 8kg in weight including the radome.

Figure 7(c) shows another type of BS reception system. Further miniaturization and lower profile are possible for an antenna system mounted on compact cars [48]. High efficiency and tilted beam have been realized by the combination of the radial waveguide and the annular ring microstrip array. The antenna structure becomes drastically simpler because the circular shape of the radial waveguide is suitable for the horizontally rotating antenna section. Furthermore, a feeding circuit without the conventional rotary joint and the direct drive mechanism rotating the array antenna itself contribute to simplifying the antenna structure. The array antenna has the maximum gain of 25.1dBic with tilted beam and an efficiency of 70%. The dimensions of the antenna system including the radome are 400mm in diameter, 29mm in height and 3.3kg in weight. Another model of this antenna system on the market, which also includes the BS receiver in the antenna radome, is 400mmX400mm square, 60mm in height and 5kg in weight.

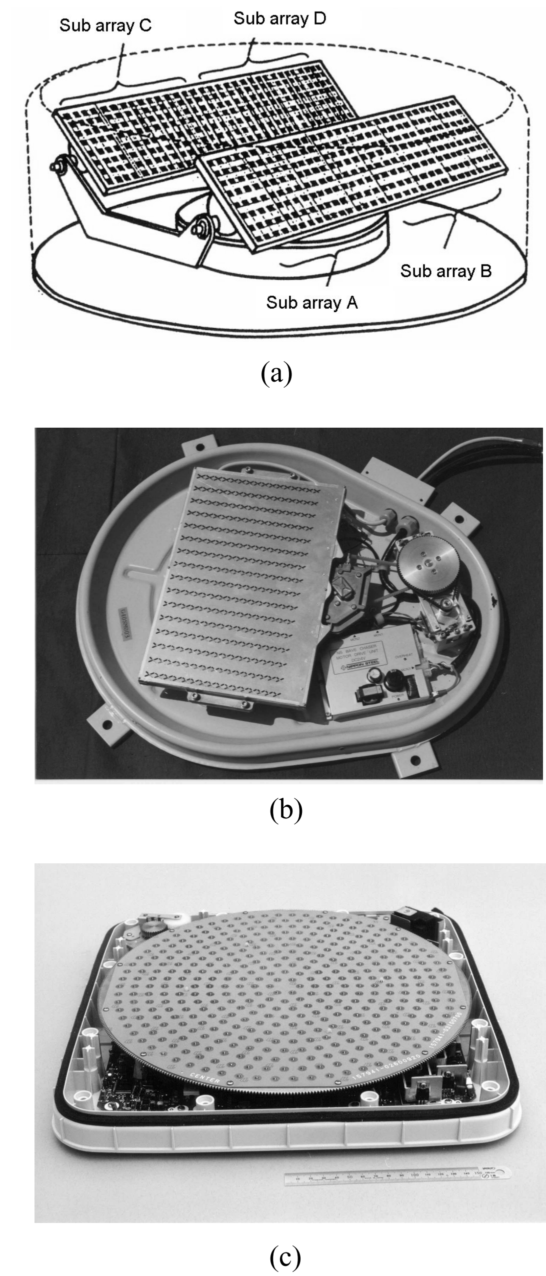
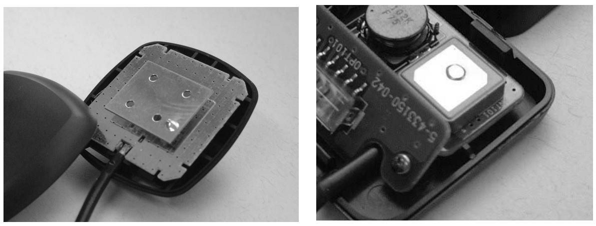


Fig. 7 BS reception antenna system. (a) MSA array type, (b) Wave guide slot array type, (c) Annular ring MSA array with radial wave-guide type.

3.4 Antennas for Intelligent Transport Systems (ITS)

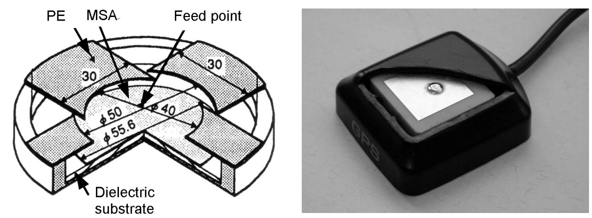
(1) Communication and Navigation
The toll gate antenna for Electronic Toll Collection (ETC) systems is about 5m above the road lane, while the communication area is specified to be an area of 4m long and 3m wide at a height of 1m above the lane. The MSA used at the toll gate is designed to have the radiation pattern that uniformly illuminates the communication area and has low sidelobes in order to avoid interference caused by the fixed objects around the gate [50]. The antenna gain is less than 20dBic for the roadside and less than 10dBic for the vehicle, and right-hand circular polarization is used. Cost effectiveness is especially important for the car mount antennas. Figure 8(a) shows a typical example of the currently used ETC antennas which are mounted in the car cabin. It is a kind of MSAs, and consists of a metal plate without a dielectric substrate. The ETC antenna is usually set on the dashboard. It is reported that the radiation pattern and the axial ratio are degraded by the windshield and adjacent objects [54]. It is not necessary for the cabin mount antenna to have an omnidirectional radiation pattern, but is necessary to consider the effects of adjacent objects.

The Vehicle Information and Communication System (VICS) operates in the 2.4GHz band, and its road-



(a) (b)

Fig. 8 Antennas for ETC and VICS. (a) ETC, (b) VICS.



(a) (b)

Fig. 9 GPS antennas. (a) MSA with parasitic elements, (b) MSA with high permittivity substrate.

side antenna with two beams is specifically designed so that the direction of vehicle motion may be identified and vehicles can get information in relation to the direction of travel [52]. The radio beacon employs a spot zone (70m long and 10-15m wide) for communication on a lane. Commonly used car antennas in VICS are a MSA, and they are set on the dashboard similar to the position of the ETC antenna. Figure 8(b) shows an example of car mount VICS antenna, which uses high permittivity ceramic substrate. The gain of the antenna is more than -1dBi with VSWR of less than 2.

Antennas for GPS reception should provide uniform sensitivity over the entire upper hemi-sphere over which the satellites may be visible, but reception when the GPS satellites are below 10 degrees above the horizon should be avoided because of the severe multipath and troposphere effects. Omnidirectional antennas such as QHAs and MSAs are potential candidates for GPS reception. Although QHAs have advantages such as wide beam coverage and wide frequency bandwidth properties, MSAs are most commonly used for land vehicles because of their low-profile and compact nature. In particular, MSAs with high permittivity ceramic substrate are the best choice for compact cars because of its extremely small size. Figure 9(a) shows a MSA designed to avoid reception performance degradation at low elevation angle [51]. By arranging the parasitic elements above the circular patch, wide angle coverage of 160degrees with axial ratio less than 3dB was realized across 3.3% band width. Figure 9(b) shows a MSA using ceramic material with high permittivity of 20. MSAs using high permittivity substrates feature particularly small size, but very narrow bandwidth. Consequently, it is very important to design such cabin mount antennas in consideration of the effect of the antenna radome and the metal fixture on the input impedance.

(2) Automotive Radar

It is indispensable for automotive radars to have lateral detection ability so that it may not miss the target on a curved road. Consequently, a beam steering function which changes the beam direction in response to a curved road, a beam scanning function and a multibeam function, etc. are adopted for detecting the lateral position of the preceding car.

Mechanical systems are the simplest method of scanning a narrow beam antenna. The tri-plate antenna shown in Fig. 10(a) was used in such a mechanically scanned system [55]. It had the gain of approximately 30dBi and beam cross section of 2.8degrees by 2.8degrees. This tri-plate array antenna features high efficiency and 45degrees tilted linear polarization. The waveguide slot array shown in Fig. 10(b) and other types such as the dielectric leaky wave antenna and the parallel plate slot antenna, etc. are excellent antennas with fixed beam and high efficiency of more than 70% [57]–[59]. As an antenna for another type of mechanical systems, a dielectric lens antenna has been developed for the mechanical beam switching radar [60].

Antennas for electrically scanning radars such as beam switching, mono-pulse and holographic radars have also been actively studied and have been proposed one after another [60]–[63]. Although the MSA array has desirable advantages of thinness, lightweight and ease of mass production, it is usually difficult to obtain high radiation efficiency in the millimeter-wave band because of ohmic loss and manufacturing defects. However, the MSA array shown in Fig. 10(c) features high efficiency of more than 50%. It was developed for holographic radar [61],[64]. This array antenna consists of sub-arrays of series fed rectangular MSAs. The radiation quantity of each MSA element was finely controlled by its dimensions to achieve the desired illumination along the length of each sub-array.

3.5 Antennas for Train communication Systems

Figure 11(a) shows the inverted L type antenna for train communication systems in the 150MHz band [67]. This antenna was mounted on the roof of the head train and was used in common with a sensor of overhead power line voltage. The antenna system shown in Fig. 11(b) was adopted for the 400MHz band communication system. It was a directional flush antenna with the beam switching circuit of changeable to forward or backward direction of the train [68]. The antenna was composed of an array of parasitic monopoles. In order to make the antenna height low, a circular disk was loaded to the top of the monopole. The typical per-

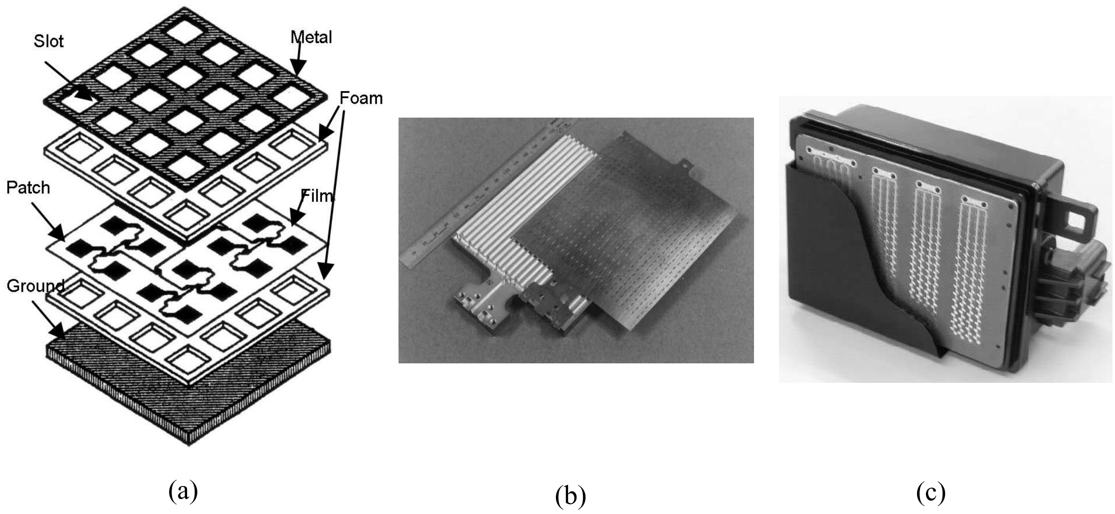


Fig. 10 Antennas for automotive radars. (a)Tri-plate array type, (b) Wave-guide slot array type, (c) MSA array type.

formance of the antenna is as follows. The half-power beam width in the horizontal plane is more than 60degrees and the maximum gain is approximately 4dBd for the vertical polarization.

LCX systems adopted as the communication system for Tohoku and Joetsu Shinkansen have two LCX cables along the railway. Train has two array antennas composed of four folded slot elements on each side of its head vehicle. Structure of one folded slot element is shown in Fig. 11(c) [70]. The train mount antennas have the broad beamwidth of approximately 110degrees in the vertical plane and the maximum gain is 5dBd.

4. Conclusions

Advances in land vehicle antennas developed in Japan have been reviewed. Most engineers concerned with communication systems today recognize the important role of vehicle antennas in mobile communication systems. Designers of vehicle antennas always consider many factors, besides the electrical performance of the antennas themselves. That is, the effect of close proximity to the vehicle body, environment, propagation problems and tracking capability, etc. An antenna system equipped with advanced functionality which can selectively receive only the desired signal is most desirable for land vehicles moving in various environments. In order to realize such functionality, future antenna systems will definitely incorporate intelligence, which will be realized by the use of signal processing technologies and highly integrated devices with the antenna system. Adaptive arrays are already being used in practice. In addition to this, sophisticated intelligence such as recognition, comprehension, and noise deduction which an animal may have is expected to be introduced into antenna systems in the future.

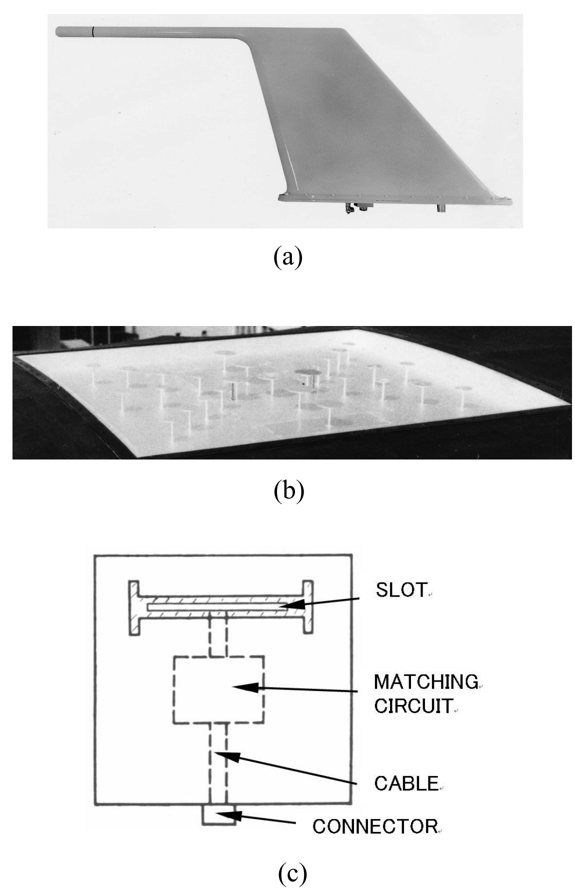


Fig. 11 Train mount antennas. (a) 150MHz band antenna for space wave radio system, (b) 400MHz band antenna for space wave radio system, (b) Train mount antenna for LCX communication system.

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