SUMMARY This paper reviews the antenna system for Japanese cellular systems and PHS (Personal Handphone System). The unique features of the Japanese cellular system are multi-band operation, compact diversity antennas, electronic beam tilting, and indoor booster systems. The original antennas for the above purpose will be described. The PHS is also a unique mobile communication system in Japan, and is mainly used for high speed, low cost data transmission. Its original antennas are also presented in this paper.

key words: Cellular system, phase shifter, multi band antenna, diversity antenna, PHS, adaptive antenna

1. Introduction

Japanese mobile telephone service started in 1979. After the liberalization of mobile communications services in 1988 and terminal markets in 1994, the subscribers of mobile terminal were rapidly increased. Four operators provide digital cellular services using frequency band of 900MHz and 1.5GHz. In 2001, the third generation mobile communication service called IMT-2000 was introduced using 2GHz frequency band. As shown in Fig. 1, several frequency bands are assigned for cellular telephone service and PHS (personal handyphone system) in Japan. In the view point of base station antenna technologies, the unique features of the Japanese cellular system are multi band operation and use of electrical beam tilting techniques for high capacity systems. The key components are multi band antenna elements and phase shifters. In addition, every base station uses a diversity system to receive a weak uplink signal affected by multi-path fading. Three kinds of diversity antenna configurations, space, polarization, and radiation pattern, are used. The second unique topic is the antennas for a micro cellular system. This system provides services inside buildings, tunnels and subway stations. The coverage area is 20 m to 1 km, and the antenna gain of such a base station is relatively low. Another mobile communication service, PHS has started in 1995. This micro cellular system uses different base station antenna configuration from cellular system.

This paper presents the outdoor and indoor base station antenna systems, which are commercially used for the Japanese cellular system and the PHS. The dual and triple band antenna element and variable phase shifter for cellular system are described first. The diversity configuration and micro indoor antenna systems are also presented. Then, the antennas for the PHS are described. The omni-directional, bi-directional antennas and their diversity configurations are presented. In the last part of this paper, adaptive array antennas for the base stations including that for PHS which is the first adaptive array antenna used in commercial mobile communication systems are described.

2. Base Station Antennas for Cellular System

The Japanese cellular system adopts a small cell size of 1.5 km radius to increase the capacity of subscribers. The interference between cells using the same frequency band is suppressed to a very low level by the radiation pattern in the vertical plane. The cell is divided into several sectors in the horizontal plane to suppress the interference between mobile terminals. The FDMA/TDMA system uses different frequency bands between adjoining sectors, while the CDMA system uses the same frequency band in all the sectors. The sector shaped pattern is also very important for the CDMA system to increase the capacity of subscribers.

Figure 2 shows the exterior of the cellular base station antenna. The main components of a base station antenna are an antenna element, a feed circuit network,
and a phase shifter. An antenna gain of 10 to 24 dBi is required for the macro cellular system with a coverage area of 1 km to 5 km in radius. This high gain is obtained by using the array structure. A simple array structure uses the same amplitude and phase excitation for broadside radiation, however, the phase of each element is adjusted to obtain the tilted beam pattern in the vertical plane. The beam is tilted in order to suppress the interference between the cells using the same frequency band and to adjust the overlapping region between sectors.

This section presents a dual band antenna element for practical usage in the current system, and a tri-band antenna element for the introduction of IMT-2000 in Japan. A discussion on the design and use of a feed network circuit and variable phase shifters is also included in this section.

2.1 Dual/Triple Band Antenna Elements

A printed dipole antenna is the most popular antenna element for base station antennas of the cellular system, because a half wavelength dipole antenna has a wide frequency bandwidth of more than 15% for an input VSWR (voltage standing wave ratio) of less than 2. The omni-directional radiation pattern in the H plane of the dipole antenna is formed to be a sector beam by mounting the reflector. The feed circuit network of the printed dipoles consists of a microstrip line for the array structure in the vertical plane. The balanced feed of the dipole antenna is connected to a balun for the unbalanced feed of the microstrip line. For the mass production of the antenna element, the printed dipole with the balun circuit is used.

In the printed antenna used for the cellular base station, the parasitic element is placed on the same substrate. It is easy to obtain a multi resonant antenna by using a parasitic element to meet input impedance characteristics. However, it is difficult to realize equally divided sector beams in the horizontal plane for every frequency. This is because the electrical length between the antenna and the reflector is different from that of between the parasitic element and the reflector. The pattern of the dual frequency antenna can be adjusted by varying the reflector shape and by adding other parasitic elements [2].

Another technique to obtain dual band operation is to use a matching network circuit, while keeping the electrical spacing from the antenna to the reflector the same and exciting the antenna [3]. Figure 3 shows an example of the dual band antenna using a matching network. The height of the flange is adjusted to obtain the same beam width in the horizontal plane as that in the vertical plane. This dual band antenna has a vertically mounted conductor plate for the wide band impedance matching at 900 MHz.

Two operators are assigned to the 900 MHz band and three operators to the 1.5 GHz band as shown in Fig. 1. A major operator, NTT DoCoMo, has been assigned to both frequency bands, and uses a dual frequency band antenna for the base station [1]. The dual band antenna has two resonant frequencies for a single input port. Signals with two different frequency bands are fed through a combiner. A multi-resonant antenna element is necessary for the dual band antenna.

The introduction of IMT-2000 uses an additional frequency band at 2 GHz, which requires installation of another base station antenna or exchange of present antenna system to a multi-band one. The remarkable increase of subscribers for the mobile communication system has left few places for new base station building. Therefore, a multi-band antenna to replace the present system is required. The dual band antenna for 900MHz/2GHz and for 1.5/2GHz is obtained by the same technique described above. However, a triple band antenna is also used to cover 900MHz, 1.5 GHz and 2GHz. In the IMT-2000 system, a sector beam with a 60° half-power beam width is also used in addi-
tion to the conventional 120° and 90° sector antenna. The triple band antenna with the same sector beam of 120° is obtained by adding another parasitic element to the dual band antenna as shown in Fig. 4 [4]. The two horizontal parasitic elements are used to enhance the bandwidth of the 900MHz band. This antenna element gives triple frequency band with almost the same half power beam width in the horizontal plane. The deviation of the beam width are the three frequencies is 120 ± 7°.

2.2 Antenna Feeding Network and Variable Phase Shifter

Base station antennas in the Japanese cellular system consist of array structures for high gain and beam tilting in order to suppress the interference with an adjoining cell. Though adjusting the phase of each antenna element tilts the beam, the antenna array is divided into several sub arrays and the phases of these sub arrays are changed by using phase shifters as shown in Fig. 5. The array consists of seven sub-arrays with four antenna elements in each sub array. Phase shifters control the phases of the upper three and lower three sub-arrays using the central sub-array as a reference [6].

A low loss variable phase shifter consists of a tri-plate transmission line and movable dielectric plates sandwiching the strip line as shown in Fig. 5. By moving the dielectric block, the phase velocity of the stripline is changed by an amount that depends upon how much the stripline is covered by the dielectric block. The relative dielectric constant of the plate is 50 for the miniaturization of the phase shifter. This phase shifter has two input and two output ports designed for the base station antenna beam tilting. The phase delay difference between the two output ports is determined by the offset of the dielectric plates. The phase origin

is determined when the sandwich of dielectric plates is at center. The maximum range of phase change is 130° with an error of 8°, and the insertion loss is about 0.2 dB at 2 GHz [7]. Figure 6 shows the feed circuit network for a seven-sub array antenna structure. This tournament feed network using two-port phase shifters enables beam tilting in the vertical plane of base station antenna.
3. Diversity Antennas for Macro Cellular System

In this section, antennas for a macro cellular system are described. Up-link diversity reception is mandatory for base station antennas in order to decrease multi-path fading and to compensate for power imbalance between uplink and downlink signals, as the uplink signal is weaker than the downlink signal. Two major diversity schemes, a space diversity and a polarization diversity antenna, are presented. In addition, a unique radiation pattern diversity system is also presented.

3.1 Space Diversity Antenna

For a three-sector zone in the horizontal plane, a total of six base station antennas are required in the space diversity system if each antenna is installed independently. Due to the space limitation for base station antenna placements in big cities, the location of the antenna has become very restricted. Thus the number of antennas in one base station should be minimized. For this reason a three-sector antenna system uses a radome housing for two antennas facing different sectors as shown in Fig. 7 [4].

A three-sector zone is mainly used for Japanese cellular systems in the 900 MHz and 1.5 GHz bands. However, six-sector zones are also adopted in the IMT-2000 system in the 2 GHz band in addition to the three-sector zone. In order to replace present dual band antennas with triple band antennas, two types of base station antennas are required. One is with a 120° beam width for all three bands and the second is with 120° beam width for 900 MHz/1.5 GHz and a 60° beam width for 2 GHz. The latter case needs three more 2 GHz antennas to cover the whole area. To decrease the number of base station antennas, two 60° beamwidth antennas are placed side by side about the center of the 120° beam of the lower frequency antenna. The 2 GHz antennas are placed vertically in the form of an array. The cell allocation using this hybrid antenna is shown in Fig. 8. This antenna covers the present cellular system with three-sectors in the 900/1500 MHz bands and with six-sectors in 2 GHz band.

3.2 Polarization Diversity Antennas

Recent developments in electronics technology have produced very small and light portable handsets. As a result, everyone now uses a handset placed near an ear at a tilted angle. According to the statistical data presented in [8], the tilt angle is about 60°. This decreases the vertical radiation component by 6 dB and the horizontal component by 5 dB. This operating condition requires an increased horizontal electric field component in the uplink, making the polarization diversity an effective tool.

The polarization diversity gain measurement using a handset has been found to be about 7 dB more than the space diversity case for the line of sight region, and 1 dB more outside the line of sight region [9]. The polarization diversity system using vertical and horizontal components also has the merit of minimizing the antenna installation space, and has been adopted for Japanese cellular systems.

A base station antenna employing polarization diversity in both vertical and horizontal polarization uses a pair of circular patch antennas [10]. The antenna is excited by adjusting the phase difference to obtain the same beam width in the E and H plane. As a 90° beam width antenna of polarization diversity, a printed twin dipole element with parasitic element as shown in Fig. 9 is also used. The parasitic element expands the frequency bandwidth while keeping the beam width at the same value. This twin dipole antenna has equal beam widths in the E and H planes. Antennas are arranged in a vertical array as shown in Fig. 10. Three polarization diversity arrays are built in one radome to reduce the number of base station antennas.

3.3 Radiation Pattern Diversity Antenna

The omni-directional pattern antenna is installed in suburbs. The simple omni-directional diversity antenna consists of four 180° beam width antennas and two hybrid couplers as shown in Fig. 11(a). A pair of back to back antenna combined with the hybrid has many grating lobes in the horizontal plane as shown in Fig. 11(b).
3.8 Pair dipole pattern (bottom surface)
Parasitic element (top surface)

Fig. 9 Printed twin dipole element with parasitic element.

Fig. 10 Redome housing for polarization diversity antenna.

Null positions of each pair has an orthogonal pattern to reduce the correlation coefficient. The effect of nulls in the radiation pattern cannot be seen by the multi path uplink signals from the mobile terminal.

4. Antennas for Micro/Pico Cellular System

The cellular phone service has been started to cover a terrestrial area, and the coverage area is expanding to include tunnels, subway stations, and inside large buildings such as shopping malls and hotels. A system covering these areas is referred as an In-Building System. This system uses a booster for the relay station between the outside base station and the new coverage area, or a micro cellular system using an exclusive base station. The booster system receives a downlink signal from the outdoor base station, then re-radiates its downlink signal after amplification, and vice versa for the uplink. A leaky coaxial waveguide has been widely used for the

900 MHz cellular system to expand its coverage area to the underground tunnels in the metropolitan highway in Tokyo [11]. An in-building system has been installed in the newly built undersea tunnel in 1994. This novel system uses an optical fiber as a transmission line and a flat antenna as a radiating element to provide 1.5 GHz band service in addition to the 900 MHz band [12]. In this system, an optical laser diode is directly modulated by the downlink RF signal from the outdoor base station, and its modulated optical signal is transmitted to inside the tunnel by an optical fiber. A very small transmission loss and a wide bandwidth enables the optical fiber to carry two frequency bands at 900 MHz and 1.5 GHz. After the transmission by the optical fiber, the downlink signal is re-radiated by low gain flat antennas installed on the side wall at a few hundred meters apart. The reverse is done for the uplink.

In addition to the highway tunnels, the in-building system has also been introduced to subway stations. Recently, this system has also been introduced into private facilities, such as huge shopping malls, big hotels, etc. This section describes low profile and small antennas used for the present in-building system and presents a method to expand its frequency band corresponding to IMT-2000 (2 GHz). The system using leaky coaxial cable is still used for areas where the length of the cable is not very long, however, the discussion presented below only covers antennas for systems using optical fiber as a transmission line.

4.1 Tunnel Booster Antennas

The required characteristics for an antenna used inside a tunnel are a bi-directional radiation pattern and a low profile structure. Its height should be less than one-tenth wavelength at 900 MHz. The shape of the bi-directional pattern has a figure of eight in both E and H plane. It has a null position in front of the antenna. This pattern is obtained by a two-element half wavelength dipole array. The elements are excited out of phase and are spaced half wavelength apart. This ar-
ray gives a figure of eight pattern in the H plane, however installing a ground plane near the antenna element drastically changes this pattern. The tunnel booster antenna needs a mounting conductor plate because the electrical characteristics of the tunnel walls are affected by the wet or dry surface conditions of the concrete wall. The ground plane is necessary for the tunnel antenna so that it is not affected by the surface conditions of the wall.

The frequency bandwidth of 900 MHz Japanese cellular system is about 17%. This bandwidth covers all the operators in Japan. The highway tunnel is regarded as a public space, and the in-building system is for common use. An antenna element for the highway tunnel is a pair of notch antennas excited out of phase, which has wide frequency bandwidth in spite of its low profile structure [13]. A pair of notch antennas cut on a small ground plane is shown in Fig. 12. It does not have a dominant resonant notch but has a resonant feeding strip line with a length of one quarter wavelength [14]. The current flowing on the ground plane radiates the cross polarization component, and a crank shaped ground plane may be used to suppress the undesired radiation [15]. However, the radiation of the cross polarization is not a serious problem for low gain antennas in the mobile communication system, as it often increases frequency bandwidth at the input port and thus it is not necessary to suppress cross polarization to a negligible level.

A low gain bi-directional antenna is installed at an interval of 200 m for short tunnels less than 2 km. After opening the undersea tunnel at Tokyo bay in 1996, high gain types have been introduced for long tunnels more than 2 km. As the antenna gain increases, the number of electric to optical and optical to electrical converter units becomes smaller and the cost of the system becomes cheaper.

Directors attached to the bi-directional notch antenna increase the directivity as in a Yagi-Uda array. A few directors of length 0.4 wavelength are placed in parallel to the feeding strip line on both sides, as shown in Fig. 13, increases the antenna gain by 3 to 5 dB [16]. The maximum gain is restricted by the size of the ground plane. When the director is located close to the edge of the ground plane, an increase in the backward radiation limits the directivity.

For the triple band operation of the tunnel booster antenna, one technique that may be of use is to replace the dual band notch antenna by a single band element. The dual band notch antenna is designed by mounting the parasitic element above the feeding strip line [17], which is effective in low gain antenna structures. To keep the same interval between booster antennas, the antenna gain of the 2 GHz band is adjusted to compensate for the propagation loss which increases in proportion to the operating frequency. In the initial service of IMT-2000, high gain notch antennas for 2 GHz band were introduced in addition to the current antenna.

4.2 In Building Antennas

The antenna shape installed on the ceiling depends on the ceiling condition. When protruding decorations cover the ceiling, wire antennas such as a sleeve and a collinear array are easier to install rather than flat antennas. On the other hand a low profile antenna is appropriate for a flat ceiling. The low profile antennas used for the in-building system are modified to a semicircular shaped monopole antenna with an ultra wide band [18], a very low profile top loaded monopole antenna (TLMA) [19][20], and a miniaturized TLMA filled with dielectric materials [21]. These antennas are shown in Fig. 14. The impedance matching at the feed
point of the TLMA is achieved by placing shorted posts near the feed probes as shown in Fig. 14.

Places to install such small antennas are on the ceilings of a department building, a hotel, and an underground parking lot. The up link and down link antennas are mounted separately for both the 900 MHz and 1.5 GHz bands. A rooftop shaped TLMA with two shorting pins is used for the 1.5 GHz band, and a dielectric filled TLMA is used for 900 MHz band. The rooftop shaped plate increases the frequency bandwidth of the TLMA. The dielectric block is effective in reducing the antenna size, however it decreases the antenna gain up to about 2 dB due to the loss of dielectric and the radiation of the cross polarization. The principal polarization is vertical, similar to the terrestrial system, and the cross polarization is horizontal. This miniaturized antenna is able to achieve the minimum requirement for the antenna gain for an in-building system, which is 0 dBi.

Another example is the ceiling antenna for the subway station. This antenna operates in the frequency bands of 280 MHz, 900 MHz and 1.5 GHz, covering all the frequency bands allocated for pager and cellular phone system in Japan. Three dielectric filled TLMA s are used to cover the split frequency band plan at 900 MHz [22]. The subway station is a public space, and in-building systems are operated by all the cellular operators. The antenna elements are arranged to minimize the distortion of radiation pattern and to obtain more than 15 dB isolation between uplink and downlink antennas.

The introduction of IMT-2000 has forced operators to add a new antenna for the 2 GHz band or to replace the current dual band antenna with a new triple band antenna. New antennas can easily be installed by adding small uplink and downlink antennas only for the 2 GHz band. For the antenna replacement case, the current TLMA for 1.5 GHz is exchanged for a dual band TLMA operating at the 1.5 GHz and 2 GHz bands. A dual band monopole antenna is normally obtained by adding a parasitic element in the vicinity of the original monopole antenna, however this technique cannot be applied for dual band TLMA. For the dual band TLMA, a square loop is attached on the top disk as shown in Fig. 15 [23]. The loop is electrically connected to the top plate by a short pin to make it resonant in the high frequency band for the TLMA. The original resonance of the TLMA moves lower due to the mutual coupling between the square loop and the top plate. The upper square loop is rotated by 45 degrees so as to protrude the loop corner from the square plate. These protruding parts make additional resonance. The triple band antenna is thus obtained by replacing the TLMA for 1.5 GHz by the dual band TLMA with square loop. The current flowing on the loop and the plate does not radiate excessive horizontal polarization, because their image currents in the ground plane cancel each other. This composite structure produces a quasi monopole radiation pattern in the vertical plane and an omnidirectional pattern in horizontal plane.

5. PHS (Personal Handy Phone System) Base Station Antennas

The service of PHS which is a microcellular system in Japan has started in 1995. The major system specifications are shown in Table 1. PHS uses the 1.9 GHz band and adopts TDMA-TDD [24], [25]. The frequency bandwidth is 1.2 %. PHS employs a diversity configuration in the uplink and transmission diversity is also adopted in the downlink. The base stations are located at a low height such as the top of telephone boxes and utility poles as well as a relatively high height such as the roof top of buildings. The cell size ranges up to several hundred meters. Many base stations are also placed in doors such as in buildings, underground shop-
Table 1  System specifications of PHS.

<table>
<thead>
<tr>
<th>Frequency band</th>
<th>1.9GHz band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier spacing</td>
<td>30kHz</td>
</tr>
<tr>
<td>Multiplex method</td>
<td>TDMA TDD</td>
</tr>
<tr>
<td>Multiplex number</td>
<td>4</td>
</tr>
<tr>
<td>Modulation type</td>
<td>$\pi/4$ shifted QPSK</td>
</tr>
<tr>
<td>RF output power(except public type)</td>
<td>Up to 10 mW</td>
</tr>
<tr>
<td>RF output power(public type)</td>
<td>Up to 500 mW</td>
</tr>
<tr>
<td>Antenna gain(for private)</td>
<td>Up to 2.14 dBi</td>
</tr>
<tr>
<td>Antenna gain(for public)</td>
<td>Up to 10 dBi</td>
</tr>
<tr>
<td>Transmission rate</td>
<td>384kbps</td>
</tr>
</tbody>
</table>

ping areas, and subway stations. In the historical view of the base station antennas for PHS, omni-directional antennas suitable for microcellular systems have been developed first. Bi-directional antennas have also been developed to enlarge the cell size in street microcell environments. As for the diversity configurations, the appropriate antenna arrangement for space diversity used in microcell environments were first investigated. Then space diversity antennas suitable for microcell systems have been developed. Some of those antennas have been installed to the commercial systems from the start of the PHS services. After the above antennas was developed, the effectiveness of the polarization diversity were investigated and several types of polarization diversity antennas suitable for microcellular systems have been developed. Adaptive array antennas for PHS have also been developed and have been installed from 1998. The following describes the details of the antenna configurations. The detail of the adaptive array antennas are described in the next section.

5.1 Omni-directional Antenna

Collinear antennas are mainly used as the configurations of omni-directional antennas. Since microcellular systems require many base stations to cover large service areas, base station antennas must be low cost and suitable for mass-production. For this purpose, collinear antennas composed of electro-magnetically coupled cylinders have been developed [26]. Figure 16 shows the configuration of an element of the antenna. A rectangular patch is formed on a dielectric substrate and it is covered with an aluminum cylinder. The patch is electro-magnetically coupled to the cylinder, thus the patch and cylinder work as exciting and radiation elements, respectively. Note that the ground plane and the patch on the dielectric substrate are not in contact with the cylinder. This antenna is easy to fabricate because the feeding network can be formed on a dielectric substrate and peripheral slots are placed on the metal ground side to form the exciting patches. This establishes a beam-forming network using microstrip lines and exciting elements on the middle substrate. This antenna is called ‘Bi-directional Narrow Patch Antenna (BNPA) array’. Using this configuration, a bi-directional antenna can be actualized with almost the same appearance as an omni-directional antenna. The half power beamwidth of the BNPA in the H-plane is about 90 degrees. The beamwidth is suitable for street microcells [30]. The BNPA array achieves approximately 3 dB higher gain than that of an omni-directional collinear antenna with the same antenna length. Field test results in terms of cell size taken in street microcell environments reveal that the BNPA array achieves a 1.3 to 1.4-fold larger communicable cell than that formed by omni-directional antenna [31]. This reduces the installation cost of microcell systems. Another type of a bi-directional antenna has also been proposed [32]. It is a planar antenna and is intended to be mounted on building walls. The antenna is composed of two Yagi-Uda...

Substrate

Aluminum cylinder

Rectangular patch

Ground plane

Feed line

Fig. 16  Configuration of collinear antenna composed of electromagnetically coupled cylinder.

other type of collinear antenna configuration, a printed antenna which does not require parasitic cylinders has also been reported [28].

5.2 Bi-directional Antenna

Bi-directional antennas have also been developed for PHS. Figure 17 shows the configuration of a bi-directional rod antenna [29]. This antenna is composed of three narrow dielectric substrates. Rectangular patches with the same size are printed on both sides of the middle substrate and the patches are fed along the length of the patch by microstrip lines. The patches work as exciting elements. The symmetrical currents flowing on the patches in opposition produce a bi-directional pattern. Two parasitic patches printed on the different substrates are placed on both sides of the exciting patches. The parasitic patches increase the antenna efficiency and the frequency bandwidth. A metal ground is placed on one side of the middle substrate and peripheral slots are placed on the metal ground side to form the exciting patches. This establishes a beam-forming network using microstrip lines and exciting elements on the middle substrate. This antenna is called 'Bi-directional Narrow Patch Antenna (BNPA) array'. Using this configuration, a bi-directional antenna can be actualized with almost the same appearance as an omni-directional antenna. The half power beamwidth of the BNPA in the H-plane is about 90 degrees. The beamwidth is suitable for street microcells [30]. The BNPA array achieves approximately 3 dB higher gain than that of an omni-directional collinear antenna with the same antenna length. Field test results in terms of cell size taken in street microcell environments reveal that the BNPA array achieves a 1.3 to 1.4-fold larger communicable cell than that formed by omni-directional antenna [31]. This reduces the installation cost of microcell systems. Another type of a bi-directional antenna has also been proposed [32]. It is a planar antenna and is intended to be mounted on building walls. The antenna is composed of two Yagi-Uda...
antennas which are printed on a dielectric substrate in opposition and are fed out of phase. The bi-directional beams are directed to the endfire directions.

5.3 Diversity Configurations

Element arrangement and element spacing are important to employ space diversity in mobile communication systems. The influence of element spacing on diversity performance has been clarified when antennas are placed at a high height [33]. Diversity performances of several element arrangements in street microcell environments have also been experimentally investigated [34]. Figure 18 shows the element arrangements considered in the report. Three cases have been tested, perpendicular to a street, parallel to a street, and vertical. In the measurement, base station antennas were placed on the sidewalk at a height of 3.5 m and the mobile antenna moved along the sidewalk at the height of 1.5 m. The number of elements was two. The street width was 28 m and the frequency was 2.6 GHz. The correlation and the difference of received power between the elements were measured and diversity gain was calculated according to the definition described in [35]. Figure 19 shows the relationship between the element spacing and the diversity gain for those three cases. The diversity gain represented in the vertical axis is the value at the cumulative probability of 10% over the communicable cell (within 200 m from the base station). As shown in Fig. 19, the arrangement perpendicular to the street obtains the largest diversity gain of the three when element spacing is narrow. However, when the element spacing is more than five wavelengths, the diversity gain is almost the same among the three arrangements. According to the results, vertical arrangement has been used for the base station antennas placed at the top of telephone boxes because it simplifies the antenna placement. Figure 20 shows the configuration of the vertically arranged omni-directional diversity antenna using the electro-magnetically coupled cylinders. Two antenna arrays are serially arranged in a long radome. The coaxial cable for feeding the upper antenna array is attached on the ground side of the dielectric substrate as shown in Fig. 20. The vertically arranged bi-directional diversity antennas using BNPA arrays use a similar way to feed the upper antenna array.

Polarization diversity configurations have also been investigated as the base station antennas for microcellular systems. The polarization diversity is especially effective when terminals are located in line-of-sight (LOS) environments because the polarization of the waves propagating from the terminals is maintained in the LOS environments and the polarization of base station antennas is generally vertical while terminal antennas are often inclined. Figure 21 shows the configuration of a bi-directional polarization diversity antenna [36]. This is a modification of the BNPA array described above. Slot antennas are placed between the BNPA elements, so that a bi-directional polarization diversity antenna can be actualized with almost half the length of the bi-directional space diversity antenna using BNPA arrays.
6. Adaptive Array Antennas for Base Stations

With increases in the data-rate and the number of users of mobile communications, reducing inter-symbol interference (ISI) and improving spectrum efficiency are the important issues for mobile communication systems. Adaptive array antennas are promising candidates to overcome the problems and numerous works have been done to apply them to the base stations [46] to [67]. All the adaptive array antennas considered for the base stations adopt digital beam forming (DBF) configurations.

The first adaptive array antenna testbed for base stations of mobile communication systems in Japan was developed by the Communications Research Laboratory in 1989 and they conducted field tests in Tokyo [46], [47], [48]. The testbed worked in the uplink. The four element square array with an element spacing of 0.444 wavelengths was used and 256 kbps GMSK modulated signals transmitted from a mobile site were received by the testbed. The measurement results demonstrated the reduction of the ISI caused by multipath and approximately 20 dB improvement of received $E_b/N_0$ performance at the BER of $10^{-2}$ was observed by applying the adaptive array antenna to the base station.

The research activities concerning the adaptive array antennas for base stations in Japan have dramatically increased from 1995 [49]. The target systems are mainly PHS and IMT-2000. The following describes some of the works for PHS and IMT2000.

6.1 Adaptive Array Antennas for PHS

An adaptive array antenna for PHS base stations has been developed and it has been installed from 1998 [50], [51]. This is the first adaptive array antenna used in commercial mobile communication systems anywhere in the world. PHS is relatively easy to apply adaptive array antenna technology because PHS uses time-division-duplex (TDD) and it allows only a relatively slow movement for the terminals, so that the propagation channel characteristics estimated in the uplink can be applied to the downlink. Figure 22 shows the exterior of the adaptive array antenna for PHS. As for the array configuration, a square array with an element spacing of 5 wavelengths is used. This array configuration is the same as the conventional four branch diversity base stations. The transmitting power of the adaptive array antenna is 125 mW while the transmitting power of the conventional base station was 500 mW because of the difference of the antenna gain. Adaptive beam forming is applied to only communication channels. Because since adaptive array antennas automatically form their beams, cell planning becomes difficult when applying the adaptive array antenna to control signals. The field test results using the base station show that the adaptive array antenna achieves a 5.3 dB improvement on the received signal power at a terminal than that obtained by the conventional base station in the downlink, and approximately 10 dB more interference suppression is observed than the conventional base station antennas [52].
A base station configuration which forms the beams for both control and communication signals has also been proposed [53]. The base station has two base station units that work at different time slots in the control channel of PHS. Both units have adaptive beam forming functions. For the control channel, the base station controls the radiation patterns of both the units simultaneously to make the combination of the patterns omni-directional while each unit forms its beam to suppress the co-channel interference at each time slot. This configuration allows more base stations to be placed in a limited area than conventional base stations. The field test results show that this configuration using three antenna elements can obtain almost 5 fold more available slots than that of the conventional omni-directional base stations.

To further improve the channel capacity, a base station that can apply space division multiple access (SDMA) has also been developed and some field test results have been reported [54], [55].

6.2 Adaptive array antennas for IMT-2000

Many works concerning adaptive array antennas for the IMT-2000 systems have been done in Japan as well as in the USA, Europe and other Asian countries [56] to [61]. The work range includes communication frame format for beam forming [62], beam forming algorithms for the downlink [63], [64], calibration [58], [59], [60], simplification of the hardware [61], and so on. Prototypes of base stations comprising adaptive array antennas have been developed and field tests have been conducted [65][66]. The field test results demonstrate the effectiveness of the adaptive antenna against the conventional space diversity antenna. An adaptive array antenna controlling polarization as well as the radiation pattern has also been proposed[67]. The configuration is especially effective for a base station placed in a sector cell where the range of the angle of arrivals of the incoming waves from the users is narrow. The works concerning adaptive array antennas in Japan have been also summarized on the paper entitled “Adaptive antennas” in this special issue and [55].

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References


(in Japanese).


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