PAPER Special Issue on Historical Review of Antenna Systems in Japan

# Antennas for Wireless Terminals

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**SUMMARY** This paper reviews antenna technologies for cellular phone terminal in Japan. In regard to the technologies two technical subjects are addressed: a diversity system and miniaturization of terminal size. These subjects provide motivation for studies on design methods for diversity antennas, development of built-in antennas, and control methods for surface current on terminal cavity. These studies are progressing.

***key words:*** *antenna, wireless terminal, built-in, diversity,*

## 1. Introduction

Antenna technologies for cellular phone terminals have developed dramatically in line with the policy of NTT DoCoMo Inc., was the first service provider of a mobile communication system in Japan. NTT DoCoMo decided to employ a diversity receiving system for cellular phone terminals and tried to shrink the volumes of terminals. In view of these decisions, antenna researchers tackled various technical subjects, with the objective of mounting two antennas on a small area, namely the surface of a terminal. Three key technologies concerning the above-mentioned subjects were released in 1982.

Fujimoto and Hirasawa did the first important research [1], [2]. They investigated the influence of surface current on terminal cavity quantitatively; the results showed that the current produced an unexpected radiation. This influence had both an advantage and a disadvantage, that is, whereas the antenna bandwidth is improved, the radiation pattern is changed. Therefore other researchers subsequently studied this influence from various perspectives.

The second concerned development of planar inverted F antenna (PIFA) [3], [4]. Haruki and Kobayashi tried to construct slot antenna by using planar element on terminal cavity, and found that the antenna operates as inverted F antenna, which is a low-profile monopole antenna. The development of planar inverted F antenna influenced many researchers engaged in the study of built-in antennas, and this also emerged as an important technical subject.

The third major study was that of by Sawaya et al. [5]. They proposed a novel design method for diversity antenna for automobiles. This method employed antenna coupling to minimize correlation coefficient value between antennas. The method formed the basis of a design method for diversity antenna for wireless terminals. Since antenna coupling resulted in both improvements and degradations respecting diversity antenna performance, the design method for diversity antenna remained a research subject.

Tsunekawa and Taga started a comprehensive study of the above-mentioned three subjects, and it resulted in antennas of practical terminals [6]; such as the personal digital cellular system (PDC) and the personal handy phone system (PHS). These subjects continue to be addressed by many researchers.

This paper reviews research on terminal antennas in Japan.

Fujimoto released a review of antenna systems for mobile communications in Japan. The review included not only antenna technologies but also peripheral technologies of antennas; such as a propagation technologies and system technologies [7]. Tokumaru released a review of technologies for small antenna in Japan [8]. He reviewed antenna technologies in terms of theoretical approaches.

Therefore, this paper focuses on the main features of technical subjects concerning practical terminal antennas; namely, studies of current on terminal cavity, development of built-in antenna, and a design method for diversity antenna (Table 1). Furthermore, in order to introduce various technologies developed in Japan, this paper reviews papers and abstracts published in Japanese.

## 2. Study on a Current of a Terminal Cavity

NTT DoCoMo started cellular-phone service in Japan in 1986. The antenna used for the first cellular phone terminal was half-wavelength monopole antenna. Fujimoto and Hirasawa clarified that this antenna reduces current on cavity, in comparison with quarter-wavelength monopole antenna [1], [2].

### 2.1 Influence of Current on Cavity

Fujimoto and Hirasawa, who have focused on the influ-

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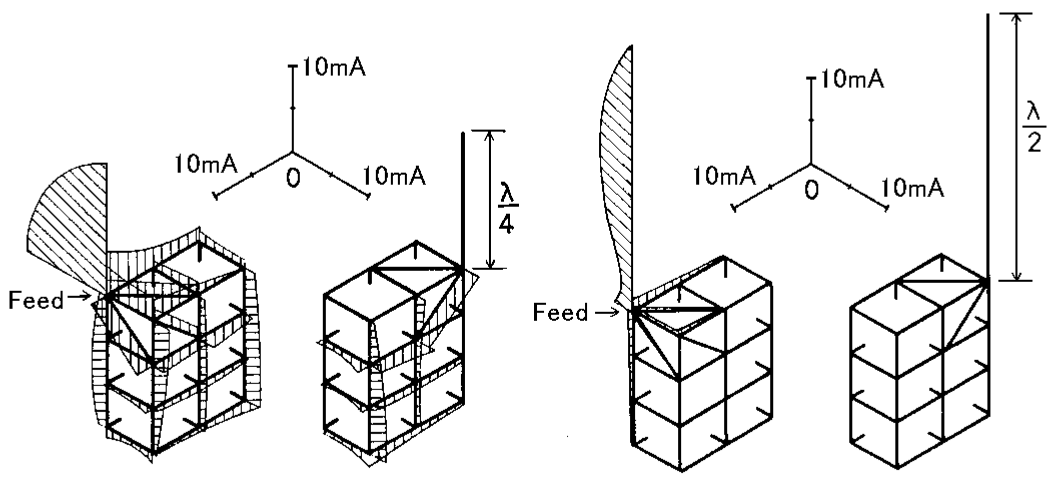
**Table 1** Overview of antenna for wireless terminal.

| | 1980–1989 | 1990–1999 | | 2000– |
|---|---|---|---|---|
| System | Mobile telephone<br>(800MHz) | PDC<br>(800MHz 1.5GHz) | PHS<br>(1.9GHz) | IMT-2000<br>(2GHz) |
| Cavity effect | Half wavelength monopole antenna [1], [2]<br>3/8 wavelength monopole antenna [1], [2] | Sleeve antenna<br>[17],[18],[19] | Notch on cavity<br>[16] | Half wavelength monopole antenna with feed element [32], [65]<br>Built-in half wavelength dipole antenna<br>[67], [68]<br>Built-in half wavelength monopole antenna<br>[69]<br>Built-in folded dipole antenna<br>[70] |
| Inverted-F antenna / Small antenna | Planar inverted F antenna (PIFA) [3]<br>Merging with dielectric filter [22]<br>Miniaturization [21]<br>Wideband characteristic<br>[25],[29],[31]<br>User effect reduction [24] | Dual resonance<br>[34]-[37] | Chip antenna<br>[47]-[52]<br>Slot antenna<br>[44],[45] | |
| Diversity | Antenna coupling effect<br>[5], [60]<br>PIFA for diversity [37] | Arrival wave effect [61]<br>User effect [63]<br>System effect[64] | | |




(a) Bottom-fed λ/4 antenna (b) Bottom-fed λ/2 antenna

**Fig. 1** Current distribution on terminal surface [1], [2].

ence of terminal cavity, evaluated quantitatively radiation patterns of various antennas on terminal cavity by using the moment method and wire grid model [1], [2]. The approximation by wire grid model provides rather high calculation accuracy of radiation pattern, even if the resolution of the model is rather coarse [9].

The results showed that a quarter-wavelength monopole antenna causes rather big leakage current to terminal cavity, in comparison with half-wavelength monopole antenna (Fig. 1). Moreover, the results showed that not only the cavity operates as an antenna due to such a leakage current but also length of cavity changes the radiation characteristics of an antenna. Research on the influence of current on terminal cavity has continued and resulting in the detailed clarification of current distribution on microstrip antenna on a finite ground plane by high-definition grid model [10].

The change of radiation pattern has been investigated by isolating radiations from antenna and terminal cavity individually. The simulation results showed that change of radiation pattern is caused by the difference in phases of these partial radiation patterns [11].

The relation between terminal size and antenna gain has been evaluated by experiments in a real field. The results showed degradation of antenna gain according to terminal size [12].

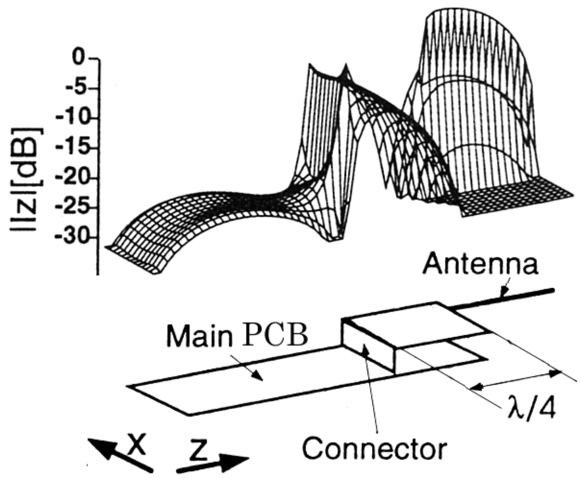



**Fig. 2** Current distribution on main printed circuit board [13].

Radiation pattern is also changed by adding planar element to terminal cavity [13]. The planar element is a quarter wavelength and is shorted to terminal cavity; therefore, this element causes a rather strong current distribution on both element and cavity (Fig. 2). As this result, these currents cause radiation that cannot be ignored.

## 2.2 Practical Monopole Antennas

Since the input impedance value of a half-wavelength monopole antenna becomes very high, a technical problem arises in that it is hard to match the impedance value with that of a feeding cable. As solutions to this problem, the 3/8 and 5/8 wavelengths monopole antennas have been proposed [1], [2]. These antennas execute greater control of current on terminal cavity than does quarter-wavelength monopole antenna, and provide easier matching with feeding cable than does half-wavelength monopole antenna.

The length of the half-wavelength monopole antenna is also one of the problems. In the case of the PDC terminal operated at 800 MHz, this antenna requires its length of 33cm; that is, this length is not suitable for a handy terminal. Therefore the method for shrinking the antenna length has been proposed [14], [15]. This method employs either a disk or a helical element as a top load element of the monopole antenna, and these elements increase the electrical length of the antenna.

## 2.3 Control of Current on Cavity

A notch on a cavity has been proposed to control current on terminal cavity [16]. A quarter-wavelength notch at the point from a feed point by quarter wavelength realizes chalk for current on cavity, this notch reduced current on terminal part beyond it (Fig. 3). This method was put into practical use for PHS terminal.

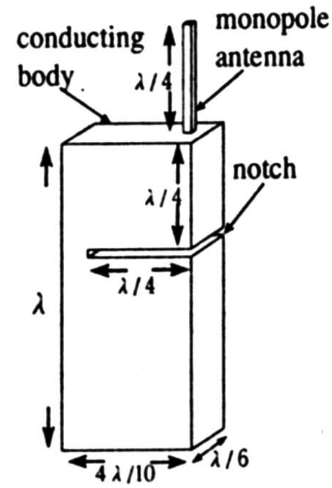



**Fig. 3** Monopole antenna on a cavity with notch [16].

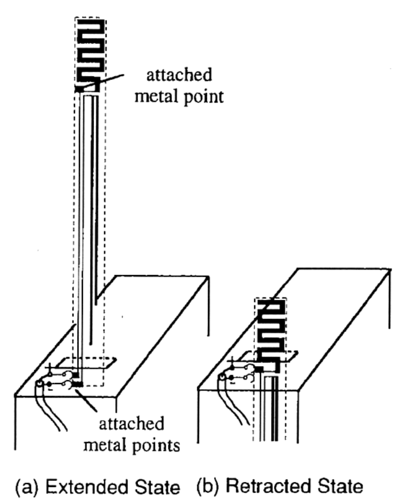



**Fig. 4** Retractable sleeve antenna [18].

The characteristics of sleeve antenna with a balun are the same as those of half-wavelength dipole antenna. Also, this antenna reduces current leakage on terminal cavity. The antenna requires flexible feeding cable. Therefore, microstrip line [17] and parallel strip line [18] have been proposed in place of coaxial cable. Furthermore, in order to achieve wideband characteristics of a balun, a method of attaching two baluns has been proposed, and the validity of this antenna was confirmed in [18] and [19](Fig. 4).

# 3. Planar Inverted F Antenna

In order to deal with the expansion of communication area, in 1989 NTT DoCoMo decided to employ a diversity system for cellular phone terminals as a counter measure for fading so as to improve communication performance. To realize the diversity system, planar

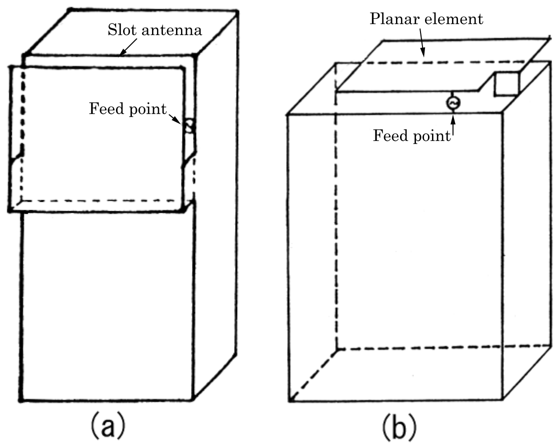



**Fig. 5** Cavity slot antenna (a) and planar inverted F antenna (b) for wireless terminal [3], [20].

inverted F antenna was employed.

A study on development of built-in antenna was started in 1980, and, as a result, planar inverted F antenna realized [3]. This antenna has a planar element instead of the wire element added on top part of the conventional inverted-F antenna [71]. The antenna was put into practical use for many terminals. This antenna is a current antenna, which is produced by a modification of magnetic-current antenna.

Considering of the validity of magnetic-current antenna in the vicinity of a human body, Haruki et al. started research, which lead to the realization of magnetic-current antenna on cellular phone terminal [20]. Their objective was development of half-wavelength slot antenna, composed of a conductive plate arranged parallel to terminal cavity (Fig. 5(a)). They finally created planar inverted F antenna (Fig. 5(b)). This antenna has a slot, which is composed of a conductive plate whose circumference is half-wavelength and is shorted to terminal cavity at its edge; however, this antenna operates as monopole antenna rather than slot antenna, because current on terminal cavity generates rather strong radiation.

Many researchers have devoted themselves to realizing the practical use of planar inverted F antenna, focusing on miniaturization, achievement of wideband characteristics and development of a new built-in antenna.

### 3.1 Miniaturization Methods

Methods miniaturizing inverted F antenna have been proposed in order to shrink terminal volume. A notch on planar element has been proposed for miniaturization of planar element (Fig. 6). A notch near a feed point was efficient for miniaturization of planar inverted F antenna [21]. This notch operates as a detour for RF current and increases the electrical length of the antenna.

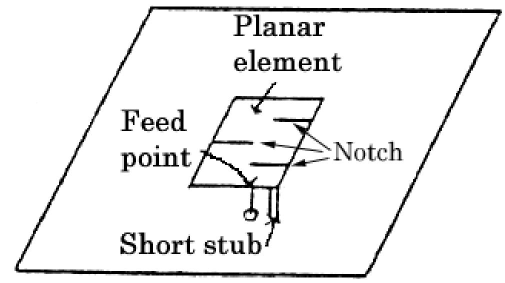



**Fig. 6** PIFA with notch for miniaturization [21].

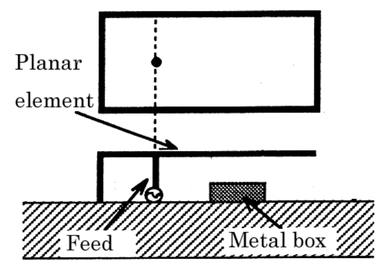



**Fig. 7** PIFA with metal box [23].

As in the case of microstrip antenna, the method of loading a dielectric between planar element and terminal cavity has been put into practical use for cellular phones [38]. A method of putting a conductive box between planar element and terminal cavity has been proposed [22]. This method was put into practical use by employing a dielectric filter as the box [23] (Fig. 7). Furthermore, a method of bending an edge of a planar element was proposed in [24] (Fig. 12). These methods cause antenna capacitance to increase, which lowers resonance frequency of an antenna.

### 3.2 Methods for Realizing Wideband Characteristics

Three methods have been proposed for realizing the wideband characteristics of inverted F antenna; optimization of the shape of inverted F antenna, addition of an element, and optimization the length of terminal cavity.

It has been clarified that a square is the optimum shape of planar element for realizing wideband characteristics of the antenna [25]. Also, it has been shown that appropriate selection of terminal cavity structure is required for further improvements in antenna bandwidth [6]. Moreover, it has been shown that a half wavelength of terminal cavity achieved maximum bandwidth [26].

With the view to realizing an inverted F antenna with wideband characteristics, a study of a method of adding an element started at an early period. Wideband inverted F antenna, which has an added element near its feed point and also has a parasitic element at

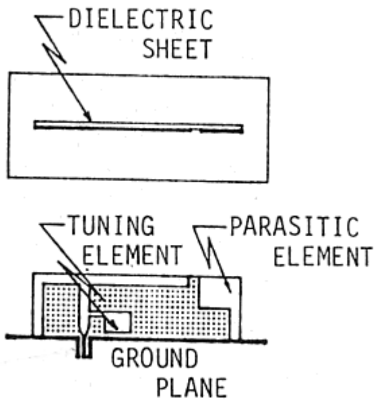



**Fig. 8** Print IFA with parasitic element [27].

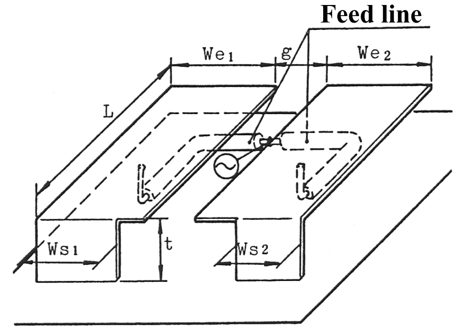



**Fig. 9** PIFAs fed by parallel lines [31].

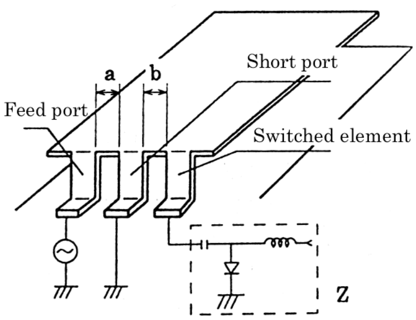



**Fig. 10** PIFAs with switch element[34].

the open end of antenna element (Fig. 8), has been proposed [27]. The parasitic element causes dual resonance and the added element is for matching its impedance with that of feeding cable.

The antenna, composed of two planar inverted F elements mounted on the same cavity, has wideband characteristics. These characteristics are caused by electromagnetic coupling between two antennas, which differ slightly in size [28].

Also, wideband characteristics have been achieved by adding planar element at a point near the feed point [29]. The parallel resonance characteristics of the additional element cause these wideband characteristics [30]. Wideband characteristics have been achieved by two parallel-fed planar inverted F antennas [31]. This antenna employed two planar inverted F antennas, each having different resonance frequency, and feeding cables whose length was optimized to eliminate antenna coupling (Fig. 9).

A method of adding shorted parasitic element parallel to inverted F antenna has been proposed. The structure of the element, which reverses the feed point and the short point of the antenna, causes strong coupling between antenna and parasitic element [32]. A meander inverted L antenna is proposed as a similar type of this antenna. This antenna realizes a wideband characteristic by using a meander parasitic element, which is fixed under the antenna element [33].

### 3.3 Dual-frequency Operation

To respond to the rapid increase in cellular phone users in the second half of the 90s, NTT DoCoMo had to decide how to expand of its operating frequency band, and several methods were proposed for realizing PIFA for such a requirement.

PIFA with switched short element has been proposed (Fig. 10). The element changes the width of shorted element of PIFA [34]. Shorted microstrip antenna with a slit and loading capacitances on each edge has been proposed [35]. Furthermore, shorted microstrip antenna with a slot on its planar element has been proposed. This slot operates as both a round-about path for a low-frequency current and a choker for a high-frequency current [36].

### 3.4 Reduction of Influence from Human Body

The first influence from the human body to be noted was a change of terminal angle in the talk position. According to measured statistical data, the inclined angle was almost 60 degrees. The influence of a mounted position of planar inverted F antenna on terminal cavity was investigated in the case of such an angle, and the result showed that type C in Fig. 11 realized high averaged gain [37].

Directivity characteristics of inverted F antenna are employed to reduce an influence from a human body [24]. Inverted F antenna mounted on the center area of terminal cavity has good F/B ratio. Because of such these characteristics, an influence from the human body behind an antenna is reduced (Fig. 12). In order to investigate these characteristics in detail, the F/B ratios of planar inverted F antenna mounted on terminals of various lengths have been clarified [38].

Furthermore, it has been clarified that an operation frequency changed degradation of radiation efficiency of planar inverted F antenna by a human body [39]. This study progressed and it has been clarified that shorted microstrip antenna had an efficient per-

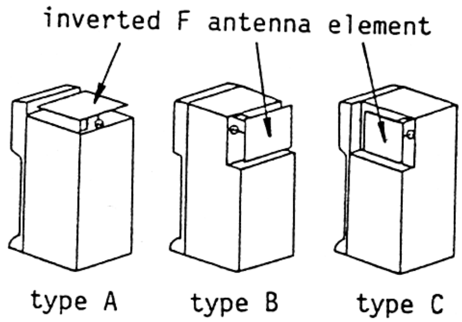



**Fig. 11** Mounted side of planar inverted F antenna [37].

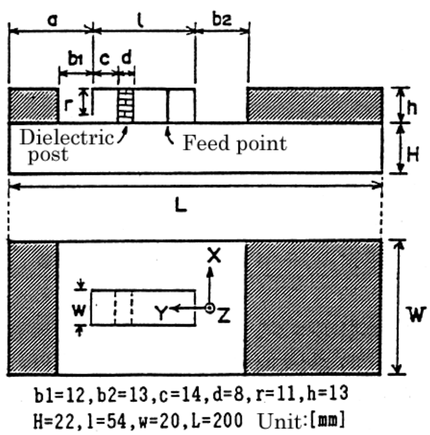



**Fig. 12** inverted F antenna for reducing influence from a user [24].

formance because of its rather high directivity [40].

### 3.5 Other Built-in Type Antennas

Besides the inverted F antenna, various low-profile monopole antennas have been proposed. They include folded monopole antenna (Fig. 13) [41], S-shaped antenna (Fig. 14)[42], and shorted microstrip antenna fed by electrical coupling element [43].

The last-named antenna achieved dual-frequency operation by using switched element coupled with planar element.

Cavity back slot antenna for wireless terminal has been realized and put into practical use on a PHS terminal [44]. Based on this antenna, tunable resonance antenna was realized by putting switched element in its slot [45] (Fig. 15).

One of the problems concerning terminal antennas is that the posture of a terminal often changes. Rotating microstrip antenna was proposed as a solution to this problem. This antenna is fed by an electromagnetically coupled feeder, which also acts as an axis of rotational element [46].

A dielectric loaded antenna is known as a small volume antenna [2]. This antenna has progressed uniquely in Japan; that is, the antenna has become a low profile.

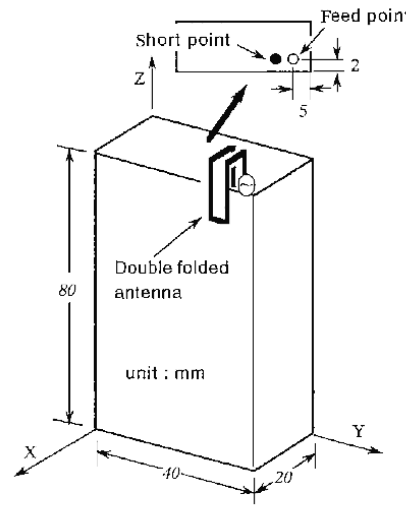



**Fig. 13** Folded monopole antenna [41].

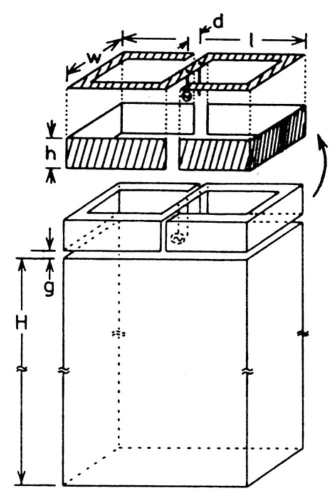



**Fig. 14** S-type antenna [42].

This progress realizes a surface mount like other chip parts by a chip-mounting machine.

This antenna includes a monopole antenna type [47],[49] and an electrical coupled antenna type [47]-[52] (Fig. 16). Monopole antenna type realizes a drastic miniaturization by employing a helical element [49], and electrical coupled antenna type has a wideband characteristic [47]-[50]. Both of two types are put in practical use; and, recently, an influence from a human body is studied [51],[52].

Moreover the antenna technologies for pagers are briefly reviewed here.

Fujimoto et al. reported the first important results. They clarified that magnetic-current antenna is suitable for use in the vicinity of a human body [2]. For example, gain of loop antenna is raised when it is arranged perpendicular to the human body, because its aperture is almost doubled by the human body,

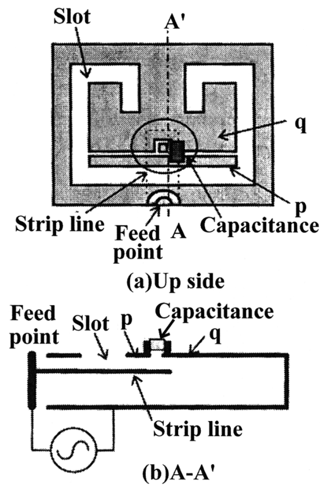



**Fig. 15** Slot antenna with variable capacitance [45].

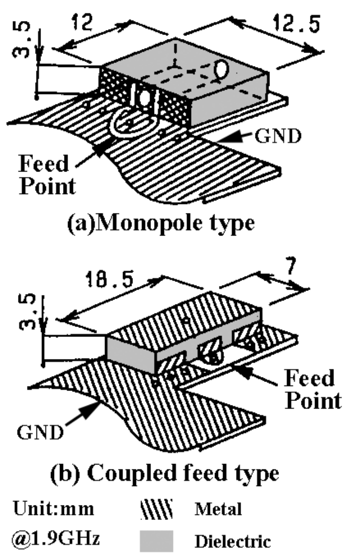



**Fig. 16** Two types of chip antenna [47].

which works as a ground plane. This research resulted in miniaturization and low-profile pager antenna [53], and it resulted in the development of an antenna for a wristwatch-type terminal [54].

## 4. Diversity System

In line with the expansion of a communication area, a counter measure for fading has been required order to improve communication performance. Therefore, NTT DoCoMo decided to employ a diversity system for cellular phone terminals. This decision opened up new technical subjects, for example, design methods for diversity antennas mounted on terminal cavities.

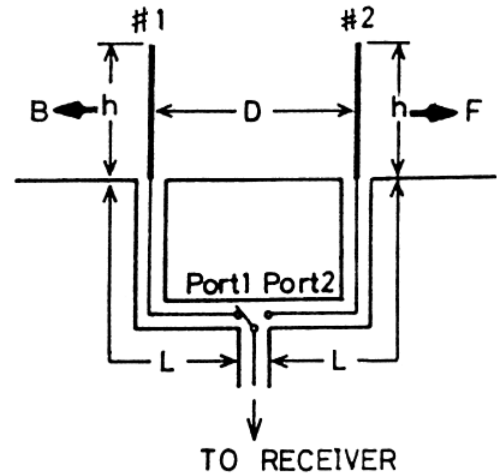



**Fig. 17** Monopole antennas for antenna selection diversity [5].

### 4.1 Diversity Antenna with Electromagnetic Coupling

Sawaya et al. proposed optimization of correlation coefficient between monopole antennas on a ground plane (Fig. 17) by using electromagnetic coupling between antennas [5]. A feed line for an unselected branch works as reactance element for antenna selection diversity. The reactance values change the strength of electromagnetic coupling between antennas. The coupling changes a radiation pattern of antennas; and the radiation pattern changes correlation coefficient between antennas. Therefore, correlation coefficient keeps a small value by optimization of the length of feed lines.

Recently, this method has been employed for diversity antennas for terminals [55]. Using a terminal model consisting of a combination of monopole antenna and inverted F antenna, it was found that electromagnetic coupling lowers correlation coefficient but then degrades matching characteristics. Therefore, an optimization method for the shape of an inverted F antenna has been proposed in place of electromagnetic coupling to lower correlation coefficient. Moreover, a design method for termination reactance of inverted F antenna has been proposed as a method of reducing electromagnetic coupling [56].

### 4.2 Evaluation of Diversity Performance

In the early stage of the study on diversity antennas for cellular phone terminals, correlation coefficient was clarified only as an experimental result.

Taga and Tsunekawa clarified correlation coefficient of two planar inverted F antennas mounted on terminal cavity in outdoor experiments (Fig. 18) [57], [58]. The moment method with wire grid model has been employed to simulate diversity antennas; characteristics of two dipole antennas arranged on top of terminal cavity have been calculated. The results showed

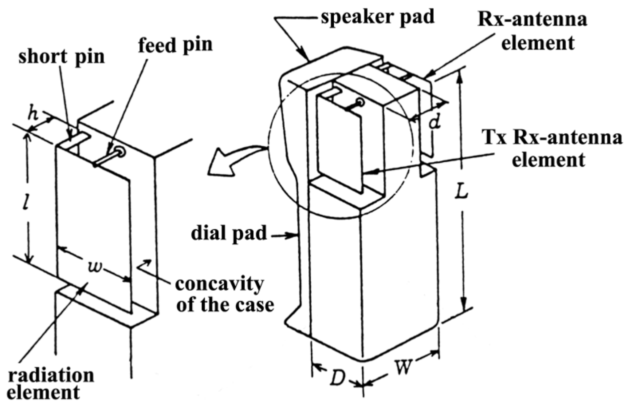



**Fig. 18** PIFA for diversity antenna [57].

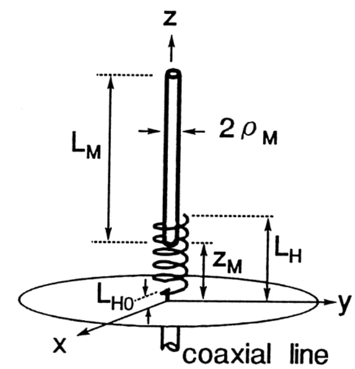



**Fig. 19** Half-wavelength monopole antenna fed by helical element [32].

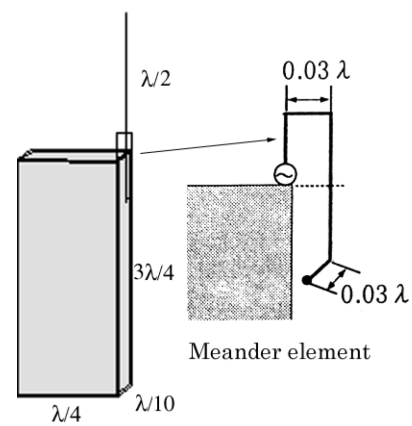



**Fig. 20** Half-wavelength monopole antenna fed by meander element [65].

that a value of correlation coefficient is relatively low when the distance between the antennas is comparatively small, because radiation patterns are changed by electromagnetic coupling between antennas [59], [60].

In order to count on a distribution of an arrival wave to an evaluation of an antenna for a cellular phone, the distribution over solid angles in a real field of an urban area has been measured, and a typical value was obtained [61]. Furthermore, performance of polarization diversity antenna, which is constructed by a cross dipole antenna, was evaluated by using the typical distribution values, and the obtained results showed the validity of the typical value.

Correlation coefficient between half-wavelength monopole antenna and planar inverted F antenna mounted on a terminal has been evaluated under various arrival wave distributions [63],[62].

In order to predict diversity gain of a real terminal, it is necessary to consider the details of a radio system. Diversity gain of an antenna mounted on a terminal has been evaluated in the case of the PDC communication system [64].

## 5. The Latest Topics; Antennas after IMT2000 Terminals in Japan

In 2001, the IMT2000 system service started in Japan. The terminals for W-CDMA system employed built-in antenna or half-wavelength monopole antenna. This section reviews these antenna technologies.

### 5.1 Half-Wavelength Monopole Antennas

2GHz band is employed for the IMT2000 system, because its rather short wavelength provides flexibility in antenna design; for example, half-wavelength monopole antenna is employed.

Half-wavelength monopole antenna requires a matching circuit; therefore quarter-wavelength element is employed for a matching circuit. Electromagnetic coupling of these two elements has been proposed for realizing both wideband characteristics and dual-frequency operation [32] (Fig. 19).

Undesired radiation from quarter-wavelength element is one of an important issue. It has been clarified that fixing a connecting point of these two elements close to the surface of a terminal cavity reduced surface current [65] (Fig. 20).

### 5.2 Built-in Half-Wavelength Antenna

In 1986, Taga and Tsunekawa proposed a built-in dipole antenna with a balun in their patent [66]. The antenna has been restored for the IMT2000 terminal (Fig. 21) [67]. They proposed a wideband method for the antenna in which parasitic element is used.

A method of arranging a built-in dipole antenna into a flip portion of a terminal has been proposed (Fig. 22). This antenna employs a matching circuit, which changes an antenna impedance in accordance with the opening-and-closing state of a flip [68].

T-type monopole antenna that operates in a parallel resonance mode has been proposed. This antenna is a microstrip dipole antenna, and its self-resonance characteristic avoids undesired radiation from terminal

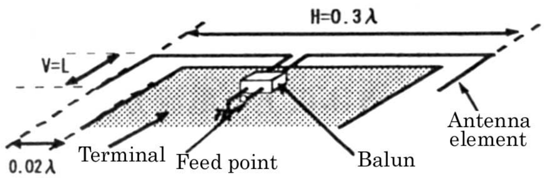



**Fig. 21** built in type dipole antenna [67].

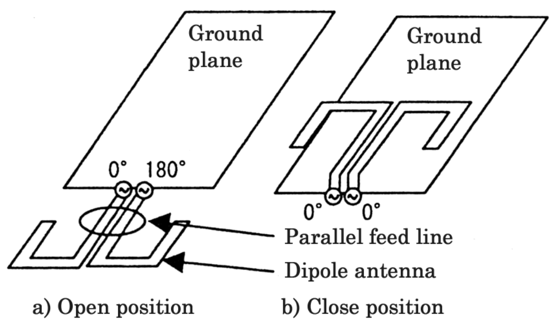



**Fig. 22** built in type dipole antenna on terminal flip [68].

cavity. [69].

Morishita et al. has proposed a folded dipole antenna [70]. A novel folded loop antenna (Fig. 23) for a wireless terminal has been proposed together with an advanced design concept [70] for handset antennas.

The design concept satisfies the principal requirement for terminal antennas namely (1) small size and yet (2) has capability of mitigating degradation of antenna performance due to the body effect, and (3) of reducing SAR value in the human head at the handset talk position, in addition to the indispensable requirements for handset antennas such as (4) low profile, and (5) light weight.

The technology makes this antenna (a) an integrated structure, which is a typical application of a fundamental concept for making antennas small and (b) a balanced structure which has been proved to be very effective in satisfying requirements (2) and (3).

The folded loop antenna is essentially a two-wire transmission line, folded at about a quarter-wavelength to form a half-wave folded dipole, and yet appears to be a loop of one wavelength. This antenna also has an integrated structure, which is composed of radiation element and reactive element; these being constituted by using a two-wire transmission line, and folded at a quarter-wavelength to form a folded half-wave dipole equivalently. The equivalent folded dipole acts mainly as the radiator and the two-wire line is used for adjusting the antenna impedance [72]. This antenna can be designed to have enough gain and bandwidth to be applied to handsets currently in practical use.

## 6. Conclusion

This paper has reviewed technologies for terminal cavity current, small antennas and diversity antenna. Antenna technology for cellular phones has long been extensively researched in Japan. This research has contributed to the miniaturization of terminals used worldwide. The technology developed as a result of this research is expected to be applied in development of smart antennas (beam scan, wideband characteristic) for IMT2000 terminals from now on.

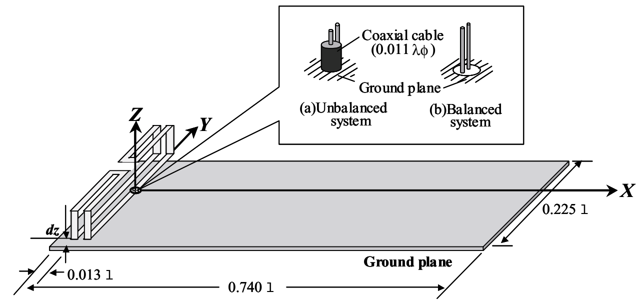



**Fig. 23** Built-in folded dipole antenna [70].

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