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Recent Technologies in Japan on Array Antennas for Wireless Systems

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SUMMARY Array antenna technology for wireless systems is highly integrated for demands such as multi-functionality and high-performance. This paper details recent technologies in Japan in design techniques based on computational electromagnetics, antenna hardware techniques in the millimeter-wave band, array signal processing to add adaptive functions, and measurement methods to support design techniques, for array antennas for future wireless systems. Prospects of these four technologies are also described.

key words: *array antenna, multiple antenna, computational electromagnetics, millimeter-wave, antenna measurement, signal processing*

1. Introduction

In recent years, demands on various wireless systems, such as mobile communications, radar, sensing and measurement, are rapidly growing in all societies. There are two demands on antenna for these wireless systems: one is multi-functionality and the other is high-performance. Array antenna technology is one of the best solutions as integrated antenna system having these features, and has been studied and developed by many researchers and engineers. The technology is based on the following four key elements. They are computational electromagnetics as basis of array designs, millimeter-wave antennas expected wideband usage as array antenna hardware, array signal processing to add adaptive functions to array antennas, and measurement methods to support design techniques. Low power consumption is important in millimeter-band technologies, however, it is out of scope in this paper due to the space limitation.

This paper surveys the current states and discusses their directions focusing on these four technologies important for future wireless systems. This paper is organized as follows. Section 2 gives a brief description of recent studies mainly performed by one of the authors on the computational electromagnetics for large-scale problems, such as large-scale array antennas and reflectarrays. Section 3 deals with millimeter-wave band array antennas as examples of array antennas, because they could have higher functionality coming from the small physical dimension in comparison with microwave-band array antennas. Section 4 describes array signal processing technologies such as adaptive array for interference suppression and MIMO system for high-speed wireless communications. Section 5 treats recent measurement technologies on array antennas. Calibration methods of array antennas themselves and various measurement techniques using array techniques for wireless systems are described.

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2. Computational Electromagnetics for Large-Scale Array Antennas

The field of computational electromagnetics (CEM) has attracted a great deal of attention in the last few decades in Japan, because there has been a strong demand from the Japanese electric and electronics industry for devolving various types of antennas to support the innumerous wireless systems which are keeping continuous evolution. In the early stage of the CEM research, a satisfied numerical analysis was only limited to the conducting and electrically small antennas. Numerical analysis for more and more complex antenna geometries and scattering dielectric bodies has become available from 1990s, because of the rapid development of the finite difference time domain (FDTD) method power by efficient absorbing boundary conditions [1]–[5]. Among the numerous publications on antenna modeling by the FDTD, [1] was one of the earliest publications, demonstrating the input impedance and gain of a monopole antenna on a conducting box. Since then, the techniques of FDTD has been largely improved and enhanced so that it is capable of dealing with large-scale problems, especially with the radiation and scattering of large-scale array antennas and electromagnetic scatterers. For example, the beam steering characteristics of a large-scale array antennas consisting of cavity-backed slot antenna elements were analyzed by the FDTD to take into account the feeder geometry and phase shift [6], [7]. The FDTD, hybridized with the method of moments (MoM) and high frequency approximations was applied to numerically analyze the indoor propagation where tens of cubic scatterers between transmitting and receiving antennas were modeled to investigate the effect of these scatterers on the channel capacity in indoor environment [8], [9]. Nowadays, the FDTD modeling becomes more and more complicated, and the model size becomes larger and larger because more and more powerful computers and efficient algorithms are developed continuously.

Some MoM based fast algorisms such as the fast multipole method (FMM) [10], [11] and the characteristic basis function method (CBFM) [12] have been developed, demonstrating that the computational cost of the MoM can be largely reduced. Various large-scale problems can be solved using a combination of the FMM and CBFM [13], [14]. However, because the FMM and CBFM include many parameters to speed up the numerical analysis, it is still a challenging work to find a relation between these parameters and computation cost. Konno et al., have derived the computational cost of the FMM and CBFM analytically and demonstrated that the computational cost of the FMM depends on the shape and dimensions of analysis model while that of the CBFM does not [15], [16]. It was also found that the iterative algorithm is very effective in solving the impedance matrix equation, which is very time-consuming process in the MoM analysis of large-scale array antennas. It was found that the computation cost can be reduced greatly for the array antenna analysis if the impedance matrix is decomposed into a number of sub matrices, which describe the self and mutual impedances between the groups of the array [17]. The algorithm can be applied to the sub domain MoM with a fast convergence if the grouping technique is properly used [18]. Furthermore, based on the iterative technique, a method using a sub-array preconditioner to accelerate the convergence of conjugate gradient (CG) iterative solver in the FMM and fast Fourier transform (FMM-FFT) was proposed for analyzing a large-scale periodic array antenna with array elements of arbitrary geometry [19].

An approximate method based on statistical approach was studied in [20] to analyze a huge-scale periodic array antenna supposed to be composed of millions of array elements. Recently, researches on developing algorithms to make maximum use of potential ability of computers for large-scale problems were reported [21], [22].

The great progress in the CEM research has provided a solid foundation and effective tools for the researches on millimeter wave antennas, wireless systems as well as antenna and propagation measurements, which are introduced in the following sections.

Nowadays, most of the antennas for small electric devices are closely integrated with the wireless devices and systems. In order to take into account the effect on the antenna performance, such as the EM scattering and interference, temperature variation caused by these wireless devices and systems, it is required to model both the antennas and the devices, systems, and even the propagation environment in terms of EM radiation, scattering, and thermos diffusion. This requirement caused a great attention and hot topics in the CEM research to solve the multiscale and multiphysics problems.

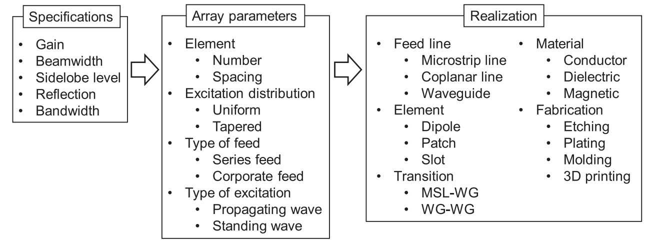

Fig. 1 Flow for realization of an array antenna.

3. Millimeter-Wave Band Array Antennas

3.1 Basic Considerations

Figure 1 summarizes the flow for realization of an array antenna. The antenna specifications such as gain, beamwidth, sidelobe level, reflection, and the bandwidth convert to the array parameters such as the number and spacing of the elements, the excitation distribution, the type of the feed, and the type of the excitation. For the realization of an array antenna, the selection and the combination of the feedline, the elements, the transition, the material, and the fabrication techniques are important.

The following considerations are required especially in the millimeter-wave band. The electromagnetic wave absorption by vapor and oxygen is significant in the millimeter-wave band. There are various ways to compensate the absorption by antenna gain, antenna efficiency, and transmission power. The antenna gain can be increased simply by making the size of antenna apertures or the number of elements in array antennas larger, in comparison with other methods. An array antenna consists of a feed line and radiating elements. Careful evaluation of the combination of the two is important to reduce losses. A planar radiating element such as a patch antenna is preferable for a planar feed line like a microstrip line, while an aperture such as a slot antenna is suitable for a waveguide that is a metal pipe confining an electromagnetic wave. The bandwidth of a series-fed array antenna is dominated by the long-line effect of the feed line, and to increase the bandwidth, partial or full corporate feed is introduced. The loss reduction of the feed line is important to achieve high antenna efficiency. Further, for the millimeter-wave band, antenna characteristics such as radiation pattern, gain, and reflection as well as the connection with an RF circuit, have to include an evaluation of the permittivity and conductivity of the materials used in the antenna fabrication.

3.2 Survey of Current Technologies

After discussing the basic considerations for realizations of array antennas in the millimeter-wave band in the previous sub-section, this sub-section surveys their current technologies on microstrip array antennas, waveguide slot array antennas, connections between antenna and RF circuit, evaluations of the permittivity and conductivity of the materials, beam-switching circuits, and fabrication techniques.

Microstrip array antennas fed by microstrip lines were developed for automotive radars [23], [24], where a simple feed structure was introduced by placing the feed line and the radiating elements in the same substrate. A multilayer parasitic microstrip antenna array was discussed on polytetrafluoroethylene (PTFE) substrate [25], where the multilayer parasitic structure would increase the antenna size without feed lines. An array of Fermi antennas was applied to imaging because of its broadband characteristics [26]. Slot array antennas on the broad-walls [27], [28] or the narrow-walls [29] on hollow waveguides give high antenna efficiency because of their low transmission loss, however the bandwidth becomes limited due to long line effects. Slot array antennas fed by a laminated-waveguide [30] or a substrate-integrated-waveguide [31] were developed because of the simplicity of print-circuit-board fabrication techniques. A hollow-waveguide full-corporate-feed slot array antenna provides both high antenna efficiency and wide bandwidth [32]. Radial line slot antennas were discussed because of the simple and light-weight structure [33], [34]. Rectangular parallel plate slot array antennas fed by post-wall waveguides are provided [35], [36] and the addition of an air layer in low temperature co-fired ceramic (LTCC) parallel plates reduces both the equivalent dielectric constant and the transmission loss. An array antenna introducing metamaterial structure was also investigated, however the loss here is generally large [37].

A low-loss connection between antenna and RF circuit is important. Various types of transitions between a microstrip line and a hollow or post-wall waveguide were proposed [38]–[41]. Investigation of beam-switching circuits to increase the functionality of array antennas and also to mitigate the signal processing such as the Butler matrix is required for low-loss connections with an array antenna for multi-beam operation [42], [43]. Knowing and measuring the permittivity of dielectric and conductivity values of metal are important to evaluate the loss quantitatively [44], [45]. Various types of fabrication techniques such as post-wall waveguides [46], laminated waveguides [47], injection molding [48], [49] and diffusion bonding of laminated plates [50] have been discussed to become able to realize waveguide slot array antennas.

3.3 Future Prospects of Millimeter-Wave Band Array Antennas

This section describes the future prospects related to millimeter-wave band array antennas. The simple prospect is to increase the operating frequency. Electromagnetic-wave operation would be identical for the same electrical size normalized by wavelength in the lossless case. However, material constants such as permittivity, permeability, and conductivity limit the operating frequency and the antenna electrical size. Improvements in antenna fabrication techniques such as 3D printing can be expected to play a role here. 3D printing can make complicate waveguide structures seamlessly. Surface roughness could make loss, however, which does not affect significantly in 15 GHz-band waveguide 8x8-slot array antennas with antenna efficiency of 90% in present [51]. Both loss reduction of the material itself and roughness reduction of the metal surface in the fabrication are important. Beam-switching circuits could be applied to orbital angular momentum communication and LOS-MIMO to increase throughput. An array antenna with a large number of elements can create a volume with uniform field intensity in the non-far region, which could develop into a communication method different from the conventional use in point-to-point, or point-to-multipoint communication. The loss reduction of the beam-switching circuits is also important. Presently single-layer hollow-waveguide 8-way Butler matrix gives small loss of 0.25 dB in measurement in the 22 GHz band [42].

4. Spatial Signal Processing Using Array Antennas

4.1 History of Array Antennas with Signal Processing

In recent years, directional pattern control techniques including spatial signal processing technologies for land mobile communication and terrestrial broadcasting has been developed. Figure 2 shows the history of array signal processing technologies. In this chapter, array signal processing for wireless communication system developed in Japan is introduced with Fig. 2. Here, we call the system which treats single information stream as 'Adaptive Array'. On the other hand, we call the system which treats plural one as 'MIMO system.'

4.1.1 Adaptive Array

Directional patterns of array antennas can be controlled by weighting coefficients and combining the weighted signals. Signal processing antennas where the coefficients are adaptively controlled are called "Adaptive arrays" [52]–[55]. A number of adaptive algorithms for controlling the weight coefficients were developed in the 1960s, however, most were proposed to counter jamming of radar systems. In the period, main purpose of the signal processing was interference

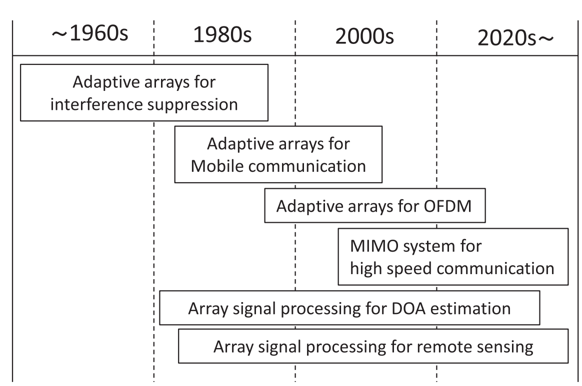

Fig. 2 History of array signal processing technologies.

suppression and maximizing SIR.

Many kinds of adaptive arrays for land mobile communication were developed to counter co-channel and multi-path interference since 1980s in Japan. The code division multiple access (CDMA) and orthogonal frequency division multiplexing (OFDM) transmission schemes were introduced in commercial wireless communication systems around 2000. Adaptive arrays for the CDMA and OFDM transmission schemes were also developed to improve the reception quality of wireless communications [55]–[58].

Adaptive arrays for OFDM transmission are categorized in two typical configurations [59]–[62]. One is a Pre-FFT type adaptive array that was first proposed for OFDM transmission. Received signals are weighted and combined first, and then the combined signal is separated into the respective subcarriers by a fast Fourier transformer (FFT). In this configuration, a usual OFDM receiver can be utilized and 'diversity gain' is obtained in usual situation; however, the performance is degraded by multi-path waves when the delay is beyond the expectation. Pre-FFT type adaptive array is one of an important configuration to reduce A/D converter in massive MIMO system, which is introduced in later section.

The other is a Post-FFT type adaptive array. Received signals of several antenna elements are separated into subcarriers by FFT respectively, and then the signals are weighted and combined. The diversity gain and an effect of multi-path combining are obtained by this configuration. Several FFT processors are required in the Post-FFT type adaptive array, however, the performance of that is superior to the Pre-FFT type. The cost of digital signal processing has decreased in recent years and today the Post-FFT type adaptive array is used in mobile reception system for terrestrial digital broadcasting.

4.1.2 MIMO Systems

Since weighting coefficients of the MIMO system are controlled according with the radio propagation environment, measuring and modeling of the radio propagation environment (the MIMO channel) is very important. Research on MIMO channel modeling has advanced greatly in the 2000s [63]–[65]. An appropriate weighting for the whole of the frequency band is difficult in broadband systems because the MIMO channel in multi-path environments depend on the frequency. Multiple narrow band subcarriers are used in OFDM transmission systems, and the weighting for MIMO transmissions can be controlled in the respective subcarriers. Broadband MIMO communication can be realized by a combination of MIMO and OFDM transmission schemes.

In cellular mobile communication, multiple user terminals (UT) access a single base station (BS). (A UT access plural BS in coordinated multi-point system (CoMP)). To save the costs of UT, a large array antenna has been proposed for the BS allowing fewer antenna elements to be assigned on the UT. This novel MIMO system concept is termed a "massive MIMO" [66], [67], and both computer simulations and experimental investigations have been conducted. The massive MIMO scheme is expected to be a key technology that will enable realization of next generation high speed wireless communication systems.

4.1.3 Remote Sensing and DOA Estimation

The array antenna technology is also utilized in the fields of measurement and monitoring. One useful technology here is "Aperture synthesis." In aperture synthesis, one antenna element is used for measurements and the measurements are repeated with the location changed, then by combining much data in off-line procedures, it acts as a virtual large array. Application of "aperture synthesis" technology include remote sensing for monitoring the whole of the earth which utilizes the measured data gathered by flying vehicles and orbiting satellites [68].

A further application of array antennas is the analysis of radio propagation. To analyze the propagation in mobile communication environments, algorithms to estimate the direction of arrival (DOA) have been developed. In recent years, a super high resolution technique using eigenvalue decomposition or recursive calculations have also been developed [69], [70].

4.2 Future Prospects for Spatial Signal Processing in Wireless Communications

The present situation of wireless communication systems could not be predicted because the evolution has been very fast. It is also hard to predict the situation of the future, however, we will attempt to imagine what future wireless systems that use array signal processing efficiently could be like.

Figure 3 is a conceptual image of such a future wireless system. It has been posited that the key technology for realizing high speed communication is the MIMO transmission technology. In the future, this technology would be applied to satellite communications, terrestrial communications, and indoor communications. Especially, MIMO satellite communications will be realized by using a multitude of satellites. It is preferable that the user terminal cost is low and the number of antennas at the user terminal would

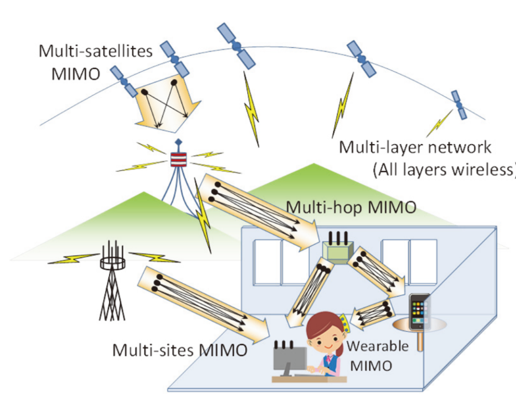

Fig. 3 Conceptual image of a future wireless system.

be small in the first stages. In the further future, for example in 30 years, fully developed MIMO systems using large arrays for both transmission and reception would be realized by utilizing high frequencies. To speed up the realization of high speed wireless communications, a range of MIMO technologies including Multi-hop MIMO, Multi-site MIMO, wearable MIMO, and others would be developed.

5. Measurements Using Array Antennas

Research on the measurement technologies for various antennas has been widely carried out [71]. In this section, we focus on calibration of array antennas, over-the-air method, fast evaluation of mobile devices MIMO propagation for various applications, virtual array methods as array measurement technologies developed in Japan.

5.1 Calibration Techniques of Array Antennas

Array calibration is the key technology for various wireless systems (DOA, radar, MIMO, etc.) mentioned above to reduce measurement errors because the employed array antenna has mutual couplings [72]. The rotating element electric field vector (REV) method has been developed as a practical calibration technology for a phased array antenna, that can measure both amplitude and phase of excitation by only the amplitude receiver [73]. Also, a decoupling method to reduce coupling, matching loss, and pattern distortion due to mutual coupling has been studied [74]. For the technologies, there is the decoupling method with multi-port conjugate matching and bridge-susceptance [75]. Wide band decoupling circuits have been designed by using short stubs for mobile terminal array antennas [76]. A MIMO antenna decoupling method using mutual admittance without phase shifter and matching circuit has also been studied [77].

5.2 Over-the-Air Measurements

Fading wave in multi-path environments is the most important barrier to be overcome for mobile communications. Conventionally a fading simulator has been employed to connect two diversity ports of equipment directly during tests via cables. However, a spatial fading generator over the air (OTA) without cable connections via array elements would be attractive for estimates of base station digital beam forming (DBF) array antennas. In these situations, a number of fading generators using array techniques with spatial spread characteristics have been proposed. A novel type of fading generator using rotating scattering array objects was developed for massive DBF array antennas and MIMO antennas [78]. The generator is a passive device that can be used for both Tx and Rx using radio wave scattering characteristics and has a very simple structure. An active type spatial fading generator has been studied for handy phone antennas using phase shifters and multi-probes [79]. These spatial fading generators with high performance specifications and multi-function MIMO-OTA estimation systems were proposed and developed by many researchers worldwide [80], [81].

5.3 Fast Measurement of Mobile Devices

Radiation efficiency is also one of the most important parameters to evaluate the small antennas used in mobile devices. However, the efficiency measurement is time consuming because a 3-dimentional scan is needed, and many simultaneous measurement methods utilizing array antennas and scatter objects were proposed to overcome this problem [82]–[84]. Since it usually takes time of several tens of minutes to measure the total radiated power by using the power integration method, much effort has gone into reducing the measurement time [85]. A measurement method using a modulated probe array technique was proposed for the fast measurement of radiated power [86]. The accuracy of antenna measurement is usually degraded by scattering from the feed cables of probe antennas, especially the multi antennas are used as the probes in the measurement. This problem can be overcome by using electric/optical (E/O) array sensors. There has been many researches on how to improve the sensitivity and stability of the E/O array sensors as the antenna probes [87]–[90]. The SAR measurement is important to evaluate the electromagnetic exposure to the human body caused by mobile devices. An accurate and fast SAR measurement system has been developed using O/E probe array [91].

5.4 MIMO Propagation for Various Applications

Array techniques are also very useful for propagation for various wireless applications. A number of MIMO propagation research studies have been reported recently as many radio systems have adopted MIMO technologies [92], [93]. The MIMO technique can be applied to communications and sensing or radar systems that are non-communicative, by employing MIMO propagation characteristics [94], [95]. There is also a scheme for secret key agreement based on radio propagation characteristics using array antennas that have been developed as a novel approach to this application [96].

5.5 Measurements Using Virtual Array

The synthetic aperture array (virtual array) technique can be applied to not only radar systems mentioned above but also antenna and radio propagation measurements for mobile communication systems. The far field pattern of a 1-dimensional long antenna such as a base station antenna is commonly measured in the far field range or in the very near field range. However, the far field pattern and gain can be measured at the middle range by simple calculations using a synthetic aperture [97]. As this method has the practical of using ordinary equipment for far field pattern measurement systems without special attachments, the method is commonly employed for R&D tests and inspections. This method can also be widely applied to measure special and temporal propagation profiles in multi-path environments. In general, the rotating measurement method using a mono directional antenna such a horn antenna is widely used for DOA estimates. The method using a synthetic aperture sets the mono directional antenna not at the center of the turntable but at a point which is offset by several wave lengths [98]. The DOA profiles can be obtained with high resolution by using calculations similar to those in reference [97] when propagation environments are stable.

6. Conclusions

Recent technology and the future prospects with computational electromagnetics, millimeter-wave band operation, spatial signal processing, and measurements in arrays antenna engineering have been reviewed and discussed. New numerical techniques need to be developed for multiscale and multiphysics problems. Fabrication techniques need to be developed to realize millimeter-wave band array antennas. A wide range of MIMO techniques have to be developed to realize future high-speed wireless communications. Novel multi-channel measurement techniques will be required in the future.

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