ANTENNA SYSTEM IN TELECOMMUNICATIONS

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Contents

Summary

Antenna system is a necessary component in telecommunications. In this chapter, the studies and applications of traditional and modern antenna technologies have been summarized. Various parameters and some basic knowledge of antenna, such as radiation pattern, directivity, radiation impedance and radiation principle, have been introduced. Friis transmission formula of radio wave is presented to reveal simply the influence of antenna performance on wireless communications. Some main antenna forms, include wire antenna, aperture antenna, reflector antenna, traveling antenna, and so on, are presented to show their applications in telecommunications. Furthermore some new efforts of traditional antennas, such as microstrip antenna with bandwidth-enhancing and size-miniaturizing, antenna on package, antenna with harmonic suppression, have also been presented. Reconfigurable antenna, fractal

antenna and frequency selective surface (FSS) are indicated as the new concepts of modern antenna technologies. Phased-array antenna, adaptive antenna array and the advanced array antenna technology of multi-input-multiple-output (MIMO) antenna system have been outlined to demonstrate their improving for telecommunications. The propagation modelling has also been mentioned as a part of the whole telecommunication systems. As a potential technique for wireless signal transmitting, time reversal (TR) technique is also recommended.

1. Introduction

Heinrich Hertz invented the first antenna system around 1886, before long Marconi applied the antenna technology to commerce. In 1983, the IEEE standard definitions of term for antennas defined the antenna or aerial as “a means for radiating or receiving radio waves.” In other words, the antenna is the transitional device between free-space and a guiding device, as shown in Figure 1. The guiding device transports the electromagnetic energy between the transmitting source and the antenna. In transmitter, the antenna, called transmitting antenna, radiates the electromagnetic wave and in receiver the antenna, called receiving antenna, receives the electromagnetic wave.

Besides transmitting or receiving the electromagnetic wave, an antenna is also usually required to radiate energy with special manners, for example, enhancing the radiation in some directions and suppressing it in others. Thus the antenna must also serve as a directional device. For satisfying requirements of modern telecommunication systems, various antennas are developed. Nowadays, the antenna has been one of the most critical components in telecommunication systems. An antenna with excellent operating performance can ease the system of its requirements and improve communication performance. The antenna serves to telecommunication system the same purpose that eyes sever to human.

2. Radiation Performance

Some important parameters are defined by IEEE standard definitions of term for antenna to describe the radiation performance of an antenna, such as directivity, gain, antenna efficiency, half-power beam width, bandwidth, polarization, and so on. However, not all of them need to be specified for description of every antenna.

The antenna radiation pattern, determined in the far-field region ($R \geq 2D^2/\lambda$, where R is the distance between the antenna and the observer’s position, D is the largest dimension of the antenna and λ is the wavelength in free space), is a spatial distribution of the radiation properties of the antenna as a function of the observer’s position along a path or surface with constant radius. Radiation properties include power flux density, radiation intensity, field strength, directivity, and so on.

The radiation pattern of most concern is the one of the radiated energy. If the antenna has the property of radiating or receiving electromagnetic waves more effectively in some direction than in others, it can be called a directional antenna, otherwise it can be called an omni-directional antenna.

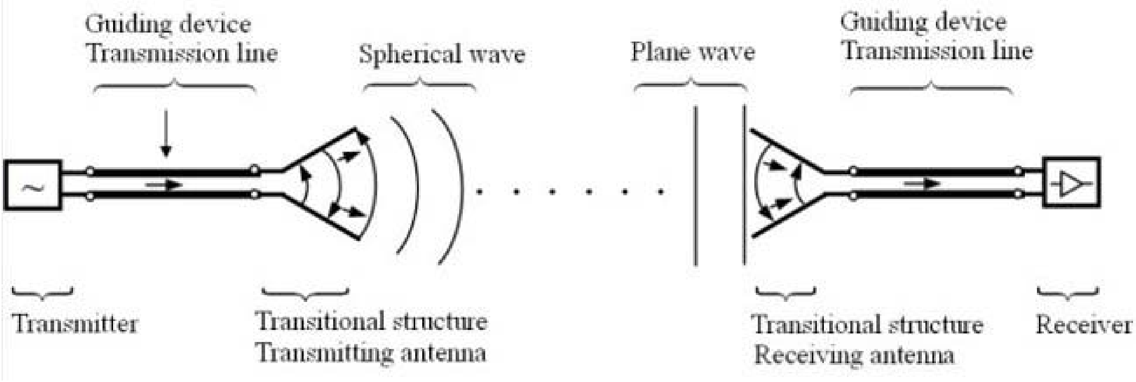

Figure 1: The transmitter and receiver antenna in telecommunication system

Various parts of a radiation pattern may be sub- classified onto main lobe, minor lobe, side lobe and back lobe, as shown in Figure 2. The vector which is used to describe the radiated electric field at a point in far-field region as a function of time is always directed along a line, the field is said to be linearly polarized. If the trace of the electric field is an ellipse, the field is said to be elliptically polarized. Linear and circular polarizations are the special cases of elliptical polarization. The concept of *E*-plane and *H*-plane are often used in describing the radiation performance of linearly polarized antenna. The E-plane is the planes containing the electric-field vector and the direction of its maximum radiation. The *H*-plane is the plane containing the magnetic-field vector and its maximum radiation.

The far-zone *E*- and *H*-field components radiated by antenna are orthogonal to each other and form TEM (to *r*)) mode fields. The radiated time-average power density *S* in given direction on a surface of constant radius R_0 larger than $2D^2/\lambda$ can be calculated by Poynting vector:

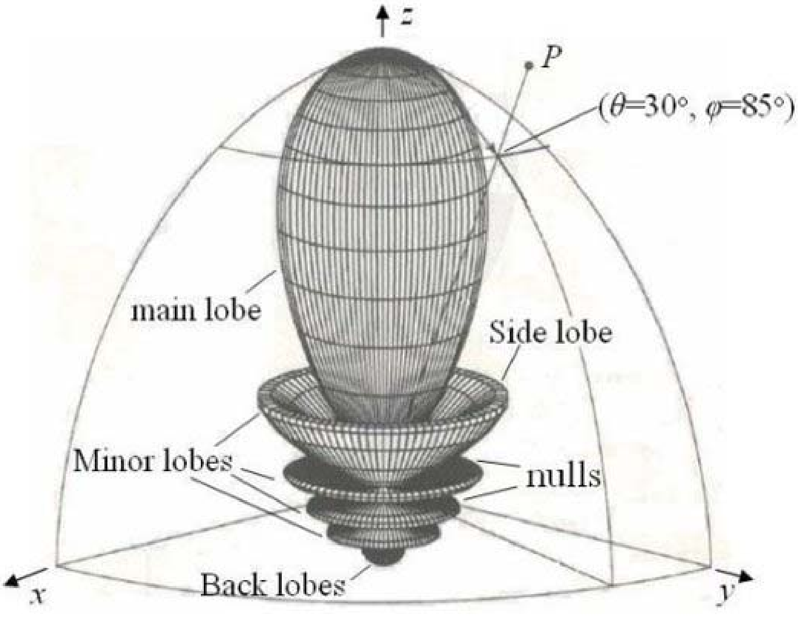

Figure 2: Typical radiation pattern of the antenna

$$S(\theta,\varphi,R_0)=\frac{1}{2}E(\theta,\varphi,R_0)\times H^*(\theta,\varphi,R_0) \qquad (1)$$

where *E* and *H* fields represent peak values of the electric field and magnetic field, respectively, symbol * denotes conjugate complex number. Because the field point is in far-field region, ***S*** is predominately real. The half-power beamwidth is defined as: “In a plane containing the direction of the maximum of a beam, the angle between the two directions in which the radiated power density is one-half the maximum of the beam.”

The radiation intensity in the given direction, defined as the power radiated from an antenna in per unit solid angle, is calculated with

$$U=S\times R_0^2 \qquad (2)$$

U is not related to distance. The total power crossing a closed surface can be obtained by integrating the radiated power density over the entire surface or integrating the radiation intensity over the entire solid angle

$$P_\mathrm{r}=\oiint Sds \quad \text{or} \quad P_\mathrm{r}=\iint Ud\Omega \qquad (3)$$

The radiated average power density over entire sphere or radiation intensity over entire solid angle is,

$$S_0=P_\mathrm{r}/(4\pi\times R_0^2) \quad \text{or} \quad U_0=P_\mathrm{r}/(4\pi) \qquad (4)$$

The directivity of an antenna is the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all direction. Usually, the directivity of an antenna implies the one in the direction having maximum radiation intensity and is expressed as

$$D_0=U_\mathrm{max}/U_0=4\pi\times U_\mathrm{max}/P_\mathrm{r} \qquad (5)$$

For most applications, the radiation patterns of the antenna are so complex that closed form mathematical expressions are not available. So to get an accurate directivity, the numerical technology needs to be applied to calculate the integration expression (3) instead of using the analytical method.

The ratio of the radiated power to the fed power P_f into the antenna is defined as antenna efficiency κ, that is,

$$\kappa=P_\mathrm{r}/P_\mathrm{f} \qquad (6)$$

where $P_\mathrm{f}\geq P_\mathrm{r}$, the losses come from the conductor and the dielectric of the antenna structure, however, the losses of impedance and polarization mismatches should not be included. The antenna gain is defined as,

$$G_0 = \kappa D_0 \tag{7}$$

The bandwidth of the antenna is the frequency range within which the antenna performances (such as input impedance, pattern, polarization, side lobe level, antenna efficiency, gain and beamwidth) satisfy a specified standard. For narrowband antennas, the bandwidth is described as a percentage of the frequency difference between the upper point and the lower point over the center frequency of the bandwidth. However, generally, the bandwidth is defined as the ratio of the upper-to-lower frequencies of the bandwidth for broadband antennas.

Effective area of the antenna is another important parameter for understanding antenna function in telecommunication system. It is used to describe the power capturing characteristics of the antenna when a wave impinges on it from certain direction. A receiving antenna has a physical aperture (i.e. area) A_p, and is used to receive the uniform plane electromagnetic wave with a time-average power density S_i. The effective area A_e of the antenna in a given direction is defined as

$$A_\mathrm{e} = \frac{P_\mathrm{re}}{S_\mathrm{i}}\,(\mathrm{m}^2) \tag{8}$$

where P_re is the received total power by receiving antenna. A typical wireless link in telecommunication system is shown in Figure 3. The distance between transmitting and receiving antenna is r_TR. Power P_t generated by transmitter is fed into the transmitting antenna whose gain and effective area is G_t and A_et, respectively. Receiving antenna has a gain and effective area G_r and A_er, respectively. If the intervening medium is linear, passive and isotropic, the power density at receiving antenna is

$$S_\mathrm{r} = \frac{P_\mathrm{t}}{4\pi r_\mathrm{TR}^2} G_\mathrm{t} \tag{9}$$

Assume the receiving antenna is lossless and matched perfectly (i.e. impedance-matched to the load and polarization-matched to the incoming wave), the received power by receiving antenna is

$$P_\mathrm{r} = S_\mathrm{r} A_\mathrm{er} \tag{10}$$

The relationship between the effective area and the directivity of an antenna is shown as,

$$D = 4\pi \frac{A_\mathrm{e}}{\lambda^2} \tag{11}$$

When the antenna is matched perfectly, the gain is same as the directivity based on Eqs. (6) and (7). Therefore, combining Eqs. (9), (10) and (11) the relationship between transmitting and receiving power can be expressed as

$$\frac{P_{\mathrm{r}}}{P_{\mathrm{t}}}=\frac{A_{\mathrm{er}}A_{\mathrm{et}}}{r_{\mathrm{TR}}^{2}\lambda^{2}} \tag{12}$$

or

$$\frac{P_{\mathrm{r}}}{P_{\mathrm{t}}}=\left(\frac{\lambda}{4\pi r_{\mathrm{TR}}}\right)^{2}G_{\mathrm{r}}G_{\mathrm{t}} \tag{13}$$

which are called the Friis transmission formula. The term $\left(\lambda/4\pi r_{\mathrm{TR}}\right)^{2}$ in Eq. (13) is regarded as the free-space loss factor. Friis transmission formula is significant to direct the design of the wireless link in telecommunication system. For example, if the receiving power sensitivity P_{rmin} of the receiver, gains of transmitting and receiving antennas are known, we can determine the maximal communication distance under the condition of limited transmitting power, also, we can determine the minimal transmitting power under the condition of limited communication distance. However, generally speaking, the practical propagation environment of radio wave is very complex compared with free-space, so free-space loss factor in Equation (13) should be replaced by practical propagation loss in the applied environment for actual telecommunication system design. A special research field, which is called as propagation channel modelling, has been developed for this important issue. It will be mentioned in *Propagation channel modelling*.

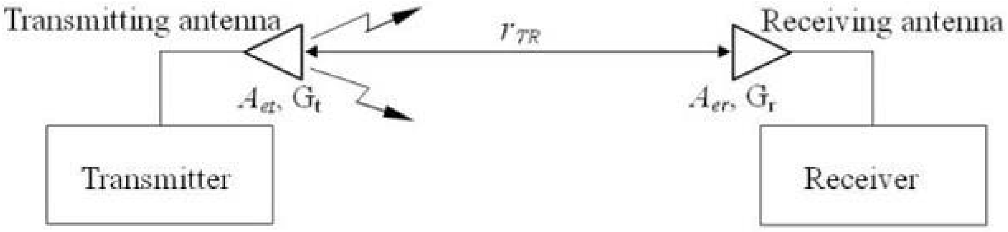

Figure 3: The wireless link between the transmitter and receive antenna in telecommunication system

3. Equivalent Circuit Model

According to the view of circuit, the energy in transmitter system is depleted when the electromagnetic wave is fed into the antenna structure. Therefore, the antenna can be equivalent to a resistance in transmitting mode, just as demonstrated in Figure 4, where $Z_{\mathrm{s}}=R_{\mathrm{s}}+jX_{\mathrm{s}}$ represents the source internal resistor, Z_{T} represents the characteristic impedance of the transmission line, R_{L} denotes the conduction and dielectric losses associated with the antenna structure, R_{r} denotes the radiation impedance which is used to represent radiation by the antenna. R_{r} can be understood as a resistance through which the real power is radiated. The input impedance of the antenna at the input port is $Z_{\mathrm{in}}=R_{\mathrm{L}}+R_{\mathrm{r}}+jX_{\mathrm{A}}$, where X_{A} denotes the antenna reactance. Under conjugate matching condition ($Z_{\mathrm{in}}{}^{*}=Z_{\mathrm{s}}'$), the maximum power can be delivered from source to the antenna. The equivalent circuit in Figure 4 can also be used for the antenna system in the receiving mode. At that time, the source needs to be replaced by a receiver, and the radiation resistance R_{r} represents the transfer of electromagnetic energy from the free-space wave to the antenna. It is easy to calculate R_{r} for a lossless dipole antenna shown in Figure 5. The total radiated power is P_{r}, the current amplitude at reference point of input port is I_{in}, the radiation resistance R_{r} (R_{r} is relative to the reference point) is able to be calculated by,

$$R_{\mathrm{r}} = P_{\mathrm{r}} \Big/ \left(\frac{I_{\mathrm{in}}}{\sqrt{2}}\right)^2 \tag{14}$$

The reflect factor Γ or the VSWR of the antenna are defined for describing the matching characteristics of the antenna to the connected transmission line. They can be expressed as,

$$\Gamma = (Z_{\mathrm{in}} - Z_{\mathrm{T}})/(Z_{\mathrm{in}} + Z_{\mathrm{T}}) \tag{15}$$

and

$$\mathrm{VSWR} = (1+\Gamma)/(1-\Gamma) \tag{16}$$

respectively. Based on Eq. (15), input impedance Z_{in} close to Z_{T} is desired.

4. The Basic Principle of the Radiation

The solutions for the electromagnetic problem are based on Maxwell's equations.

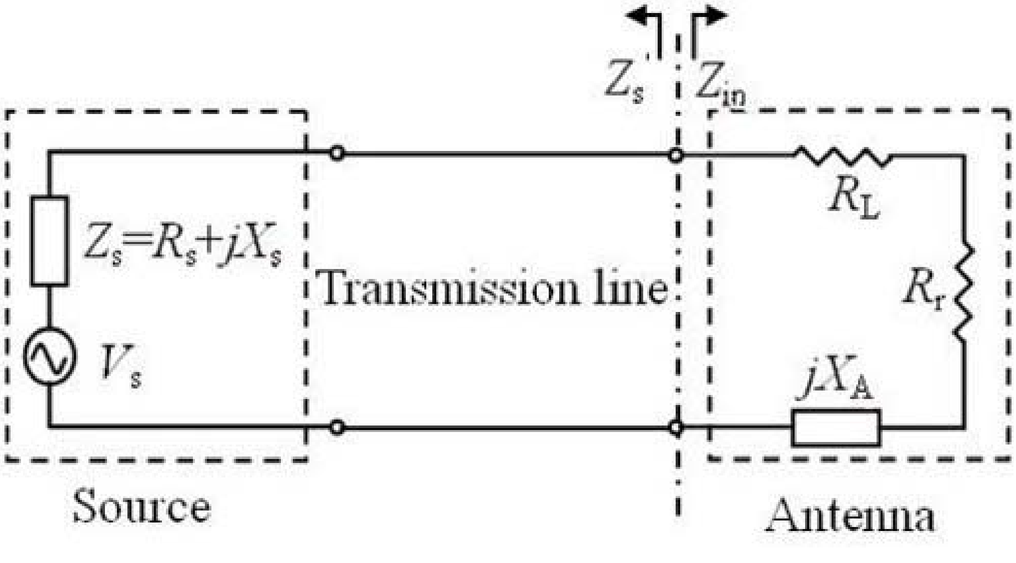

Figure 4: The equivalent circuit model for the transmitter and receiver antenna

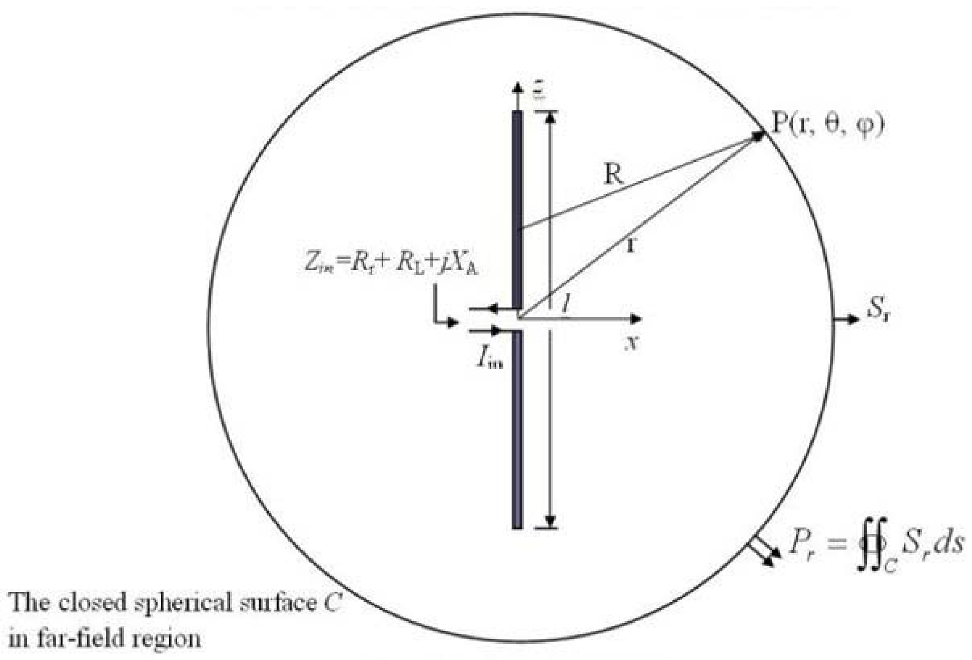

Figure 5: The sketch of the dipole antenna

The auxiliary functions, such as vector potential **A** for electric current source **J** and vector potential **F** for magnetic current source **M**, are introduced usually to simplify the solution of Maxwell’s equation. If **J** and **M** are specified, the auxiliary function **A** and **F** can be determined as,

$$\mathbf{A} = \frac{\mu}{4\pi}\iiint_V \frac{\mathbf{J}e^{-jkR}}{R}dv' \tag{17}$$

and

$$\mathbf{F} = \frac{\varepsilon}{4\pi}\iiint_V \frac{\mathbf{M}e^{-jkR}}{R}dv' \tag{18}$$

respectively. In (17) and (18), $k=\omega\sqrt{\mu\varepsilon}$ (ω is angle frequency) and R is the distance from source to observation point. The electronic field and the magnetic field generated by **J** are,

$$\mathbf{E}_A = -j\omega\mathbf{A} - j\frac{1}{\omega\mu\varepsilon}\nabla\left(\nabla\bullet\mathbf{A}\right) \tag{19}$$

and

$$\mathbf{H}_A = \frac{1}{\mu}\nabla\times\mathbf{A} \tag{20}$$

respectively. In the far-field region, the radiated **E**- and **H**- fields have only θ-direction and φ-direction components in polar coordinates. They can be expressed as,

$$\begin{aligned} E_r &= 0 \\ E_\theta &= -j\omega A_\theta \\ E_\varphi &= -j\omega A_\varphi \end{aligned} \tag{21}$$

and

$$\begin{aligned} H_r &= 0 \\ H_\theta &= j\omega A_\varphi / \eta_0 \\ H_\varphi &= -j\omega A_\theta / \eta_0 \end{aligned} \tag{22}$$

where η_0 is the intrinsic impedance of free space. Similarly, the electric field and the magnetic field generated by **M** are,

$$\mathbf{E}_F = -\frac{1}{\varepsilon}\nabla\times\mathbf{F} \tag{23}$$

and

$$\mathbf{H}_F = -j\omega\mathbf{F} - j\frac{1}{\omega\mu\varepsilon}\nabla\left(\nabla\bullet\mathbf{F}\right) \tag{24}$$

respectively. The **E**- and **H**- fields radiated by **M** in the far-field region have also only θ-direction and φ-direction components. They can be expressed as,

$$\begin{aligned} E_r &= 0 \\ E_\theta &= -j\omega\eta_0 F_\varphi \\ E_\varphi &= -j\omega\eta_0 F_\theta \end{aligned} \tag{25}$$

and

$$\begin{aligned} H_r &= 0 \\ H_\theta &= -j\omega F_\theta \\ H_\varphi &= -j\omega F_\varphi \end{aligned} \tag{26}$$

Then the total **E**- and **H**- fields radiated by **J** and **M** are

$$\mathbf{E} = \mathbf{E}_A + \mathbf{E}_F \tag{27}$$

and

$$\mathbf{H} = \mathbf{H}_A + \mathbf{H}_F \tag{28}$$

In the far-zone, the **E**- and **H**-fields have no **r**-direction components, and their components are orthogonal to each other. The radiated electromagnetic waves propagate to **r**-direction. The ratio between E_θ and H_θ or between E_φ and H_θ equals to the intrinsic impedance of free space, that is

$$\left|\frac{E_\theta}{H_\varphi}\right| = \left|\frac{E_\varphi}{H_\theta}\right| = \eta_0 \tag{29}$$

Based on the introduced principle, in the analysis of the radiation problem, the usual procedure is to specify the source and require the auxiliary functions, and then determine the fields radiated by source.

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Biographical Sketches

Shaoqiu XIAO received Ph.D. degree in Electromagnetic and Microwave Engineering from UESTC in 2003. From January 2004 to June 2004, he joined UESTC as an assistant professor. From July 2004 to March 2006, he worked for the Wireless Communications Laboratory, National Institute of Information and Communications Technology as a researcher with the focus on the planar antenna and smart antenna design and optimization. Now he is working for University of Electronic Science and Technology of China (UESTC), China as an associate professor. His research interests include microstrip antenna, integrated antenna, smart antenna and distributed algorithms. He has authored/coauthored more than 30 technical journal and conference papers. He is a member of IEEE.

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Honglin HU received his PhD degree in communications and information system in Jan. 2004, from the University of Science and Technology of China (USTC), Hefei, China. From Jul. 2004 to Jan. 2006, he was with Future Radio, Siemens AG Communications in Munich, Germany. Since Jan. 2006, he joins the Shanghai Research Center for Wireless Communications (SHRCWC). Meanwhile, he serves as an associate professor at the Shanghai Institute of Microsystem and Information Technology (SIMIT), Chinese Academy of Science (CAS). He is working for international standardization and other collaborative activities. He is a member of IEEE, IEEE ComSoc, and IEEE TCPC. In addition, he serves as a member of Technical Program Committee for IEEE WirelessCom 2005, IEEE ICC 2006, IEEE IWCMC 2006, ACM Q2SWinet 2006, and IEEE ICC 2007. From Jun. 2006, he serves in the editorial board (EB) of Wireless Communications and Mobile Computing, John Wiley & Sons.

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