WIDEBANDWIDTH BASEBAND COMMUNICATION : FACT OR FICTION ?

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ABSTRACT: There are two different ways to communicate with wide bandwidth signals. One is to take a signal with a very narrow instantaneous bandwidth and use a frequency hop technique as being currently used in a CDMA type of environment to generate a wideband signal. This is easy to implement and currently being done for transmission and reception of signals which have small instantaneous bandwidth. The other approach is to deal directly with transmitting a wide baseband signal. For wide baseband data transmission, like signals from computers, the instantaneous bandwidth is very large. The point of this paper is that antennas are highly dispersive devices and their impulse responses must be taken into account in the design of any system which plans to transmit a wide baseband signal. Without taking the antenna effects into account, the wide transmitted baseband signals are quite meaningless. Simple expressions are derived to illustrate that even a point source type of antenna which is virtually nonexistent produces a severe distortion to the signal. The objective of this paper is to bring out the importance of antenna in any wide baseband type of transmission. Also, it is important to note that the transmit waveform is not equal to the receive waveform so the reciprocity of the antenna patterns do not hold in the time domain!

1. INTRODUCTION: In contrast to the acoustic case (where an isotropic source exist), in the electromagnetic case there are no isotropic point sources. Even for a point source, which in the electromagnetic case is called a *Hertzian dipole*, the radiation pattern is not isotropic, but it can be omnidirectional in certain planes.

1.1 Transmission Properties of a Point Radiator

Any element of current or charge located in a medium will produce electric and magnetic fields. However, by the term *radiation* we imply the amount of finite energy transmitted to infinity from these currents. Hence, radiation is related to the far fields or the fields at infinity. A static charge may generate near fields, but it does not produce radiation, as the field at infinity due to this charge is zero. Therefore, radiated fields or far fields are synonymous. We will also explore the sources of a radiating field. If we consider a delta element of current or a Hertzian dipole located at the origin represented by $\mathbf{J}\delta\,(0,\,0,\,0)$, the electric field at any point in space is then given by

$$\mathbf{E}(x,y,z) = -j\omega\mathbf{A} - \nabla\psi = -j\omega\mathrm{A} + \frac{\nabla(\nabla\bullet\mathbf{A})}{j\omega\mu\varepsilon} = \frac{1}{j\omega\mu\varepsilon}\left[k^2\,\mathbf{A} + \nabla(\nabla\bullet\mathbf{A})\right] \qquad (1)$$

However, some simplifications are possible for the far field (i.e., if we are observing the fields radiated by a point source at a distance of $2D^2/\lambda$ from the source, where D is the largest physical

0-7803-8197-1/03/$17.00 (c)2003 IEEE

dimension of the source and λ is the wavelength). For a point source, everything is in the far field. Therefore, for all practical purposes, observing the fields at a distance $2D^2/\lambda$ from a source is equivalent to observing the fields from the same source at infinity. In that case, the far fields can be obtained from the first term only in (1). This first term due to the magnetic vector potential is responsible for the far field and there is no contribution from the scalar electric potential ψ. Hence,

$$\mathbf{E}_{\text{far}}(x,y,z) = -j\,\omega\mathbf{A} = -j\,\frac{\omega\mu}{4\pi}\,\mathbf{J}_i\,\frac{e^{-jkR}}{R} \qquad \text{with} \qquad R = \sqrt{x^2+y^2+z^2} \tag{2}$$

and one obtains a spherical wavefront in the far field for a point source. It is clear that one obtains a spherical wavefront in the far field radiated by a point source. The situation is quite different in the time domain, as the presence of the term ω in the front of the expression of the magnetic vector potential will illustrate.

We consider a delta current source at the origin of the form

$$\boldsymbol{J}_i\,\delta(0,0,0,t) = \hat{z}\,\delta(0,0,0)\,f(t) \qquad \text{and therefore} \qquad \boldsymbol{A}(\mathbf{r},t) = \frac{\mu}{4\pi}\,\frac{\hat{z}\,f(t-|R|/c)}{R} \tag{3}$$

where $\hat{z}$ is the direction of the orientation of the elemental current element and $f(t)$ is the temporal variation for the current fed to the point source located at the origin. There will be a time retardation factor due to the space-time connection of the electromagnetic wave that is propagating. Now the transient far field due to this impulsive current will be given by

$$\boldsymbol{E}(\mathrm{r},t) = -\frac{\partial\boldsymbol{A}(\mathrm{r},t)}{\partial t} = -\frac{\mu\hat{z}}{4\pi R}\,\frac{\partial f(t-|R|/c)}{\partial t} \tag{4}$$

Hence, the time domain field radiated by a point source is given by the time derivative of the transient variation of the elemental current element. Therefore, a time-varying current element will always produce a far field and hence will cause radiation. However, if the current element is not changing with time, there will be no radiation from it. Equivalently, the current density $\boldsymbol{J}_i$ can be expressed in terms of the flow of charges; thus it is equivalent to $\rho\upsilon$, where ρ is the charge density and υ is its velocity. Therefore, radiation from a time-varying current element in (4) can occur if any of the following three scenarios occur:

1.) The charge density ρ may change as a function of time.
2.) The direction of the velocity vector υ may change as a function of time.
3.) The velocity υ may change as a function of time, or equivalently, the charge is accelerated or decelerated.

Therefore, in theory any one of these three scenarios can cause radiation. For example, in a dipole the current goes to zero at the ends of the structure and hence the charges decelerate when they come to the end of a wire. That is why radiation seems to emanate from the ends of the wire and also from the feed point of a dipole where a current is injected or a voltage is applied and where the charges are induced and hence accelerated. Current flowing in a loop of wire can also radiate as the direction of the velocity is changing as a function of time even though its magnitude is constant. So a current flowing in a loop of wire may have a constant angular velocity, but the temporal change in the orientation of the velocity vector may cause radiation. To maintain the same current along a cross section of the wire loop, the charges located along the inner circumference of the loop have to decelerate, whereas the charges on the outer boundary have to accelerate. This will cause radiation. In a klystron, by modulating the velocity of the electrons, one can have bunching or change of the electron density with time. This also causes radiation. In summary, if any one of the three conditions described above occurs, there will be radiation.

By observing (4), we see that even a point transmitting antenna acts as a differentiator of the transient waveform fed to its input. The important point to note is that an antenna acts as a differentiator on transmit, and therefore in all broadband simulations the differential nature of the point source must be taken into account. This implies that if the input to a point radiator is a pulse, it will radiate two impulses of opposite polarities—a derivative of the pulse. Therefore, when a modulated digital signal is fed to an antenna, what comes out is the derivative of that pulse. It is rather unfortunate that very few simulations in mobile communications really take this property of an antenna into account in designing multiple input/multiple output (MIMO) systems.

1.2 Reception Properties of a Point Receiver

On receive, an antenna behaves in a completely different way than on transmit. We observed that an antenna acts as a differentiator on transmit. On receive, the voltage received at the terminals of the antenna is given by $V = \int \boldsymbol{E} \bullet \mathrm{d}\ell$ where the path of the integral is along the length of the antenna. Equivalently, this voltage, which is called the *open-circuit voltage* V_{oc}, is equivalent to the dot product of the incident field vector and the effective height of the antenna and is given by $V_{\mathrm{oc}} = \boldsymbol{E} \bullet \boldsymbol{H}_{\mathrm{eff}}$ with $H_{\mathrm{eff}} = \int_0^H I(z)\, dz = H\, I_{\mathrm{av}}$ where H is the length of the antenna and it is assumed that the maximum value of the current along the length of the antenna $I(z)$ is unity. I_{av} then is the average value of the current on the antenna. This equation is valid at only a single frequency. Therefore, when an electric field E^{inc} is incident on a small dipole of total length L from a broadside direction, it induces approximately a triangular current on the structure. The effective height in this case is $L/2$ and the open-circuit voltage induced on the structure in the frequency domain is given by $V_{\mathrm{oc}}(\omega) = -\dfrac{L E^{\mathrm{inc}}(\omega)}{2}$ and in the time domain as the effective height now becomes an impulse-like function, we have $V_{\mathrm{oc}}(t) = -\dfrac{L E^{\mathrm{inc}}(t)}{2}$. Therefore, in an electrically small receiving antenna called a *voltage probe* the induced waveform will be a replica of the incident field provided that the frequency spectrum of the incident electric field lies mainly in the low-frequency region, so that the concept of an electrically small antenna is still applicable.

Thus the transmit and the receive patterns are not reciprocal in the time domain even for a delta function type point antenna!

2. RADIATION AND RECEPTION PROPERTIES OF FINITE-SIZED DIPOLE-LIKE STRUCTURES

The reason for choosing finite-sized structures is that the impulse responses of these wire-like structures are quite different from the cases described in the preceding section. For a finite-sized antenna structure, which is comparable to the wavelength at the frequency of operation, the current distribution on the structure can no longer be taken to be independent of frequency. Hence the frequency term must explicitly be incorporated in the expression of the current.

2.1 Radiation Fields from Wire-like Structures in the Time Domain

For a finite-sized dipole, the current distribution that is induced on it can be represented mathematically to be of the form $\mathrm{I}(z) = \sin\left[k\left(\frac{L}{2} - |z|\right)\right]$ where $k = 2\pi/\lambda = \omega/c$, where c is the velocity of light in that medium and λ is the wavelength for the current at the frequency of operation. We here assume that the current distribution is known. However, in a general situation we have to use a numerical technique to solve for the current distribution on the structure before we can solve for the far fields. This is particularly important when mutual coupling effects are present or there are other near-field scatterers. When the current induced on the dipole is a function of frequency, the far-zone time-dependent electric field at a spatial location r is given by

$$E_\theta(t) = \frac{\eta}{2\pi r \sin\theta} \left\{ \begin{array}{c} I\left(t - \frac{r}{c}\right) + I\left[t - \frac{r}{c} - \frac{L}{c}\right] - I\left[t - \frac{r}{c} - \frac{L}{2c}\,(1+\cos\theta)\right] \\ - I\left[t - \frac{r}{c} - \frac{L}{2c}\,(1-\cos\theta)\right] \end{array} \right\} \tag{5}$$

where $I(t)$ is the transient current distribution on the structure. It is interesting to note that for L/c small compared to the pulse duration of the transient current distribution on the structure, then from [14] the far field can be written as

$$E_\theta \simeq \frac{\eta}{2\pi r}\left(\frac{L}{2c}\right)^2 \frac{\partial^2 I\left(t - \frac{r}{c}\right)}{\partial t^2} \sin\theta \tag{6}$$

that is, the far-field now is proportional to the second temporal derivative of the transient current on the structure. It is important to note that this expression is quite different from (4), which is applicable for electrically small structures.

2.2 Induced Voltage on a Finite-Sized Receive Wire-like Structure due to a Transient Incident Field

For a finite-sized antenna of total length L, the effective height will be a function of frequency and it is given by

$$H_{\text{eff}}(\omega) = \int_{-L/2}^{L/2} \sin\left[k\left(\frac{L}{2} - |z|\right)\right] dz = \frac{2c}{\omega}\left[1 - \cos\left(\frac{kL}{2}\right)\right] \tag{7}$$

Hence the induced voltage for a broadside incidence will be given approximately by $V_{\text{oc}}(\omega) = -H_{\text{eff}}(\omega)\,E^{\text{inc}}(\omega)$ .In the time domain, the effective height will be given by

$$H_{\text{eff}}(t) = jc \begin{cases} +1 & 0 < t < \dfrac{L}{2c} \\ -1 & \dfrac{-L}{2c} < t < 0 \end{cases} \tag{8}$$

Hence the transient received voltage in the antenna due to an incident field will result in the following convolution (defined by the symbol ✪) between the incident electric field and the effective height, resulting in

$$V_{\text{oc}}(t) = -E^{\text{inc}}(t) \text{ ✪ } H_{\text{eff}}(t) \tag{9}$$

This illustrates that when (9) is used in (8), the received open-circuit voltage will be approximately the derivative of the incident field when L/c is small compared to the duration of the initial duration of the incident pulse.

3. CONCLUSION:

These simple expressions illustrate that antenna effects are extremely imporatnt when communicating with signals which have large instantaneous bandwidth. The presentation at the conference will discuss plots of the various impulse response results both theoretical and experimental to illustrate what the impulse response of some of the common antennas are very complicated and they definitely affect the data transmission process.

The other point is that the old paradigm in antenna theory which states that the antenna transmit and the receive patterns are equal in the frequency domain is no longer valid in the time domain. We know that a product in the frequency domain becomes a convolution in the time domain and therefore the transmit and the receive waveforms for an antenna are not reciprocal and this should be the new paradigm when dealing with signals which have a large instantaneous band width.