Elements of an Ultra-Wide Bandwidth (UWB) Radio

Bill Brouwer

Overview

- **Principles of Wireless**; information, bandwidth, channel, modulation, multiple access, carrier-less system.
- **Communications theory**; simple model, transmission and reception, orthogonal functions, sliding correlator receiver.
- **Non-sinusoidal solutions to Maxwell's equations**; radiation, large current radiator, propagation, solution for transient boundary conditions.
- **A general prescription for UWB**;
- Literature
- Conclusion

Principles of Wireless

- Typically, some information, the *baseband* or *intelligence* is impressed onto a sinusoidal carrier wave of significantly higher frequency, a process referred to as *modulation*.
- One or two features of the carrier then has/have some time variation and hence information is transmitted.
- Width of frequency spectrum produced referred to as the *bandwidth*; *amount* of information transmitted, received expressed by Hartley as

$$\text{information} \propto \text{bandwidth} \times \text{time of transmission}$$

- *Channel*; a path over which we may send information

•Conventional wireless system great for antenna design and selectivity, due to resonance of sinusoids with L-C circuits.

•Limited by bandwidth, the amount of information transferable, *or* number of users allowed through some means of *multiplexing*, e.g., Time Division Multiplexing (TDM) or Frequency Division Multiplexing (FDM)

•Hence motivation for ***Ultra Wide Bandwidth (UWB)***, a system utilizing vast frequency spectrum.

•Essentially a *carrier-less* system which sends baseband pulses directly; Fourier analysis reveals frequencies for a pulse from D.C. up to ~ reciprocal of pulse length, e.g., ns pulse has energy spread thinly from D.C. up to GHz range

***Example:* Covert operation using carrier-less transmission**.

- Conventional system uses frequency hopping (e.g., over 50 channels) referred to as *spread spectrum.*
- One accessible channel of large bandwidth 100 MHz may have applied to it a sine wave with period 0.1 ns, lasting 10ns.
- Carrier free system using pulse of 0.1ns length has 100 pulses in such time.
- Pulses with amplitude +/- 1 may be arranged 2^{100} ways.
- Information may be transmitted using Pulse Width Modulation (PWM) and hence each pulse sequence may represent a *different* channel.
- Consequently, there is $\sim 10^{30}$ *increase* in the number of available channels over a conventional spread spectrum system.

Communications Theory

- Mathematical theory involving probability, statistics, analysis etc.
- Simple transmitter model has input m_i generating a series of impulses s_{ij}, fed to N filters, the impulse response of the jth filter denoted by $\phi_j(t)$.
- N "building block" waveforms $\phi_j(t)$ are orthonormal, i.e.,

$$\int_{-\infty}^{\infty} \varphi_i(t)\varphi_j(t)dt = \delta_{ij}$$

- Sum of the filter impulse responses is transmitted signal $s_i(t)$, one probable member of the set $\{s_i(t)\}$, $i=0,1,\ldots, M-1$.

•Functions *$\phi_i(t)$* may be either *time* or *frequency* displaced in nature; the particular functions used are dependent on the application.

•*Sinusoids have been used predominantly in r.f. engineering, owing to ease of solution of Maxwell's equations for sinusoidal variation, coupled with principle of circuit resonance.*

•Recovery of the signal vectors follows using orthonormality;

$$\int_{-\infty}^{\infty} s_i(t)\varphi_l(t)\,dt = \int_{-\infty}^{\infty}\left[\sum_{j=1}^{N} s_{ij}\varphi_j(t)\right]\varphi_l(t)\,dt$$

$$= s_{il}$$

•However, during transmission over a channel, signal is subjected to noise $n_w(t)$ e.g., white Gaussian, such that received signal is

$$r_i(t)=s_i(t)+n(t).$$

•In an ideal receiver, the input message m_i must be 'guessed at' using a knowledge of the probabilities for the individual m_i.

•Usually a system is composed of several channels and hence there is a set of $r_i(t)$ (hence $s_i(t)$), referred to as a vector **r** (hence **s**).

•Determining the input message amounts to *maximizing* a function containing dot product of **r** and **s** and a constant.

•In a *correlation receiver*, **r** is recovered from a bank of *N* multipliers and integrators. Dot product is obtained from a *weighting matrix*.

Non-Sinusoidal Solutions to Maxwell's Equations

- Sinusoidal waves represent *particular* solutions to M's equations, using Bernoulli's product method (separation of variables.)
- Curiously enough, these are *analytic* functions, on their own can not transmit information and are non-casual.
- Fourier analysis perpetuates use of sinusoids as orthogonal basis in communications; e.g., we represent a non-analytic function as superposition of sine waves.
- There are orthogonal functions which respect causality e.g., 'Walsh functions', which are *non*-analytic by nature.
- We seek a much more general solution to Maxwell's equations in terms of such functions.

•Solution to Maxwell's eqs. for dipole with current having general time variation attributed to Shwarzschild, Abraham, Becker and Sauter.

•The vector and scalar potentials ϕ, **A** are a convenient path to determine fields etc; in terms of charge and current distributions ρ, $\mathbf{j}$;

$$\mathbf{A}(x,y,z,t) = \frac{Z_0}{4\pi c}\iiint \frac{\mathbf{j}(\xi,\eta,\zeta,t\text{-}R/c)}{R}\, d\xi d\eta d\zeta$$

$$\varphi(x,y,z,t) = \frac{Z_0 c}{4\pi}\iiint \frac{\rho(\xi,\eta,\zeta,t\text{-}R/c)}{R}\, d\xi d\eta d\zeta$$

$$R = \left[(x-\xi)^2 + (y-\eta)^2 + (z-\zeta)^2\right]^{1/2}$$

with x, y, z field points; ξ, η, ζ source points,

$Z_0 = \sqrt{\dfrac{\mu_0}{\varepsilon_0}}$, the impedance of free space.

•For source term we imagine a dipole consisting of two time variable charges *+/- q(t)* , current *i(t)*; length and direction of dipole represented by dipole vector **s**, with moment **p**;

$$\mathbf{p}=q(t)\mathbf{s}\ ; \quad d\mathbf{p}/dt=i(t)\mathbf{s}.$$

•Assume field and source far removed such that *R~r*, the field distance. Power flux in the radiation zone, through spherical surface;

$$P(r,t)=\frac{Z_0 s^2}{6\pi c^2}\left[\left(\frac{di}{dt}\right)^2+\frac{2c}{r}i\frac{di}{dt}\frac{c^2}{r^2}\left(i^2+\frac{di}{dt}\int idt\right)+\frac{c^3}{r^3}i\int idt\right]$$

•Fast time variation in current contributes to greater radiated power.

•Without resonance, simplest way to increase radiated power is to increase current, hence *large-current radiator*; create a large current, radiating dipole from a Hertzian magnetic dipole.

•Solution to Maxwell's eqs. for *propagation* of non-sinusoids even more difficult, yet insightful endeavor into *limitations* of the equations.

•The equations are often singular when considering response to transient boundary conditions e.g., pulses and other such non-analytic functions.

•A prescription for success is to introduce a 'magnetic current' *s* into derivation, to be removed via a limiting process toward the end.

•Some modified equations;

$$\nabla \times \mathbf{H} = \sigma\mathbf{E} + \varepsilon\frac{\partial \mathbf{E}}{\partial t}$$

$$\nabla \times \mathbf{E} = s\mathbf{H} - \mu\frac{\partial \mathbf{H}}{\partial t}$$

•Assume a plane, transverse EM wave, travelling in the positive *y* direction; we find various partial differential equations for the magnetic and electric fields, eg., integral equations for *E(y,t);*

$$E(y,t) = -\int \left(\mu \frac{\partial H}{\partial t} + sH \right) dy + E_y(t)$$

$$= e^{-\sigma t/\varepsilon} \left(-\frac{1}{\varepsilon} \int \frac{\partial H}{\partial y} e^{\sigma t/\varepsilon} dt + E_t(y) \right)$$

•Some boundary conditions;

$$E(0,t) = \begin{cases} 0 \text{ for } t < 0 \\ E_0 \text{ for t} \geq 0 \end{cases}$$

$$E(y,0) = H(y,0) = 0$$

$$E(\infty,t) = \text{finite}$$

$$\frac{\partial E(y,0)}{\partial y} = \frac{\partial H(y,0)}{\partial y} = 0$$

•Solution $E(y,t)= E_0[w(y,t)+F(y)]$ attributed to Krylov (1929)
•Latter part is straight forward, the former requiring some heavy algebra and difficult integrals.
•$w(y,t)$ reduces to an integral which requires numerical computation, but in the simple case where σ, the conductivity of the medium, approaches zero, we have;

$$E(y,t)=\begin{cases} E_0 \text{ for } y=0,\ t=0 \\ 0 \quad y>0, ct<y \\ \dfrac{E_0}{2} \quad y>0, ct=y \\ E_0 \quad y>0, ct>y \end{cases}$$

•So a mathematical abstraction (inclusion of *s*) has allowed us to produce a solution obeying causality. *This implies that either Maxwell's equations are insufficient in describing transient phenomena, or the presence of a 'magnetic' current.*

A General Prescription for UWB

- Fast digital circuitry can generate pulse sequences for transmission.
- TDMA seems viable candidate for multiple users, particularly in dense, multi-path environments where other users can be modeled as Gaussian noise.
- A frequency independent antenna, sensor like the large current radiator.
- Computational methods to solve propagation issues, response to transient boundary conditions; dispersion will remain limiting factor.
- Correlation type receiver using non-analytic, orthonormal functions as a basis.

Literature

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Conclusion

- UWB shows potential for short range data and voice communications systems, owing to massive bandwidth
- Dispersion limits range.
- Energy of signal spread thinly from D.C. up to GHz range, hence (potentially) low interference with conventional narrow band systems.
- System requires very fast circuitry for modest returns.
- Covertness of operation, many orders of magnitude improvement over conventional spread spectrum.
- Absence of resonance reduces efficiency, but promises to simplify design.