Wireless Communications in the Undergrad Curriculum

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Abstract

The field of wireless communications even in its restriction to cellular systems continues to expand rapidly. As such, its introduction in the undergraduate curriculum is very important. However the field is highly interdisciplinary in the context of the basic disciplines of electrical engineering such as signal processing, communication systems, electromagnetics, and probability and random processes. The field is by its own nature also highly mathematical in various aspects of signal processing and probability, and in so being poses challenges in the introduction to undergraduate students who may not have the required mathematical maturity. In this paper we present an approach to the introduction of this field in the undergraduate curriculum.

1. Introduction

The field of wireless communications is a very important part of the general area of communications and signal processing. Such a course would typically be given following a course in communication systems where the classical modulation techniques are covered along with communication systems concepts such as frequency translation, phase-lock loop, multiplexing, PCM, etc, and possibly concurrent with a course in digital communications covering the classical digital modulation techniques and their performance evaluation in terms of error probability. However the field draws on many fundamental areas where a certain degree of mathematical maturity is required, and with its rapid expansion, it makes it challenging to decide exatly what topis to cover and the approach followed. In this paper we discuss a possible approach which limits the sophistication of the required mathematics such as random processes and at the same time gives insight required to understand the intricacies of system design and the evolving standards, including methodologies for multiple access, frequency re-use, power control, diversity techniques, and some of the basic standards.

2. Electromagnetics and the RF Spectrum

A course in wireless communications would start with the introduction to the electromagnetic spectrum and the various allocated bands, emphasizing the scarcity of spectrum and the different characteristics of the allocated frequency bands in terms of ease of propagation through walls, etc. Topics include the characteristics of plane wave propagation and of antenna aperture and antenna gain, leading to the important topic of the link budget. Specifics of propagation including electric and magnetic field and the poynting vector along with linear and circular polarization illustrate the higher degrees of freedom involved with wave propagation over space with the possibility to have two independent channels on the same frequency. A discussion of antennas is next important topic where various structures to emit the signal into the radio channel are discussed along with their characteristics such as omni-directional, sectored, leaky-feeder, etc. The design of a simple linear array antenna could then be presented to illustrate the principle of the design of directional antennas, including the half wavelength element spacing and the relationship of beamwidth to the size of the antenna structure, the adaptation of the beam pointing direction under electronic control, etc. The next topic is the discussion of the concept of antenna gain and the associated concept of link budget. The key ideas are developed starting with the concept of the isotropic radiator and then the definition of gain in a particular direction as the signal power relative to that for the isotropic radiator and then the gain being defined as the gain in the direction of the maximum.

The above introduction to the electromagnetics and wave propagation can be followed by a quick survey of modulation techniques with the emphasis of the structure of the modulation techniques, bandwidth of the modulation scheme, and the associated spectrum efficiency in bps/Hz. The idea is to summarize how to design bit pipes that occupy portions of the radio spectrun and not to get distracted with the implementation of the various modulation schemes, or their performance in noisy channels.

3. Multi-Path Channel Modeling

A very important topic in wireless communications is that of multi-path channel modeling. The topic is a difficult one when approached in the usual manner based on random processes. The classical analysis starts with the development of the statistics of the signal envelope at a particular point in time. The classical models of Rayleigh fading (case of many relatively weak signal components where the Raleigh distribution arises from the application of the central limit theorem), the Rician fading model where one of the components is assumed to be strong, and the Nakagami-m model are usually included in texts in wireless communications. However it is difficult to justify the application of the actual formulas for the corresponding densities. In some cases one uses these models to compute bit error probabilities for classical simple modulation schemes such as BPSK and FSK. But in modern systems all these calculations are too simplistic. Hence a qualitative discussion of these fading models with plots of typical sample functions of a narrowband noise process showing the variation in signal envelope is probably the most that one should attempt at the undergraduate level. In the end a fading channel will produce variations in the signal envelope which will lead to variations in bit error rate. Typical error probability curves for Raleigh fading are not very useful in practice because they are only based on first order properties of the random process representing the fading signal, whereas the second order properties of the fading process are the key to the modeling of real systems.

The interesting features of a multi-path fading channel are exhibited by the study of the second order statistics of a signal fading process. To be addressed properly this topic needs the use of the theory of random processes. However some of the parameters extracted from these statistics are so important for wireless system design that a qualitative study possibly involving simulations is essential in a course on wireless communications. Multipath wireless channels exist because there are multiple signal reflectors of different sizes that result in a multiple set of copies of the signal to be received. The channel can be modelled as a tapped-delay line with at set of delays and path gains. Then one studies the response of the channel to a sinusoidal input of varying frequency. The amplitude response versus the frequency can be modelled as a random process over the frequency parameter. The auto-correlation function of this process is sometimes called the spaced frequency correlation, and the width of such a correlation function, defined according to some measure, is the coherence bandwidth of the chanel. The concept can be illustrated by simulation where a number of paths with random parameters are generated. The delays could be chosen to be uniformly distributed over a range $[0, \tau_{max}]$, and the path gains could also be chosen randomly but with the variance having some kind of inverse relation to the corresponding delay. The simulation can illustrate the frequency responses at two frequencies separated by a parameter s. As this parameter increases beyond the coherence bandwidth the responses become uncorrelated. This then illustrates the benefits of frequency hopping in wireless systems. Varying the delay spread we can illustrate that in environments with small delay spread (indoors), one needs a much larger frequency separation than in environments with large delay spreads (outdoors with large link distance) in order to achieve frequency diversity. One could run simulations to compute the correlation function (spaced-frequency) and even the coherence bandwidth, but what is important is the qualitative understanding which then motivates the understanding of frequency hopping in systems such as GSM, or even the switching of RF channels in other systems where the channel is static with time.

The next aspect of channel modeling is that of of the variation of the received signal power in time. Such variation is a result of motion of the receiver relative to the transmitter. Again we assume the transmission of a single sinusoid. Multi-path results in different wave components arriving from different angles. The existence of motion together with different arrival angles determines Doppler shifts, and the addition of sinusoids with slightly different frequencies results in the variation of the envelope. Such a variation produces periods in time where the signal strength is large and other periods where the signal strength is small. These variations in signal strength can then easily be explained as leading to variations in signal to noise ratio and then to periods of time with bursts of errors. Simulations can be done for different distributions of arrival angle using the velocity as a main parameter. Plots of the Doppler spread can be drawn and we can illustrate that the rate of fading in time is inversely related to the Doppler spread. The concept of coherence time can then be discussed. The important system concept that arises is then that of power control. The transmitter power can be controlled so as to achieve a constant SNR at the receiver and a constant data rate as is the case in CDMA systems. Alternatively we can introduce the concept of variable modulation constellation size in order to adapt to the SNR. Examples of the use of these concepts in modern systems such as LTE can be presented.

After frequency and time, the next important concept deals with distance (or space). We consider a multipath channel with components arriving over different angles and a receiver with two antenna elements separated by a distance ζ. The fundamental concept can be illustrated with two antennas and two signal components. We assume that one component arrives along the line of the two antenna elements (line of antenna array) and the other component arrives perpendicular to the antenna array. Assume that the two antenna elements are separated by half of a wavelength. Suppose that the two components happen to be in phase at element A. Then they must be out-of-phase (by 180 degrees) at the second element B. This illustrates that the signal at the two elements can be quite different. Then it is a matter of running simulations to show instances of the signal at the two elements and how they differ. It is convenient to consider a channel that is also time varying. Hence the signal at each of the antenna elements varies with time. We can then compare the signals at the two elements (plotting the wavefoems from a simulation) and discuss concepts such as selection diversity (choose the strongest), equal gain combining, and maximal ratio combining.

The next related topic is that of MIMO. From a system viewpoint MIMO can be presented as a mechanism to increase the spectral efficiency in a point to point link. The inputs to the channel (transmitter antenna elements) and the outputs from the channel (receiver antenna elements) are represented by vectors. The channel is then represented by a matrix multiplication. If the multipath is rich then this matrix will have full rank. In the case of a square matrix the matrix can be diagonalized and the channel decouples to a number of parallel channels with SNRs related to the eigenvalues of the matrix. From a systems perspective MIMO can be viewed as a means to increase the spectral efficiency of the link, just like increasing the modulation constellation size.

4. Multiple Access

The next step in the development of key concepts is that of multiplexing. There are two classical approaches: 1) packet switching and 2) circuit switching. In the first case we usually consider a single RF channel with a number of users sharing the channel with some multiple access protocol. These protocols are usually classified as random access, or reservation. In the case of cellular systems we usually consider circuit switching as the basic mode of the system. The design of the various generations of systems has been driven by the voice application. The digitization of speech signals occurs in time frame blocks. For reasons of efficient coding the block size or frame size for speech packetization should be large. On the other hand in order to constrain the delay to an acceptable value for real time voice transmission the frame size should not be too large. We give examples of systems with frame sizes equal to 10 ms and 20 ms.

Basic multiple access schemes of pure FDMA, pure TDMA, and hybrid FDMA/TDMA are discussed. The case of pure FDMA is simple and is exemplified by the first generation systems. The case of pure TDMA is also simple to illustrate and we motivate it with a TDMA frame size that is equal to the speech packetization frame size. However practical systems are deployed with different amounts of spectrum such as 5 MHz, 10 MHz, 15 MHz, and 20 MHz. It is not practical to design systems with pure TDMA as the access scheme because it would amount to the implementation of different transmission rates in the different systems. The practical solution is the hybrid FDMA/TDMA systems where the RF channel bandwidth for the FDMA part is fixed – e.g. 200 KHz for GSM. The number of RF carriers is then determined by the total bandwidth available for the system.

Frequency hopping can be introduced here as a method to overcome frequency selective fading in the manner of GSM. In this case the TDMA frame size is smaller than the speech processing frame size. A speech packet is transmitted over several TDMA frames in different RF channels – as in GSM. Frequency hopping can then be implemented using a set of orthogonal hopping sequences. The sequences should appear to be random with respect to the available set of RF channels. Then, a set of orthogonal hopping sequences to be assigned to the different users is designed. If the number of RF frequencies available is Q then the set of possible orthogonal hopping sequences is also Q.

5. Frequency Re-Use

The above considerations of multiple access apply to a scenario where all of the transceivers are within radio range. The scenario is as if all the transceivers were connected to a cable and where we assume that there is no signal loss with transmission. In reality in wireless transmission signals do incur large losses in power due to propagation and it is in fact this property that allows a given frequency band to be re-used by two links if there is a sufficient separation in space. This is the concept of a cellular system. The system consists of a network of base stations where each base station is placed at the center of a cell. Within a cell a certain frequency band (or sets of bands) is used and this band is re-used a certain distance away. The result is then the central result of cellular systems where a hexagonal cell grid is assumed (the hexagon is the regular figure that tessellates the plane and that is closest to a circle) and sets of RF channels are re-used according to a pattern known as a frequency re-use cluster pattern. There is an algorithm where frequency re-use is described by a pair of integers (i, j), where each pair gives rise to a frequency re-use cluster with size given by $N = i^2 + ij + j^2$ cells. A figure of merit for the design of these systems is the system capacity in terms of the number of circuits (voice circuits) supported per cell. In the 1G system typically one RF channel supports one circuit, hence the capacity is the number of RF channels divided by the cluster size. Maximizing the capacity entails minimizing the cluster size. However there is a trade-off between the cluster size and degree of interference. The degree of interference supported by the network is related to the robustness of the modulation and FEC coding scheme. Systems such as CDMA have a high degree of robustness and can operate with a cluster size equal to 1. Systems such as LTE, which is based on OFDM typically are much more sensitive to interference. However with modern sophisticated FEC schemes and channel monitoring they are capable of operation with very small frequency re-use cluster sizes.

6. The Cellular System

After the introduction of the generic idea of frequency re-use over space one can discuss the basic architecture of a cellular system. The initial system was basically a three-level hierarchy with terminals, base stations, and a switch. Then the concept of cluster controller was introduced along with a roaming network to become a 5-level hierarchy. One can also point out that the tendency with modern systems is to connect the base stations directly to an IP network to obtain the so-called flat architecture. Within this topic one can also discuss the protocol stack including the concept of logical channels and physical channels. The logical channels include channels for control and channels for user traffic. The channels can also be classified as being common or dedicated. Some of the channels are only visible to the physical layer – e.g. pilot channels. The other channels include synchronization channels, paging channels, access channels, broadcast channels, etc. Along with this description one can also describe basic control procedures such as those involved in call set up.

Other basic characteristics of these systems include the concept and mechanism for hand-off. The first generation system used a base station based signal monitoring and hand-off scheme. In the second generation systems and with the TDMA approach we saw the introduction of mobile assisted hand-off. There is also the algorithms for paging in the process of call set up. At one extreme we can have a system where paging messages are broadcast over all the cells in the network. At the other extreme we can have a system where paging messages are sent to only one cell at a time until the terminal is located, starting with the last cell where the terminal was located. There are many possibilities for paging, and in general for the description of the network, and these are evolving. The idea is merely to touch upon a few examples to stimulate the student who can then easily go further into specific modern schemes.

7. System Optimization

One of the important topics in cellular systems is the allocation of power levels to the different terminals and base stations. Such power level allocation strategies will determine the appropriate frequency re-use cluster size to employ. In modern system analysis all of these issues are typically studied by simulation. It is important to illustrate the basic idea of simulations. As a basic scheme we consider a system where power control is performed so that the received power levels for all signals at a base station are equal (assuming equal bit rates). Signal propagation is modelled using an inverse power law and a statistical shadow fading model based on the log-normal distribution. We also model sectorized antennas where each antenna radiates over a sector of a disk. We fix some key parameters such as the shadow fading parameter sigma, the power loss exponent, and the degree of sectorization, and then run the simulations based on the concept of a drop. Terminals are placed randomly in all cells, transmission power levels are determined by the distance to a terminal's own cell and the shadow fading random variable, and then interference levels are determined to all the other cells according to the distance to the different cells, the shadow fading variables, and the power loss law. With these we determine the signal to interference radio for all the terminals and then after running many drops we plot histograms of the signal to interference ratio. Depending on the modulation scheme we determine a required threshold on the signal to interference ratio, SIR. For a given set of shadow fading parameter, power loss law, and even sectorization, we determine the appropriate frequency re-use cluster size to employ in the network and hence the network capacity per base station. There are many possible approaches that we can take to model the network and model such things as mobility, shadow fading model, etc. The key is to give a precise approach to simulation for a particular scenario. The student can then infer variations to the approach to treat more realistic models.

8. Future System Architectures

Cellular system technologies have been classified according to generations. Currently it is generally agreed that the fourth generation is the so-called LTE Advanced specification. However, going into the future it could be that similarly to the different generations of computer technology where the 5G somehow never appeared, it could be that there will not be a 5G for cellular. Instead a large number of technologies are spawning into the future. These include autonomous infrastructure deployment, small cells, femtocells, remote RF, distributed antenn systems, and many other architectures that are now evolving. All of these will require intricate methodologies for self-configuation, resource allocation, power control, and various types of interference management. The field of wireless communications will be even larger and greater challenges will be presented in presenting an introduction of the RF engineering aspects of the field to the student.