WIRELESS NETWORKS: WHAT NEXT FOR RADIOWAVE PROPAGATION RESEARCH

(Keynote Paper)

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Abstract

This paper chronicles the progress in wireless information transmission and reception, and discusses future trends in radiowave propagation research. Since the conception of wireless transmission, a number of pioneers have successfully understood and characterised the behaviour of narrowband, wideband and ultra-wideband signal transmission in a variety of environments and spectral regions. The physics of signal propagation mechanisms is now well understood and represented by deterministic and stochastic models. Frequency, spatial and polarisation properties of signal propagation have also been exploited. So are there any fundamental research problems left? The aim of this paper is to provoke discussion and debate so that the state-of-the-art of radiowave propagation is understood and further challenges are amassed.

1. Introduction

Globally, there are over 3 billion mobile phone users today and the numbers are growing. There were almost none twenty years ago. It took 20 years to reach 1 billion, only another 3.5 years to reach 2 billion and a further 4.25 years to reach 3 billion [1]. Radiowave propagation underpins the operation of these devices and carries information from the mundane and trivial to the safety critical. This is only one example of a wireless service, however, and a plethora of others also exist, such as radio and TV broadcasting (DVB and DAB), emergency services (Tetra), Internet (WLAN and WiMax), sensors (wireless key fobs, RFID), wireless interconnects (Bluetooth, UWB), radar, radio-navigation and geolocation (GPS and Galileo).

Reliable services cannot be designed without a fundamental understanding of how radiowaves propagate. Hence, radiowave propagation underpins the rapid proliferation of wireless technology that pervades our lives. So what are the key breakthroughs that have enabled this understanding and subsequent proliferation? Is the study of radiowave propagation complete, or is there still work required to enable further breakthroughs thus facilitating new services of the scale of those mentioned above?

This paper presents a time-line of key breakthroughs that have led up to today's exploitation of radiowave propagation. The state-of-the-art is presented and the "what next?" question is then addressed. The aim is to provoke discussion and debate on future directions of radiowave propagation research.

2. The Nascent Days: Pre-1950

Few observers in the late nineteenth century would have foreseen the explosive growth in the use of wireless transmission in the following century. Indeed, few technologies have made the transition from the arcane to the ubiquitous in such a short period. The transition from the theoretical work of Maxwell in 1873 (electromagnetic wave theory) [2] to its practical demonstration in 1886 by Hertz (spark-gap transmitter) [3] and implementation in 1895 by Marconi (long-range radio) [4] is unmatched. From these early beginnings the concept of free-space wave propagation prompted the proliferation of investigation within the science community. The generation and detection of waves that were not immediately observable drew on the work of many, including Faraday, Lenz and others.

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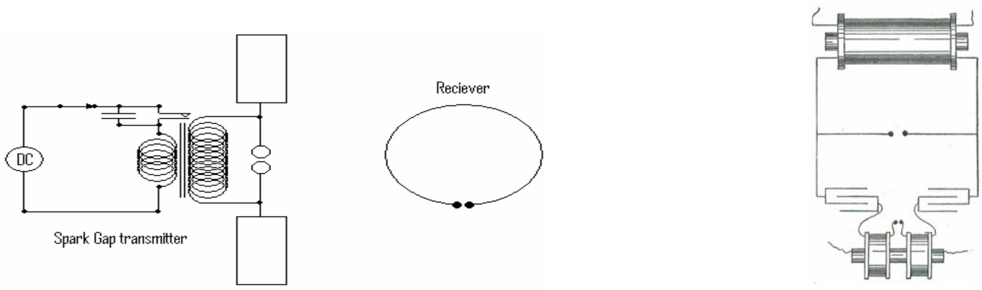
Marconi's work rapidly developed from his first patents in 1896 into the establishment of fully operational transceivers adopted by the military in 1922. The challenges at that time, after establishing that the idea did indeed work, revolved around representing the information and imposing this onto an electromagnetic wave for faithful transmission. The term "wireless telegraph" bears testimony to the framework that existed at the time. The natural progression from the wired telegraph to wireless took on many of the basic concepts of such things as Morse code. The details of how the wave arrived at the receiver were only understood at the basic level. Since there were few users, the interference experienced was largely unnoticed, and if the operator could decipher the message, it posed few problems in the conveyance of information. Key events of the demonstration and establishment of Marconi's wireless communications equipment are shown in table 1. They span a 7 year period which illustrates the intensity of activity over this short period.

Table I: Key events in the early demonstration and establishment of Marconi's wireless equipment

1896	Application filed for Marconi's first British Patent 12039 for Hertzian Wave Telegraphy
	Sir W. H. Preece lectured on Marconi's invention at Toynbee Hall
	First demonstration of directional wireless using reflectors
1897	Communication up to 18 miles between the Needles, UK, and a steamer in the sea
	Communication up to 10 miles between Spezia and San Martin Wireless Telegraph and Signal Co. Ltd. Incorporated
1898	Communication established between Royal Yacht Osborne and Ladywood Cottage, Osborne
	Lord Kelvin sent first paid radio-telegram from the Needles Station Communications up to 36 miles between the Needles Station and SS St Paul
1900	First wireless land station in Belgium opened at Lapanne
	Communications up to 60 miles between SS. "Kaiser William der Grosse" and Borkum Island
	Marconi International Marine Communication Co. incorporated
1901	First Fan Aerials erected for experiments between Poldhu and Newfoundland
	Signals received at St John's, Newfoundland, from Poldhu, a distance of 1800 miles
	Station at the Lizard opened
	Wireless communication established between Niton and the Lizard, 196 miles wireless service inaugurated in the Hawaiin Islands
	First British ship SS Lake Champain equipped with wireless telegraphy
1902	Marconi Wireless Telegraph Co. of Canada formed
	First wireless message transmitted across the Atlantic
	First magnetic detector installed in Italian cruiser Carlo Alberto
1903	First International Conference on Wireless Telegraphy held in Berlin
	Agreement by British Admiralty for use of Marconi System in the Navy

The transition from simple spark gap transmitters to tuned transceivers (Figure 1) brought a fundamental shift in spectrum management and the prospect of multiple information channels defined in the frequency domain. Information delivery rates of early wireless systems were rather limited, and speech and music were the prime information content on radio systems for the first thirty years of the 20th century.



(a) *(b)*

Figure 1. Early wireless equipment, based on the spark gap principle, used by (a) Hertz and (b) Marconi.

3. Modern Radio: Post-1950 to Date

Meanwhile the interaction of electromagnetic waves with material objects spawned the development of Radar and the propagation of radio waves became a topic that was studied in earnest. The early days of mobile radio, conceived at AT&T Bell Labs in 1947 [5], brought home the need for an understanding of the details of radio propagation within cluttered, mobile environments. This effort was led by the revolutionary ideas of Shannon who laid the theoretical foundations of digital information encoding and communication [6].

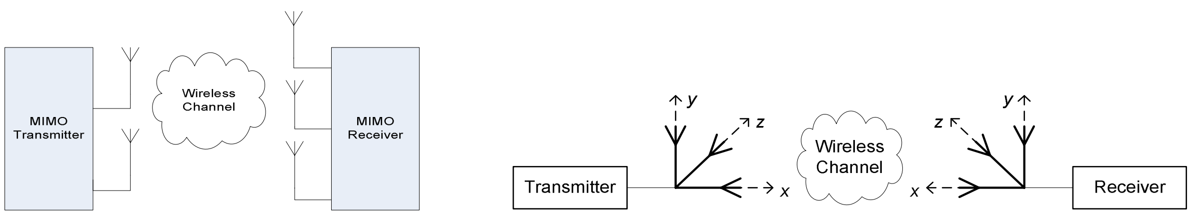
The earliest generation (1G) cellular telephony, based on FDMA technology, was deployed in the early 1980s, some of whose variants included the AMPS, NTT and NMT systems. These were followed by second generation (2G) cellular systems that appeared in the early 1990s. Prominent among these were the TDMA-based GSM system in Europe, and the TDMA-based IS-54/136 and CDMA-based IS-95 systems in the US. Most recently, third generation (3G) IMT-2000 systems were deployed in Europe offering advanced services and enhanced network capacity. The success of these systems has relied on understanding radiowave propagation in urban environments.

A number of WLAN standards were successively adopted by the IEEE 802.11 task group. This set of standards was based on wideband approaches such as CDMA and OFDM for high-rate data transmission within a restricted environment such as an office or home, The IEEE 802.15 group developed the Bluetooth specification for *ad hoc* WPAN systems. These systems required an understanding of the propagation of wideband signals.

The above technologies can be classified as narrowband and wideband, with the distinction based on the relation between the signal bandwidth and the channel coherence bandwidth. The consequence of increasing the bandwidth is a large increase in the achievable data-rates and robustness to fading, which has resulted in the trend to migrate towards wideband transmission in telephony, television and local area networks. Another means of reducing the fading has been the exploitation of signal redundancy by multiple antennas in the form of a diversity receiver [7], typically deployed at the base station where the increased device size and cost is still feasible. This approach has been used successfully over the years in commercial radio, television and telephone networks.

4. The State-of-the-Art

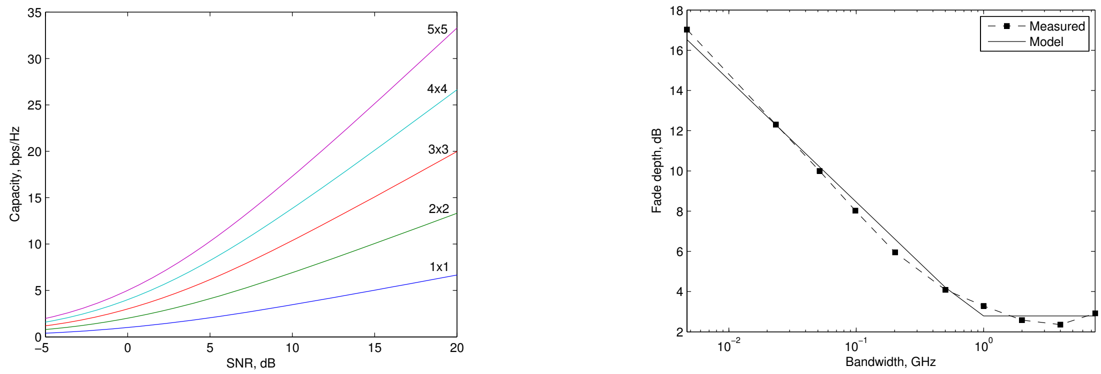
The most advanced of today's commercially available wireless systems employ wideband transmissions with multiple antennas at both ends of the link, an example of which is shown in Figure 2a [1]. Under suitable conditions, a MIMO array can scale up the achievable data-rate linearly with the array size, as shown by comparing the curves in figure 3a. For WLAN applications, the commercial systems mostly follow the MIMO-OFDM technique, incorporated into the IEEE 802.11n WiFi standard. Some implementations, such as 3G base-stations, also employ dual polarisation, which is particularly effective in dense scattering channels such as urban microcellular environments. This can also be extended to triple-polar MIMO as shown in figure 2b, and yields even more channel capacity in dense scattering channels [8]. An advantage of a polarized antenna array over spatially separated antennas is that the former can be collocated and therefore considerably more compact.



(a) *(b)*

Figure 2. Implementation of MIMO wireless systems with (a) spatial and (b) triple-polar antenna arrays.

After several years of successful deployment of wideband systems, ultra-wideband communications technology is now beginning to find its place in the consumer market [9][10]. The enhanced resilience to fading with increasing bandwidth, as indicated by Figure 3b, is a major reason for the shift from narrowband to wideband and ultra-wideband technology. Initial UWB units for short-range networking are now commercially available. These UWB devices offer peak rates of the order of gigabits, but suffer from a severe range-rate trade-off. MIMO technology [11] and antenna arrays [12][13] have the potential to solve this problem, but UWB devices do not yet employ multiple antennas [14].



(a) *(b)*

Figure 3. Wireless system performance enhancement due to (a) multiple antenna arrays (b). wide bandwidth..

The development of the above-mentioned technologies has been supported by extensive research in various propagation and system design aspects. Certain propagation conditions are critical for MIMO systems to yield any performance enhancement. The most important of these include rich multipath propagation, low inter-stream correlation and large angular spread. The suitability of the channel for MIMO operation can thus be ascertained only through comprehensive propagation characterization. For this purpose, the multipath angle-of-arrival and -departure characteristics have been studied and formulated as double-directional models [15], treating radiowaves as rays propagating through a dispersive medium. The recent interest in the propagation of microwave signals around and through the human body has been motivated by the rapidly emerging field of wireless body area networks (WBANs), which is promising for applications ranging from telemedicine to wearable computing.

5. The Future

The extremely high frequency (EHF) spectrum (30-300 GHz) is relatively unused in communications at present. A major reason is the large path-loss, which leads to reduced coverage range. The 60 GHz band, in particular, exhibits oxygen absorption. There are some distinctive opportunities: higher attenuation allows greater frequency reuse, and smaller wavelength leads to smaller antennas. There is, therefore, considerable research interest in this area at present and several studies of the radio propagation characteristics have appeared [16]. Are the millimetre-wave propagation characteristics and consequently the system design considerations expected to be fundamentally different from the conventional channels and systems?

Agile and intelligent communications modules, in the form of cognitive radio, promise to make the next generation of software defined radio (SDR). It is predicted that rather than having a collection of retro-fitted transceivers providing service capability for GSM, 3G and WiFi, these will become fully integrated and able to intelligently choose the mode of operation, waveform and spectrum occupancy to suite user requirements and spectrum demands. Beside dynamic spectrum sensing, this requires innovative and highly adaptive transceiver architectures, antennas and other modules. But does it require a breakthrough in understanding and exploiting radiowave propagation to enable cognitive radio?

With highly integrated, single chip transceivers, the concept of "everything always connected" is becoming a reality. Fully networked houses with ubiquitous devices becoming Internet-connected that provide streaming services becomes a possibility. Sensor networks, providing environmental or other data, wirelessly connected to the Internet are also attracting much attention. Are radically new insights into radiowave propagation required to realize this vision?

Some examples of emerging technologies that warrant study of propagation characteristics are: peer-to-peer ad hoc wireless networks; and wireless sensor networks. Will such a study reveal new fundamental phenomena, or serve as another characterisation exercise?

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