Wireless Personal Communications: Trends and Challenges

Theodore S. Rappaport
Mobile and Portable Radio Research Group
Bradley Department of Electrical Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0111

Abstract

Probably before the end of this century, wireless communications systems will provide ubiquitous voice and data communications to a significant number of citizens in the developed nations of the world. The social changes that will be brought about from wireless personal-communications services are certain to be profound. This paper provides an overview of how rapidly this field is expanding, and provides a survey of some propagation research results which promise to impact the design and implementation of future cellular and personal-communication services (PCS). The paper concludes with a number of antenna and propagation research problems which need to be solved to improve the spectral efficiency, and thus the system capacity, of emerging high-density personal-communication systems.

1. Introduction and Overview

The burgeoning wireless communications industry has created an interesting problem for wireless manufacturers and service providers throughout the world. Because the field of cellular radio and personal communications is changing so rapidly, and since the field involves system concepts seldom taught at universities, wireless companies are having difficulty finding entry-level graduates with sufficient education to make an immediate contribution in research or design. In particular, a large number of universities present do not offer undergraduate or graduate courses on the topics of mobile-radios propagation or wireless-communication system design. Consequently, recruiters are forced to "raid" competing companies for more-senior personnel, and the companies for which they recruit must resign themselves to spending six months to two years to train new graduates in the art and science of mobile and portable radio. In an informal survey of some of the largest cellular-radio companies in the US, the author has learned that engineers with knowledge of mobile-radio propagation change jobs often, and are in extremely high demand. Particularly in the past two years, since cellular radio has enjoyed 50% annual growth rates and new digital systems have been proposed and tried, engineers with experience in cell-site design or with computer-simulation expertise in mobile-radio propagation, traffic modeling, antenna design, and digital signal processing have been highly sought after by the wireless industry.

Virginia Tech's Mobile and Portable Radio Research Group (MPRG) is a new group within the university's Bradley Department of Electrical Engineering. Founded in the spring of 1996, it is conducting basic and applied research in the areas of radio-propagation measurement and prediction, communication-system design using measurement-based propagation models, and simulation of various digital modulation, diversity, and radio equalizer techniques. The group's mission is to develop analysis tools and computing techniques for emerging wireless personal-communication systems, while providing quality research opportunities for graduate and undergraduate students. Also, MPRG is providing opportunities for technical interchange. As examples, an EE graduate-student lecture series in the fall of 1989 featured key researchers from the cellular-radio industry. The First Virginia Tech Symposium on Wireless Personal Communications, held this June in Blacksburg, VA, featured 18 invited talks, and panel discussions by industry experts over a three-day period. It was attended by 175 people from 22 states and 8 countries. The necessity for academic research groups, like MPRG, becomes clear when one realizes the enormous, yet sudden, activity in the wireless field, and the growing demand for young graduates who can make immediate contributions to a very dynamic field. It is hoped that this article will stimulate discussion of similar activities, and will encourage contributions from mobile-communications research groups in the Antennas and Propagation Magazine. Furthermore, it is hoped that this article will encourage prospective authors to make the Transactions on Antennas and Propagation a popular forum for published work in antennas and propagation research in wireless personal-communications. Presently, communications societies throughout the world seem to be attracting the bulk of antennas and propagation papers in this area.

1. Some Examples of Demand

Data that support the premise that wireless personal-communications is emerging as a key, wide-sweeping technology, that will dramatically impact our society, can be found from numerous sources, including trade journals and government-agency reports throughout the world. As an example, in the US there were over 5.4 million cellular telephone users, as of March, 1991 [18]. This compares with 15,000 users in 1984, and 2.5 million US users in late 1989 [1]. It is clear to most industry experts that the Cellular Telephone Industry Association's (CTIA) 1989 projections, of 10,000,000 million US cellular users by 1995, will be exceeded in late 1992 [1], and that cellular-radio carriers are enjoying exponential increases in service subscriptions. This demand for mobile/portable telecommunications is a world-wide trend, and is particularly acute in Europe. For example, cellular telephone in Sweden is already enjoying a 5.4% adult market penetration [18], and market penetration has been increasing by more than 0.1% per month. Finland, Norway, and France have been experiencing similar growth rates. Although no spectrum has yet been allocated to emerging personal-communication services (PCS) in the United States, industry analysts are projecting annual U.S. revenues to be between $33 billion and $55 billion, by the year 2000 [17].

In the United Kingdom, viewed by many as the leading country for PCS initiatives, three major companies are investing hundreds of millions of dollars to install an infrastructure that may eventually allow citizens to use small, 10-mW, portable terminals to place and receive calls in populated areas throughout the country. At worst, PCS will provide relief for users which operate in congested, 900-MHz UK cellular markets, and, at best, will offer customers the ability to use a single wireless-communications unit for home, office, or automobile, thereby obviating the need for a traditional, wired phone to the home. Two of the three companies involved, Microtel, and Unitel, are actually consortia consisting of
20
radio and PCN, can he
modem demand for wireless personal
services, and hope
for PCN or other
trum
operations. PCN customers have filed
has created a special
(thoughennmeci
telephone company, and use a single, PCN terminal
. ObAll design. The radio coverage
switcled-teleplonn network (PSTN),
or via line-of-site
stations to other PCN base stations
and ceilings
irl()orne telephone loop in populated areas. PCN
the \other\eo Wnlkman or the laptop computer, PCN
ubiquitous communications
place
rtightweight
PCN refers to a computer where
excepted to become
. many of the leading telecommunications companies.
The third UK
Personal-Communications Network (PCN) service provider,
Mercury, is the leading non-wire-line service provider of
England's present, analog cellular system. These PCN companies
are expected to become some of the biggest advertisers in the UK
throughout this decade, as they strive to pioneer and market the
revolutionary PCN service [19].

The terms PCN and PCS are often used interchangeably.
PCN refers to a concept where a person can use a single communi-
cator anywhere in the world. PCS refers to a service which may
not embody all of the PCN concepts, but is more personalized (i.e.,
lightheight terminal, better performance, more flexibility and user
options, etc.) than present-day cellular radio. The idea behind
PCN is to make communications truly personal, so that anyone
can place a call to anyone else, no matter where they are. Much like
the stereo Walkman or the laptop computer, PCN will permit truly
ubiquitous communications access, no matter what the location of
the user.

The perversiveness of PCN will be made available by an
immense infrastructure of low-power, suitcase-sized base stations,
that will provide portable subscribers with wireless access to the
local telephone loop in populated areas. PCN hopes to be able to offer
wire line-communications quality, using radio as a transmission
medium. Base stations will be placed on lamp-posts, roofs
and ceilings of buildings and courtyards, and in other locations
where people congregate. Backbone links, which connect PCN
base stations to other PCN base stations and to the public
switched-telephone network (PSTN), will be supplied by one of
two methods: either via the existing telephone-wire or fiber plant,
or via line-of-sight microwave links. Of course, the wide-scale
deployment of such an extensive, high-grade, wireless telephone
system will require engineering tools and techniques, and antenna
designs, that allow rapid and accurate propagation prediction and
system design. The radio coverage of each base station will be
intentionally limited by low transmitter power, so that the same
frequencies can be reused many times within a few city blocks.
Depending on regulatory decisions by the British Post Office, PCN
could compete directly with wired residential-telephone service
in the UK. Thus, it is conceivable that the customers could bypass
the telephone company, and use a single, PCN terminal for communications at
home, office, or in the car.

In the US, over 50 experimental licenses have been issued
within the last year to regional Bell Operating Companies (RBOCs),
non-wire-line cellular-service providers, manufacturers,
cable companies, and new start-up companies hoping to pioneer
PCN service. To increase the competition and to reduce the
development time of new wireless technologies and services, the FCC
has created a special incentive, called the pioneer's preference, that
offers the exclusive use of reallocated portions of the radio
spectrum to companies that first demonstrate new technologies or
concepts for PCN or other new wireless services. Many of the US
PCN experimenters have filed petitions for rule-making with the
FCC, requesting new, dedicated or shared spectrum for PCN
services, and hope to secure an advantageous position through
pioneer's preference. Industry and government experts view the
demand for wireless personal communications to be so great that
the FCC has indicated that under-utilized portions of the existing
radio spectrum could be subject to reallocation in order to accom-
mmodate consumer demand. Several good tutorial articles, which
describe the impetus and technological challenges behind cellular
radio and PCN, can be found in the August and September, 1990,
issues of the IEEE Communications Magazine. The different,
second-generation standards that are emerging around the world
are described in several invited papers in the May, 1991, issue of
the IEEE Transactions on Vehicular Technology, which features
several invited papers on digital cellular technologies. As indicated in
the Vehicular Transactions special issue, it is conceivable that
50 to 75 million subscribers could be using wireless systems
for personal communications by the mid-1990's. This is corroborated
by a recent Morgan Stanley report, which predicts cellular
and PCN systems will achieve at least 12% market penetration in
many developed countries by the end of this century.

2. Recent Events In The Wireless Industry

In large US markets, like Los Angeles and New York, where
hundreds of thousands of users can access the cellular radio spec-
trum, the 832 cellular analog-FM voice channels are unable to
accommodate the number of users, and methods to improve
capacity and cellular system design are desperately needed. For
those not familiar with cellular radio, in each market (i.e., city)
there are two cellular service providers: the wire-line provider,
called the A-channel provider, and the non-wire-line, or B-
channel, provider. Each of the two service providers is allocated
416 duplex voice channels in a 25 MHz spectrum allocation. Each
voice channel is comprised of a 30 kHz base-to-mobile link, and a
30 kHz mobile-to-base link. Over the past four years, numerous
standards have been proposed for digital cellular radio communica-
tion interfaces throughout the world. Digital modulation offers
improved spectral efficiency and, simultaneously, offers better
speech intelligibility for a given carrier-to-interference ratio (C/I).
More importantly, digital modulation accommodates powerful
digital speech coding techniques, which further reduce the spec-
trum occupancy of voice users. With digital transmission formats,
service providers will be able to offer customers additional
features, such as dynamically-allocated data services, encryption,
etc.

In early 1990, the CTIA and the Telecommunications Industry
Association (TIA) approved Interim Standard 54, which specifies
a dual-mode cellular radio transceiver that uses both the
analog FM (the present day, US Advanced Mobile Phone System,
or AMPS, standard) and a linearized, A/D Differential-Quadrature
Phase-Shift Keying modulation format, with a Code-Excited
Linear-Predictive (CELP) speech coder (called the US Digital
Cellular, or USDC, standard) [20]. The USDC standard offers
roughly three times the capacity improvement over AMPS, by
providing three voice channels which are time-division multi-
plexed (TDMA) on single AMPS 30 kHz FM voice link. With
further speech coding improvements, six times capacity is likely to
be achieved by 1994. The dual-mode equipment will allow a
graceful transition from analog FM to digital cellular, since cell-
ular operators will be able to change out analog channels to digital
channels, depending on their geographically capacity demands. In
this manner, customers with analog phones will be assured service
in any market until some announced time in the future. A rural cell-
ular carrier that does not suffer great capacity demand would be
likely to stay with AMPS for as long as possible, probably several
years (until the mid-1990's), while a metropolitan operator would
likely change out AMPS for USDC more rapidly (within two years).
It is interesting (and also a bit troubling to those who
invested a great deal of time and money in developing the IS-54
standard, and who plan to abide by it) that since the introduction
of the USDC standard IS-54, numerous vendors have introduced
their own, competing standards, which are incompatible with [20].
Furthermore, virtually all major cellular radio-service providers
are now conducting field trials to evaluate new, competing
standards, so it is unclear if US digital cellular radio systems will be
completely compatible throughout the country, even though this
was the major goal of USDC.
In contrast with USDC, the European digital cellular system (called Group Special Mobile, or GSM) was developed for a brand new spectrum allocation in the 900 MHz band. That is to say, GSM was developed to ensure that a single access and equipment standard would be used throughout the European continent. Unlike USDC, which hoped to make a seamless transition of America's analog system to digital, GSM was developed from scratch, and made pan-European compatibility its primary objective. That is, in most European countries, the cellular systems and standards were already unique to the individual countries. In fact, today, a cellular phone which works in France can not be used in England. GSM operates in new spectrum, at 900 MHz, dedicated for use throughout Europe. Details of the GSM specification are given in [21, 25], and equipment will be available to the pan-European community by the time this article is published. GSM is the world's first TDMA cellular-system standard, and uses a constant-envelope modulation format to gain power efficiency (constant-envelope modulation allows more efficient class-C power amplifiers to be used) over spectral efficiency (constant-envelope modulation has a larger number of bits per hertz of RF occupancy than does linear modulation). GSM uses an equalizer and slow frequency hopping to overcome multipath effects, which cause inter-symbol interference and, thus, irreducible bit-error rates. As the world's first digital cellular-radio standard that has been adopted by a large market, GSM is viewed as a front-runner for early implementation of PCN throughout the world. Depending on the success of UK 1800 MHz PCN initiatives, GSM equipment could be implemented on a world-wide scale, if spectrum allocations are made available in other countries.

In February 1990, just after CTIA adopted IS-54, Qualcomm, Inc., proposed to CTIA the use of spread-spectrum and sophisticated base-station signal processing, to offer capacity improvements ten times greater than AMPS (see the paper by Glibhausen, et. al., in the 1991 IEEE Transactions on Vehicular Technology special issue on Digital Cellular Technologies). Major cellular radio service providers and manufacturers have steadily supported Qualcomm, as they develop prototype spread-spectrum cellular phones that will be ready by mid-1992 [22]. Work conducted two decades ago [26], and more recently [29], confirms that the spectrum holds great promise for accommodating huge capacity with simple frequency management, although the capacity is highly dependent on radio path loss within the service area. Of course, higher capacity means higher revenues and less churn (loss of customers) for cellular service providers, so the Qualcomm proposal received immediate attention. Today, many US companies, such as PCN America and Omnispot Data, are looking at the viability of spread spectrum to overlay existing point-to-point microwave users, such as utility companies, banks, and public safety providers, in the 1850-1990 MHz band. The concept behind overlay is that low-power spread-spectrum PCN service could be offered directly on top of existing, terrestrial microwave systems that do not have such a great degree of capacity demand, and have not been engineered to take full advantage of the spectrum. References [23] and [24] discuss the concept behind overlay, and some techniques that could be used to minimize interference between existing and new users. Recent propagation measurements, to test the levels of interference caused by PCN subscriber units to existing, fixed, microwave users, were presented in [24]. They have been detailed more recently in a report submitted on June 14, 1991, by PCN America to the FCC, as part of its experimental PCN license. Presently, major telecommunication companies are researching the effectiveness of overlay systems from a capacity standpoint. If a sufficient grade of service could be offered through spectrum sharing between new wireless service providers and existing line-of-sight microwave licences, then the FCC would be able to instantly accommodate market demand for wireless cellular/PCN, without a major, new spectrum allocation. The fear, of course, is that there could be an unsatisfactory degradation of service to both the existing microwave users and the overlaid PCN users. The overlay concept is being tested by numerous companies in the US under the FCC experimental license program, and the FCC has not, as of yet, made a decision on their position on the matter.

The cable industry has also been watching the sudden growth in cellular/PCN throughout the world. Cable companies have a massive RF network installed throughout populated regions, and it is obvious that telecommunication services could be offered over the existing cable "plant." In fact, PCN base stations could easily be installed in residential areas by splicing existing coaxial cables and by "tapping-on" base stations mounted on lamp posts or inside buildings. Indeed, several US cable companies are presently conducting experiments to determine the feasibility of PCN using the cable plant. When one realizes that US cable operators already have spectrum allocated for microwave feeds in the 2 GHz and 13 GHz bands, the possibility of utilizing the cable spectrum for PCN communications, instead of point-to-point feeders, presents a lucrative new-business opportunity for the cable industry.

For local loop, or premises applications, which merge voice and data, Belcore [15] and the European Telecommunication Standards Institute (ETSI) have proposed digital TDMA standards that offer between 400 kilobits per second (kbits) and 1100 kbits data rates in office and residential environments. While the widespread deployment of such standards will likely rely on new, dedicated portions of the spectrum for the services, significant engineering manpower has been devoted to developing the standards, and a great deal can be learned from the research. Belcore's system exploits the slow time-varying nature of indoor channels, and uses antenna-polarization diversity to improve link performance between a base station (port) and mobile terminal (portable). Belcore's proposal limits the data rate to 450 kbits, based on an extensive measurement program that determined worst-case multipath channels in a large-hungry adaptive equalizers can be avoided. Also, Belcore's system uses a novel over-sampling demodulation technique, that allows a receiver to lock coherently onto the incoming modulation with only a couple of bits of overhead. Reference [15] provides additional details about the Belcore system, and [21, 25, 34], and [35], provide additional information about ETSI and the DECT standard.

3. Federal Research Funding In Wireless Communications

Federal funding for wireless communications has been limited in the United States. The National Science Foundation has shown little interest in funding experimental or theoretical work applied to wireless communications. It is ironic that a project sponsored by NSF, at Purdue University in the mid-1970s, provided the first study of a spread-spectrum cellular-radio system [26]- a system that created interest in spread-spectrum access approaches for cellular radio communications which now, 15 years later, are being extensively commercialized by numerous companies. However, this Summer, NSF awarded Rutgers a cooperative University/Industry center. Rutgers' wireless information network (WINLAB) is working on network and access solutions for third-generation wireless personal-communication systems, and was the first US academic laboratory formed for wireless personal-communications education and research.

The National Aeronautics and Space Administration (NASA) has provided the bulk of US research funding in the mobile communications area, through the NASA mobile satellite (MSAT)
systems. While mobile satellite systems do not promise nearly the same user capacities as land-based cellular systems, several factors, such as modulation, coding, and multiple access, and the techniques used to analyze these factors, may be shared by satellite and cellular/PCN systems. Mobile satellite systems, such as Motorola’s Iridium low-earth-orbit satellite (LEOSAT) system and the Ait Propulsion Laboratory’s Personal Access Satellite System (PASS) [36], are examples of satellite networks that will become feasible over the next decade. It should be noted that the NASA MSAT program has provided multi-year research contracts to over ten universities and numerous companies in the US.

The Defense Advanced Research Projects Agency (DARPA) is funding projects to develop small, low-powered wireless devices, and is supporting technology development for rapidly deployable local-area communication systems. New design and fabrication technologies range from advanced silicon integrated circuits to software tools for propagation prediction and installation. The knowledge base, resulting technologies, and system-design tools from these projects will not only improve the US military capability, but also have relevance to the US consumer wireless personal-communications industry, as well.

It is worth noting that in contrast with the US government agencies, the European, Canadian, and Japanese governments have made substantial funding commitments to research laboratories and university programs focusing on wireless personal communications and related technologies. For example, in Europe, the RACE program (Research and Development in Advanced Communications in Europe) has committed over $100 million per year to the European Community during the period 1987-1992 [27]. A significant portion of these funds have been spent on collaborative industry/university research in wireless communications, with the goal of concurrently expanding the knowledge base and pool of technical experts. RACE appears to be yielding big dividends. The European community is widely recognized as the world leader in creating and accepting new, digital cellular-radio system techniques (recall that many European countries presently enjoy more than a 5% cellular market penetration, compared with less than 2% in the US), and it is where the concept of personal communications was first put into wide-scale practice. Casual conversations with researchers across the world indicate that over 50 European PhD students are tackling dissertations dealing with antennas and propagation for emerging wireless personal-communications systems.

In Canada, numerous initiatives are underway to encourage academic participation in research for wireless personal communications. The Telecommunications Research Institute of Ontario (TRIO) program is enhancing the technological competitiveness of Canadian industry through University/Industry partnerships in telecommunication research. TRIO was founded in 1987, and has grown steadily. This year, the Ontario province and Canadian industry will provide over $6 million dollars for university communications research in Ontario. A significant portion of these dollars are being used for mobile- and satellite-systems research for wireless personal communications. The mobile- and satellite-systems program supports over 50 graduate students at five universities, and involves about 20 Canadian communications companies. Other Canadian provinces are also providing research support for regional universities active in wireless personal communications. On a federal level, the Canadian Institute for Telecommunications Research (CITR) was established in 1989, and is providing research grants to universities throughout Canada. CITR’s budget is over $4 million annually (overhead is waived on CITR funding), and is focusing on two major thrust areas: broadband communications and wireless communications. As an example of CITR projects in the antennas and propagation area, researchers are investigating propagation and diversity techniques for indoor wireless communications at millimeter waves, fading issues for 20-30 GHz personal communications systems, and new cellular-system-design techniques. Universities involved with CITR wireless research include Carleton University, Concordia, Ecole Polytechnique, Laval University, McGill, Queens, St. Francis Xavier University, University of British Columbia, University of Calgary, University of Ottawa, University of Toronto, University of Victoria, the University of Waterloo, and the University of Western Ontario.

Japanese research programs in wireless personal communications abound, and there are numerous universities which are active in the area and which are making fundamental contributions. As an example, Kyoto university has been a major contributor in the wireless communications field, and has an active graduate program in propagation and communication-system design. Federal funding for academic research in Japan often involves interaction with industrial laboratories [27]. It seems clear that most federal governments are aware of the tremendous impact that wireless communications will make on the world’s economy, and are hoping their investments will result in new technologies and a body of experts who can engineer and develop new wireless personal-communications systems.

6. Research At Virginia Tech’s MPRG

Early efforts to obtain government funding from the National Science Foundation failed, but industry response has been excellent, and after one year, 12 major wireless companies (including regional Bell Operating Companies, major radio manufacturers, and computer manufacturers), DARPA, and the FBI have provided a funding base close to $1 million. Collaborative research projects with Purdue University, Northeastern University, and the University of California at San Diego have provided cross-fertilization of ideas and knowledge, and are helping to make the US approach to wireless communications research more synergistic.

At MPRG, students receive an educational experience that provides them with a solid understanding of the theory and practice of mobile-radio communications and emerging personal-communications systems. At the same time, they are tasked with developing and validating analyses, models, and research tools for the wireless industry. These tools help transfer knowledge from the MPRG laboratory into industry and academia. In 1990, the first year of MPRG, five MSEE students graduated with expertise in RF filter design, indoor radio-propagation measurement and prediction, adaptive noise-cancellation techniques, and urban radio-propagation prediction. Presently, there are 12 graduate and six undergraduate MPRG students pursuing degrees with an emphasis on wireless communications. As a result of student theses, several analysis and simulation software tools have been developed for internal use, and are also being used for research and development by a number of companies and universities. An EE graduate course, dedicated to the topics of cellular radio and personal communications, was offered in the spring of 1991, and enjoyed an enrollment of 34 students, making it the most popular graduate course in the EE curriculum at Virginia Tech, that term. Senior elective courses on radio-wave propagation and satellite communications are also popular EE courses at Virginia Tech.

While the research and educational mission of MPRG concerns itself with more than just propagation, the group received its first research contracts in the area of propagation measurement and prediction, and continues to maintain an active program in this area. There is extreme interest in, and demand for, propagation...
measurements and models for the proper design of emerging wireless services, such as PCN, and more powerful, site-specific channel modeling techniques and tools are needed. However, the US wireless industry often finds conducting their own measurements and propagation research to be a time-consuming and expensive task, and many industrial players view it as an expensive luxury which involves high-priced consultants. MPRG has emerged as a sensible and cost-effective alternative, since it has an established equipment arsenal, and provides research expertise in the area of propagation measurement and prediction. By pooling resources in an Industrial Affiliates Program, MPRG is generating useful tools and basic propagation models that can be shared by all affiliate members, and the resulting value of the research is much greater than the cost to an individual member. All results are published, so the entire research community benefits from the knowledge base.

Here, we briefly present results from propagation measurements in urban channels, microcellular measurements, and indoor measurements. These measurements involve wide-band characterizations, where a very short RF burst is sent and the echoes are received, as well as narrow-band (CW) characterizations, which measured signal fading over large temporal and spatial spans. As shown subsequently, antenna experiments have revealed that polarization can dramatically reduce the multipath time-delay spread and the fluctuation of delay spread in mobile channels. Results presented in this article are not meant to be interpreted as definitive work in mobile radio propagation. On the contrary, it is hoped that this article will spark interest and ongoing discussions in propagation modeling and prediction for personal communications [and future contributions in this area to both this Magazine and our Transactions! WRS].

II. Propagation Measurement And Prediction

A large part of MPRG research has dealt with measuring, and then statistically modeling, the path loss and time dispersion of multipath radio channels. Measurements and models have been made in many different environments: a) traditional urban cellular-radio channels, with base-station antenna heights exceeding many tens of meters [1, 2]; b) urban cellular-radio channels, with lower antenna heights, on the order of 15-20 meters (2); and c) indoor channels, within sports arenas, factories, and office buildings [3, 4], and open-plan office buildings [5]. Also, impulsive noise measurements have been made, inside many types of buildings, at three bands, between 900 MHz and 4.0 GHz [28], including two of the license-free Industrial, Scientific, and Medical (ISM) bands.

For urban mobile-radio channels, it has been reported that the coherence bandwidth (the bandwidth over which the received signal strength will likely be within 80% of any other frequency from the same source) is between 19 kHz to 500 kHz [6]. Consequently, to sufficiently resolve multipath components (in the time domain) that cause frequency-selective fading, a channel sounder for urban channels should possess an RF bandwidth several times larger than the maximum coherence bandwidth. This thinking led us to use a 500-ns probing pulse (4 MHz RF bandwidth) in [1, 2]. For indoor measurements, we have used probes that have durations on the order of 5 ns, thereby providing measurements that span over 400 MHz and which resolve individual multipath echoes to about 1.6 m separation distance. (The baseband pulse is DSB modulated, so there is a bandwidth expansion factor of two at RF. Thus, the baseband complex- envelope responses has a 200 MHz resolution bandwidth). We use time-domain techniques rather than swept-frequency techniques, since it is easy to identify the location and intensity of reflecting objects in the channel. This information is vital for successful development of site-specific propagation models that can re-create the channel impulse response. Our measurement systems are easy to assemble, test, and deploy, and provide instantaneous channel measurements with excellent time-delay resolution. Post-detection integration is employed to improve the signal-to-noise ratio of the measured power-delay profiles. However, our approach requires slightly more peak power than the direct-sequence systems used in [7, 8, and 9] for a specified coverage distance. Broadband discourse, Yagi, and helical antennas have been used, to ensure that no pulse spreading is attributed to impendence mismatch.

Figure 1 illustrates important parameters that indicate multipath dispersion in mobile radio channels. The rms delay spread (μτ) measures the spread of the channel-power delay profile about the centroid, and the excess-delay spread (X dB) indicates the maximum excess delay at which multipath energy falls to X dB below the peak received level. These parameters are useful measures for comparing different multipath channels, and have been used to determine approximate bit-error rates for digital modulation schemes without equalization. Historically, time- dispersion parameters, such as μτ, for ionospheric channels were computed by using a temporal average of the channel impulse response during a time period over which the channel appeared wide-sense stationary. In mobile systems, however, the time variation of the impulse response is due primarily to motion, so the parameters may be computed over a spatial average during which the channel appears wide-sense stationary [9, 30]. Particularly in indoor channels, individual multipath components fade very little between two fixed terminals, or terminals moved along a small area [31, 32]. Statistical processing on an extensive indoor-propagation data base showed that individual multipath components fade in a log-normal sense over small temporal and spatial intervals, with a standard deviation of only a couple of dB. Simultaneously CW measurements showed that the narrow-band fading between two fixed terminals is Ricean, but the CW fading can be either Ricean, log-normal, or Rayleigh, when the receiver is moved over a small area. Deep fades of individual multipath components are primarily due to shadowing, as a terminal is moved, or result from the phase sum of unresolvable multipath components within a resolution cell. Knowledge of the channel time dispersion to temporal resolutions much greater (smaller duration) than the bit durations of a communication signal, and of how the time dispersion changes over space, is important, because these factors determine the instantaneous bit-error floor, which occurs because of data spreading. By performing the time convolution of transmitted data bits with accurate spatially- (time-) varying impulse-response models,

it becomes possible to predict burst errors and to conduct real-time system-design experiments, using computer simulation instead of prototype hardware [37].

Historically, path loss has been found to be closely linked to the separation distance between transmitter and receiver, so a simple model (for the path loss at some distance, r, from a transmitter can be expressed as

\[ P(r) = P(r_0) (r/r_0)^n, \quad r \geq r_0 \] (1)

The exponent, n, in (1) represents the best-fit (in a mean-square sense) average power law at which signal power decays with respect to a free-space measurement at r, the close-in reference distance. Measurements have shown that field measurements are generally log-normally distributed about the average distance-dependent power law given in (1), independent of r. Figures 2 and 3 show different time-dispersion and path-loss results for urban microcellular measurements reported in [2]. The measurements were made throughout several existing cellular markets in Germany, using a 500-nS probing pulse and existing cellular base-station antennas, which ranged from 20 to 93 m in height [2]. Data

\[ \begin{array}{l|cc|c|c|c|c} 
\text{Antenna} & \text{Latitude} & \text{Height (m)} & \text{\sigma (dB)} & \text{Max T-f \text{-} Fit} & \text{Max T-f Fit} \\
\text{ } & \text{mp} & \text{ } & \text{Delay Spread} & \text{Delay Spread} & \text{Delay Spread} \\
\text{Location} & \text{cm} & \text{km} & \text{in km} & \text{in us} & \text{in us} \\
\hline
\text{Hamburg} & 40 & 18.0 & 3.5 & 2.8 & 7.0 \\
\text{Stuttgart} & 50 & 17.8 & 6.5 & 8.5 & 5.0 \\
\text{Dusseldorf} & 83 & 15.1 & 8.5 & 6.5 & 15.8 \\
\text{Frankfurt} & 50 & 5.8 & 7.1 & 1.3 & 12.0 \\
\text{Kromberg} & 60 & 2.4 & 8.5 & 10.0 & 19.6 & 51.3 \\
\text{All (10 km)} & 27.1 & 11.8 & 10.0 & 19.6 & 51.3 \\
\text{All (1 km)} & 30.8 & 8.9 & 10.0 & 19.6 & 51.3 \\
\end{array} \]

Figure 3. This table indicates the best-fit path-loss exponent and the time dispersion of several measured channels [2].

MPRG research has focused on measuring indoor and microcellular channels, and on developing models for such channels, since it is our belief that indoor environments and street-level systems will serve the largest number of wireless users in the decades to come. Extensive indoor propagation measurements have been and continue to be made, with the goal of deriving site-specific modeling approaches and installation tools, based on physical descriptions of building interiors [5, 13].

Along the way, we have developed statistical modeling procedures [10] to reproduce, on a personal computer, extensive propagation measurements given in [37], so that research can focus on indoor radio-communication system design, using realistic computer-generated impulse responses. Also, more recent measurements [3], [4], and measurements reported in the literature [14], have been used to generate, on a computer, impulse response and path-loss measurements in traditional, partitioned office buildings, and soft-partitioned (Herman-Miller office partitions) office buildings. The statistical-channel models are useful for determining, through simulation, irreducible bit-error rates, modulation performance, diversity implementations, and robust equalization methods. The propagation simulator, called SIRCIM (Simulation of Indoor Radio Channel Impulse response Measurements), is a valuable research tool for MPRG communications research, and also being used by 30 companies and universities. The models used in SIRCIM are detailed in [10]. While similar in nature to the SURF simulation program for urban radio propagation [11], SIRCIM is based upon measurements made over small-scale distances, and thus allows synthesis of the phase of individual multipath components, based on the Doppler shift and a random-scattering model. By computing the spatially-varying phasor sum of multipath components, SIRCIM recreates CW fading envelopes identical in nature to those measured in the field. MPRG plans to update the software as more measurements become available, and as user experiences dictate. A useful result from [3] is that propagation characteristics are very similar at both 1.3 GHz and 4.0 GHz, which means that SIRCIM models (based on measurements at 1.3 GHz) will hold up to at least 4.0 GHz, and probably at somewhat higher frequencies. At the time of this writing, MPRG measurement capabilities are limited to frequencies below 4 GHz, although new measurement equipment is being purchased for measurements at much higher frequencies. Typical examples of the data produced by SIRCIM are shown in Figure 4. Data files that contain the amplitudes, phases, time delays, and path loss, for individual mult-
d. An example of a scatter plot produced by SIRCIM in an open-plan building: 50% LOS, 50% OBS.

Figure 4. These waveforms are examples produced by SIRCIM. SIRCIM provides the user with data files which contain amplitudes, phases, and time delays of the channel impulse response, and computes fading statistics, large-scale path loss, best-fit exponent, and standard deviation. The user can specify building type, topography (LOS or OBS), and transmitter-receiver separation distance. SIRCIM is based on extensive measurements made in over ten different buildings.

Narrow-band measurements have shown how the path-loss exponent, and the deviation about the best-fit average path-loss model, can be affected by building type, or by location within a building. Table 1, extracted from [5], indicates that in different buildings, the floors can offer different values of attenuation. Figures 5 and 6 present measured attenuation factors for various obstacles in indoor environments [4, 5]. In [5], a simple two-parameter statistical model was developed to model the loss due to each partition or each wall encountered between a transmitter and receiver located within a building. Figure 7 shows a scatter plot of path-loss measurements made on three different floors of two different office buildings, and the predicted path-loss, based on the simple model in [5]. The agreement between measured and predicted path loss is very good, for the most part, and has an overall standard deviation of 4 dB. A standard deviation much greater than 10 dB usually results when only distance (and no site-specific information) is used to predict signal strength from a data base of several different types of buildings. For the measurements in Figure 7, the transmitter antenna was mounted 1.8 m above ground, and the receiver was located at desk height, slightly shadowed by movable office cubicles (soft partitions) and obstructed by concrete walls. Using a very simple model, which assumes 1.4 dB loss for each cubicle wall and 2.4 dB for each concrete wall (the walls did not span the entire floor), and free-space propagation everywhere else, it was possible to closely predict signal-strength contours.

Figures 8-10 illustrate how the simple, site-specific attenuation model can accurately predict coverage throughout the work space. Figure 9 shows a schematic of a typical 39 m x 39 m open
plan office building, with movable cloth partitions and concrete walls. Dark lines in Figure 9 denote concrete walls that extended from floor to ceiling. Lighter lines represent 2.0-m-tall soft partitions. Figures 8 and 10 can be overlaid on Figure 9, and show measured and predicted signal strength contours based on the site-specific model in [5]. A simple distance-dependent path-loss model would provide circular contours of equal radius about the transmitting antenna. Although this modeling work is preliminary, it tells us that simple descriptions about the building topology could be used to predict coverage areas and interference zones with much better accuracy than models used today. MPRG researchers are continuing measurements that will aid in developing accurate site-specific models. These models will then be incorporated into an automated system-design tool that will optimally locate base stations for minimum interference and, consequently, maximum capacity. MPRG is working to exploit knowledge of the propagation environment to improve and automate system installation without measurements.

Work in [4] has shown that antenna polarization can play a big part in reducing the delay spread (i.e., improving the bit-error performance). In [15], Cox describes the Bellcore UDPC system as using polarization diversity to open the eye in digital-modulation techniques. Our work [4] shows that, indeed, polarization diversity can be used to select the best channel at a particular location. Our work also shows that circularly-polarized (C-P) directional antennas, when used in line-of-sight channels, can provide a much lower delay spread than can linearly-polarized antennas with similar directionality [4]. Figure 11 shows how the rms delay spread

<table>
<thead>
<tr>
<th>Office Building 1:</th>
<th>FAF (dB)</th>
<th>σ (dB)</th>
<th># Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Through 1 floor</td>
<td>12.9</td>
<td>7.0</td>
<td>104</td>
</tr>
<tr>
<td>Through 2 floors</td>
<td>18.7</td>
<td>2.8</td>
<td>18</td>
</tr>
<tr>
<td>Through 3 floors</td>
<td>24.4</td>
<td>1.7</td>
<td>18</td>
</tr>
<tr>
<td>Through 4 floors</td>
<td>27.0</td>
<td>1.5</td>
<td>13</td>
</tr>
<tr>
<td>Office Building 2:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Through 1 floor</td>
<td>16.2</td>
<td>2.9</td>
<td>40</td>
</tr>
<tr>
<td>Through 2 floors</td>
<td>27.5</td>
<td>5.4</td>
<td>42</td>
</tr>
<tr>
<td>Through 3 floors</td>
<td>31.6</td>
<td>7.2</td>
<td>40</td>
</tr>
</tbody>
</table>

| Table 1a. Floor Attenuation Factors Measured in Two Office Buildings |

- **Table 1b.** Best-Fit Path-Loss Exponents, and Corresponding Standard Deviations, for Measurements in Several Types of Buildings [5]

<table>
<thead>
<tr>
<th>Item</th>
<th>Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Block Wall</td>
<td>13</td>
</tr>
<tr>
<td>Loss From One Floor</td>
<td>20-30</td>
</tr>
<tr>
<td>Loss From One Floor and One Wall</td>
<td>40-50</td>
</tr>
<tr>
<td>Right-Angle Fade*</td>
<td>10-15</td>
</tr>
</tbody>
</table>

*Observed when transmitter turned a right-angle corner in a corridor.*

In Factory Buildings

<table>
<thead>
<tr>
<th>Item</th>
<th>Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light textile inventory</td>
<td>3-5</td>
</tr>
<tr>
<td>Heavy textile inventory</td>
<td>8-11</td>
</tr>
<tr>
<td>Metallic inventory</td>
<td>4-7</td>
</tr>
<tr>
<td>Chain-link fence in area 20 ft high which contains tools, inventory, and people</td>
<td>5-12</td>
</tr>
<tr>
<td>Metal blanker 12 sq ft</td>
<td>4-7</td>
</tr>
<tr>
<td>Metallic hoppers which hold scrap metal for recycling-16 sq ft</td>
<td>3-6</td>
</tr>
<tr>
<td>Small metal pole in diameter</td>
<td>3</td>
</tr>
<tr>
<td>Metal pulley system used to hold metal Inventory-4 sq ft</td>
<td>6</td>
</tr>
<tr>
<td>Light machinery &lt;10 sq ft</td>
<td>1-4</td>
</tr>
<tr>
<td>General machinery 10-20 sq ft</td>
<td>5-10</td>
</tr>
<tr>
<td>Heavy machinery &gt;20 sq ft</td>
<td>10-12</td>
</tr>
<tr>
<td>Metal catwalk/staircase</td>
<td>5</td>
</tr>
<tr>
<td>Area where workers inspect finished metal products for defects</td>
<td>3-12</td>
</tr>
<tr>
<td>Large i-beam 16-20 in</td>
<td>8-10</td>
</tr>
<tr>
<td>Metallic inventory racks 8 sq ft</td>
<td>4-9</td>
</tr>
<tr>
<td>Empty cardboard inventory boxes</td>
<td>3-5</td>
</tr>
<tr>
<td>Concrete block wall</td>
<td>13-20</td>
</tr>
<tr>
<td>Ceiling duct</td>
<td>1-3</td>
</tr>
</tbody>
</table>

Figure 5. The measured signal loss due to common obstructions in buildings. These data were collected by comparing signal strength on either side of the obstruction.

**Figure 6.** The measured signal loss due to common obstructions in factory buildings.

<table>
<thead>
<tr>
<th>Obstacle Descriptions</th>
<th>Attenuation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 m storage rack with small metal parts (loosely packed)</td>
<td>4-6</td>
</tr>
<tr>
<td>4 m metal box storage</td>
<td>10-12</td>
</tr>
<tr>
<td>5 m storage rack with paper products (loosely packed)</td>
<td>2-4</td>
</tr>
<tr>
<td>5 m storage rack with paper products (tightly packed)</td>
<td>6</td>
</tr>
<tr>
<td>5 m storage rack with large metal parts (tightly packed)</td>
<td>20</td>
</tr>
<tr>
<td>Typical N/C machine</td>
<td>8-10</td>
</tr>
<tr>
<td>Semi-automated assembly line</td>
<td>5-7</td>
</tr>
<tr>
<td>0.6 m square reinforced pillar</td>
<td>12-14</td>
</tr>
<tr>
<td>Stainless steel piping for cook-cool process</td>
<td>15</td>
</tr>
<tr>
<td>Concrete wall</td>
<td>8-15</td>
</tr>
<tr>
<td>Concrete floor</td>
<td>10</td>
</tr>
</tbody>
</table>

changes as a mobile receiver is moved over a 2.5 track. The identical track was traversed with a receiver using omni-directional and directional linearly-polarized antennas, and directional circularly-polarized antennas. Note that the C-P helical antenna offers much less delay spread, and smaller delay-spread variability, than do the L-P omni or Yagi antennas. Also, directional antennas reduce the delay spread when compared with omni antennas. We have also seen this on cross-campus links which illuminate several buildings at a time. In outdoor links especially, it appears that when aligned off-axis, directional C-P antennas offer much more multipath resistance than linearly-polarized antennas. The multipath reduction is probably due to cancellation of odd-bounce multipath, and offers a significant performance gain, since it reduces the time dispersion of the channel. Further, this finding indicates that an accurate propagation-prediction tool must consider polarization effects.

Figure 7. The best-fit line for a simple, two-parameter model used to predict signal loss due to obstructions.

MFRG is conducting additional 900 MHz, 1900 MHz, 2440 MHz, and 4000 MHz wide-band measurements around campus to provide data for building-penetration loss, floor-to-floor loss for different shaped buildings, the correlation of signal strengths over small distances, and the importance of antenna pattern and polarization on system design. Also, further measurements will enhance the partition models presented in [5], and will reveal additional modeling parameters.

Referring back to Figure 2, there is a large amount of scatter about the best fit, indicating that surrounding buildings have a large impact on the measured path loss between a transmitter and receiver. Site-specific propagation models that predict, with good accuracy, the shadowing losses and the diffraction effects in urban canyons are needed for system design. Good progress is being made by numerous researchers throughout the world, and readers of the IEEE Transactions on Antennas and Propagation should look forward to some excellent work in this area. A recent paper shows the viability of ray tracing and shadowing for accurate propagation prediction for microcellular systems [16], and unpublished work at MFRG shows that, in fact, only a few rays and simple diffraction methods can be used, most of the time, to get surprisingly good prediction (within 3 dB) of measured signals in microcellular environments. Prof. Henry Bertoni, of Polytechnic University, organized a lively session on propagation in man-made environments for the 1991 PIERS conference, and presenters there showed several different methods, which promise to predict signal coverage using site-specific information and electromagnetic field theory.

Figure 8. A contour plot of the measured signal strength at 900 MHz inside an open-plan building with soft partitions.

III. Future Work Needed

There are a number of important issues in the antennas and propagation area that merit attention by the wireless communications industry and are ripe for study. Propagation models that predict the signal strengths around buildings (urban canyons) are vital for evaluating the effectiveness of overlay services, and for determining system layouts for line-of-sight PCN systems. Research that shows the capacity of urban-based PCN systems, which share existing point-to-point microwave spectra, are urgently needed by...
regulatory agencies and service providers. Since capacity in cellular systems is dependent primarily on co-channel interference levels, this translates the problem into one of modeling the end result of multiple users propagating in a congested area. Terrain maps, overlaid with site-specific descriptions of buildings, will probably be needed to help accurately predict the potential of overlay services. These models will need to take into account the antenna patterns and wave polarization.

Novel antennas and antenna-diversity techniques are needed for portable communications that can be placed in a person’s pocket or on a wrist watch. Models that predict microwave propagation in and around buildings at 20-60 GHz are needed, and scaling factors which relate the existing body of propagation knowledge in the low microwave (900 MHz) region to much higher frequencies would be extremely useful. Measurements of the dielectric constants of common building materials at frequencies well above 3 GHz, and how these vary among building types, are also needed, as data are limited in this area.

Adaptive antennas and algorithms to control them based on instantaneous-interference or delay-spread levels, are vital to the deployment of high-capacity cellular/RNC systems. In the communications area, extensive work has been done to adaptively equalize the inter-symbol interference caused by multipath. Incorporating the antenna with the equalizer would provide an extremely powerful anti-multipath capability for high-data-rate wireless services.

Most importantly, good, objective, in-depth experiments must be performed jointly and immediately by engineers and medical scientists to determine the health risks associated with continuous and pulsed microwave radiation. While standards exist, it is unclear if these standards actually represent safe levels for humans. If a cause and effect relationship exists between cancers and microwave radiation, this must be made known immediately, and the physical mechanisms must be learned to combat radiation effects in the future. The wireless personal communications age is coming soon. Low-level RF radiation at microwave frequencies will be near our bodies and all around us. We must be certain that it will be an environmentally-safe age, as well.

IV. Acknowledgements

The author expresses his gratitude to the MPRG Industrial Affiliates companies, and to the hard-working MPRG students and staff.

V. References


