A Fourth-Generation MIMO-OFDM Broadband Wireless System: Design, Performance, and Field Trial Results

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ABSTRACT

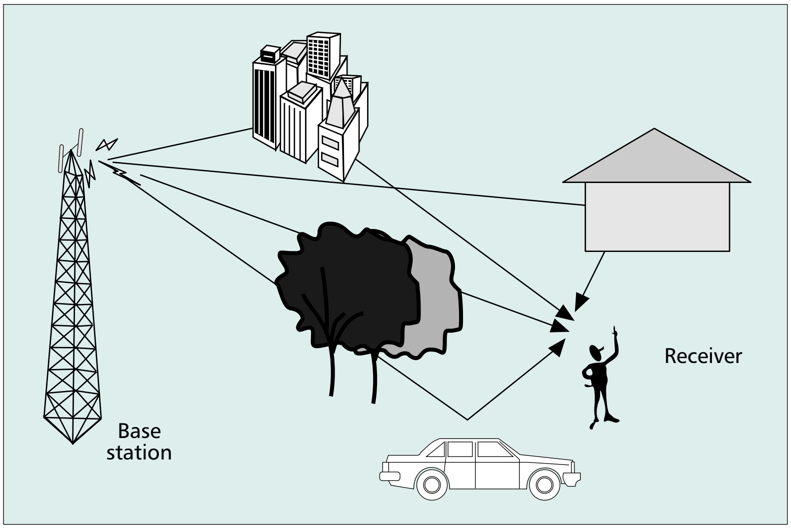
Increasing demand for high-performance 4G broadband wireless is enabled by the use of multiple antennas at both base station and subscriber ends. Multiple antenna technologies enable high capacities suited for Internet and multimedia services, and also dramatically increase range and reliability. In this article we describe a multiple-input multiple-output OFDM wireless communication system, lab test results, and recent field test results obtained in San Jose, California. These are the first MIMO system field tests to establish the performance of MIMO communication systems. Increased capacity, coverage, and reliability are clearly evident from the test results presented in this article.

INTRODUCTION

This design is motivated by the growing demand for broadband Internet access. The challenge for wireless broadband access lies in providing a comparable quality of service (QoS) for similar cost as competing wireline technologies. The target frequency band for this system is 2–5 GHz due to favorable propagation characteristics and low radio frequency (RF) equipment cost. The broadband channel is typically non-LOS channel and includes impairments such as time-selective fading and frequency-selective fading. This article describes the physical layer design of a fourth-generation (4G) wireless broadband system that is, motivated from technical requirements of the broadband cellular channel, and from practical requirements of hardware and RF. The key objectives of the system are to provide good coverage in a non-line-of-sight (LOS) environment (>90 percent of the users within a cell), reliable transmission (>99.9 percent reliability), high peak data rates (>1 Mb/s), and high spectrum efficiency (>4 b/s/Hz/sector). These system requirements can be met by the combination of two powerful technologies in the physical layer design: multi-input and multi-output (MIMO) antennas and orthogonal frequency division multiplexing (OFDM) modulation. Henceforth, the system is referred to as Airburst.

Multiple antennas at the transmitter and receiver provide diversity in a fading environment. By employing multiple antennas, multiple spatial channels are created, and it is unlikely all the channels will fade simultaneously. The Airburst system employs two transmit antennas and three receive antennas at the base station (2×3 downlink), and one transmit antenna and three receive antennas at the customer premises equipment (CPE) (1×3 uplink). Only one transmit antenna is used at the transmitter due to cost considerations. It is seen that spatial diversity in Airburst yields link budget improvements of 10–20 dB compared to a single-input single-output (SISO) system by reducing the fade margins. In addition, the two base transceiver station (BTS) antennas are used to double the data rate for users with certain channel characteristics by transmitting independent data streams from the two antennas. This technique, known as spatial multiplexing, can significantly increase system capacity [1, 2]. At the receiver, multiple antennas are used to separate spatial multiplexing streams and for interference mitigation, which makes aggressive frequency reuse a reality.

OFDM is chosen over a single-carrier solution due to lower complexity of equalizers for high delay spread channels or high data rates. A broadband signal is broken down into multiple narrowband carriers (tones), where each carrier is more robust to multipath. In order to maintain orthogonality among tones, a cyclic prefix is added that has length greater than the expected delay spread. With proper coding and interleaving across frequencies, multipath turns into an OFDM system advantage by yielding frequency diversity. OFDM can be implemented efficiently by using fast Fourier transforms (FFTs) at the transmitter and receiver. At the receiver, FFT reduces the channel response into a multiplica-



■ **Figure 1.** *A wireless propagation scenario.*

tive constant on a tone-by-tone basis. With MIMO, the channel response becomes a matrix. Since each tone can be equalized independently, the complexity of space-time equalizers is avoided. Multipath remains an advantage for a MIMO-OFDM system since frequency selectivity caused by multipath improves the rank distribution of the channel matrices across frequency tones, thereby increasing capacity [3].

Another key feature of the physical layer design is adaptive modulation and coding that allows different data rates to be assigned to different users depending on their channel conditions. Since the channel conditions vary over time, the receiver collects a set of channel statistics which are used both by the transmitter and receiver to optimize system parameters such as modulation and coding, signal bandwidth, signal power, training period, channel estimation filters, automatic gain control, and so on. The Airburst system has a proprietary link adaptation algorithm (LA) that tracks channel variations and adapts transmission parameters to perform optimally under prevailing conditions [4].

Of course, a successful broadband wireless access system must have an efficient co-designed medium access control (MAC) layer for reliable link performance over the lossy wireless channel. The corresponding MAC is designed so that the TCP/IP layers see a high-quality link that it expects. This is achieved by an automatic retransmission and fragmentation mechanism (automatic repeat request, ARQ), wherein the transmitter breaks up packets received from higher layers into smaller subpackets, which are transmitted sequentially. If a subpacket is receiver incorrectly, the transmitter is requested to retransmit it. ARQ can be seen as a mechanism for introducing time diversity into the system due to its capability to recover from noise, interference, and fades. More details on ARQ design can be found in [5].

The performance of the Airburst system is demonstrated by lab and field trial results. The performance can be measured by three key metrics: coverage, spectrum efficiency, and reliability. The first two metrics are key in determining the cost of the system. Good coverage is important initially when few base stations are installed, while spectrum efficiency defines how many users can be supported per unit of spectrum over the long-term. Reliability determines the quality of service a customer receives, and correspondingly long-term customer satisfaction. The system is currently targeted for business, home-office, residential and mobile users requiring high-rate data services.

MIMO-OFDM Design Constraints

Non-LOS Channel Models

In this section we briefly describe the key channel characteristics that influence the broadband wireless system design such as channel dispersion, Ricean *K*-factor, Doppler, cross-polarization discrimination, antenna correlation, and condition number. Figure 1 shows a typical non-LOS propagation scenario.

Channel Dispersion — An important channel characteristic that influences a system performance is channel dispersion due to reflections from close in and far away objects. The dispersion is often quantified by the rms delay spread, which increases with distance, and changes with environment, antenna beamwidth, and antenna height [6]. Typical values are in the 0.1–5 μs range.

K-Factor — The fading signal magnitude follows a Rice distribution, which can be characterized by two parameters: the power P_c of constant channel components and the power P_s from scatter channel components. The ratio of these two (P_c/P_s) is called the Ricean *K*-factor. The worst case fading occurs when $P_c = 0$ and the distribution is regarded as Rayleigh distribution ($K = 0$). The *K*-factor is an important parameter in system design since it relates to the probability of a fade of certain depth. Both fixed and mobile communications systems have to be designed for the most severe fading conditions for reliable operation (i.e., Rayleigh fading).

Doppler — The fixed wireless channel Doppler spectrum differs from the mobile channel Doppler spectrum [6]. For fixed wireless channels, it was found that the Doppler is in the 0.1–2 Hz frequency range and has close to exponential or rounded spectrum shape. For mobile wireless channels, the Doppler can be on the order of 100 Hz and has the Jake's spectrum.

Cross-Polarization Discrimination — The cross-polarization discrimination (XPD) is defined as the ratio of the co-polarized average received power P_{ll} to the cross-polarized average received power, $P_{\perp}$. XPD quantifies the separation between two transmission channels that use different polarization orientations. The larger the XPD, the less energy is coupled between the cross-polarized channels. The XPD values were found to decrease with increasing distance [6].

Antenna Correlation — Antenna correlation plays a very important role in single-input multi-output (SIMO), multi-input single-output (MISO), and MIMO systems. If the complex correlation coefficient is high (e.g., greater than 0.7), diversity and multiplexing gains can be significantly reduced (or completely diminished in the case of correlation of 1). Generally, it was found that the complex correlation coefficients are low, in the 0.1–0.5 range for properly selected base station and receiver antenna configurations.

Condition Number — The condition number is defined as a ratio of the maximum and minimum eigenvalues of the MIMO channel matrix. Large capacity gains from spatial multiplexing operation in MIMO wireless systems is possible when the statistical distributions of condition numbers have mostly low values. LOS conditions often create undesirable MIMO matrix conditions (i.e., high condition numbers) that can be mitigated using dual-polarized antennas. For low BTS antennas most propagation conditions are non-LOS with a considerable amount of scattering, in which case the multiplexing gains of MIMO systems are very significant.

RF AND HARDWARE CONSIDERATIONS

In addition to the wireless channel characteristics, we need to consider the practical hardware (HW) limitations of low-cost RF and mixed signal devices when designing a broadband wireless data system. Moreover, since wireless systems must coexist with other co-channel and adjacent-channel services, the system must meet emission specifications at the transmitter (masks, max EIRP, etc.) and must be able to tolerate specified levels of undesired interfering signals at the receiver.

The distortion effects from the HW will add to the degradation effects from the channel to yield the overall link performance. Moreover, under good channel conditions the HW distortion will ultimately determine the maximum performance of the link. For a MIMO system operating in spatial multiplexing mode, the HW SNDR requirement is only a few dB higher since the channel matrix condition number can increase the effective receive distortion. Measured field trial results of our system confirm that the HW SNDR requirement is only a few dB higher for a MIMO receiver operating in spatial multiplexing mode relative to a SISO counterpart that operates at a fraction of the data rate. On the other hand, since the effective data rate grows logarithmically with increasing SNDR, a SISO system with equal data rate would require HW specifications to get exponentially better. Moreover, for a MIMO system operating in diversity mode the HW requirements are lower than its SISO counterpart due to HW impairment diversity since the distortion is typically uncorrelated across multiple HW chains. In the 2–5 GHz frequency bands, it is possible to design low-cost wireless HW using IC components. After aggregating all the distortion effects, including both the transmitter and receiver ends, a good design will yield up to 30 dB of SNDR. With this SNDR it is possible to successfully transmit MIMO with up to 64-quadrature amplitude modulation (QAM) with light coding. There exist a large number of sources of distortion at both the transmit and receive ends of a broadband wireless system, but the most significant are:

DAC/ADC: Digital–analog and analog–digital converters, mixed signal devices, generate distortion through saturation, quantization noise, and spurs. For high-performance broadband wireless applications with adequate level control, 10 effective bits with minimal oversampling are typically enough not to degrade the overall SDR.

DAC/ADC clocks: The sampling instants at both transmitter and receiver will not be uniform spaced and will have slightly different rates. Even with timing tracking loops at the receiver to account for clock drifts, the residual timing phase noise or jitter will cause residual SDR. The timing jitter rms must be less than 1 percent of the data sampling rate for SDR > 30 dB.

Up/downconverter oscillators: The frequency converters will introduce frequency drift and add phase noise. Even with phase tracking loops, the integral of the phase noise beyond 1 percent of the OFDM tone width must be less than –30 dBc to get SDR > 30 dB.

Linearity and dynamic range: All HW components introduce noise and have a limited range over which the signal can be processed without significantly distorting it. Thus, the signal levels must be carefully controlled with a combination of power control and automatic gain control (AGC) to maximize the signal level relative to the HW noise without saturating the device. OFDM signals have slightly higher peak to average ratios (PARs) than other high-performance modulations, and extra care is required. The dynamic range and linearity requirements of OFDM can be made comparable to single-carrier modulation with PAR reduction algorithms.

MIMO-OFDM ARCHITECTURE

The combined application of multi-antenna technology and OFDM modulation (MIMO-OFDM) yields a unique physical layer capable of meeting the requirements of a second-generation non-LOS system. Herein, we discuss some key design and algorithmic choices made in implementation of the Airburst modem.

Transmit Diversity — Many transmit diversity schemes have been proposed in the literature offering different complexity vs. performance trade-offs. We chose delay diversity for downlink transmission due to its simple implementation, good performance, and no feedback requirement. In this scheme, the signal sent from the second antenna is a delayed copy of the signal at the first antenna. The delay introduced at the transmitter results in frequency selectivity in the received channel response. With proper coding and interleaving, space-frequency diversity gain is achieved without requiring any channel knowledge at the transmitter. Next-generation system system design incorporates improved transmit diversity schemes. Of particular interest are space-time codes that require no feedback [7], and linear precoding based on channel statistics that requires minimal feedback [8]. In space-time coding, the same signal is encoded differently into different streams to be transmitted across multiple antennas. Block codes are attractive since they allow linear decoding at the receiver (e.g., the Alamouti scheme) [9]. In linear precoding, the transmitted signals are linearly mapped onto multiple transmit antennas, depending on the slowly varying channel statistics such as transmit antenna correlation. Linear

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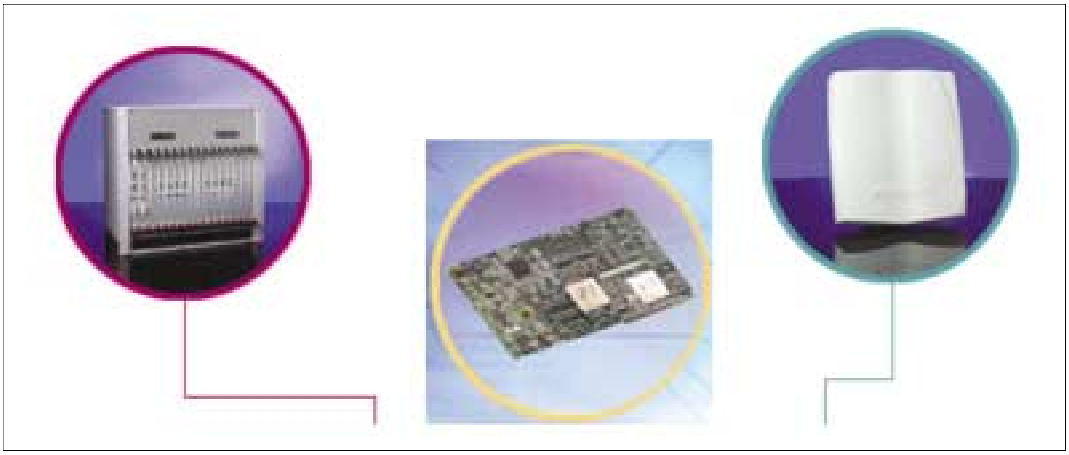


Figure 2. *From left to right: a BTS chassis, a CPE board with Airburst ASIC, and CPE.*

precoding can be used in conjunction with space-time codes to provide performance gains. Preliminary field trials have shown 2–6 dB gain over delay diversity and up to 3 dB gain over the Alamouti scheme across the cell.

Spatial Multiplexing — It is possible to transmit two separately encoded data streams from the two base station antennas. A high-rate signal is multiplexed into a set of lower-rate streams, each of which is encoded, modulated, and transmitted at a different antenna, while using the same time and frequency slot. Each of the three receiving antennas receives a linear combination of the two transmitted messages that have been filtered by different channel impulse responses. The receiver separates the two signals using a spatial equalizer, and demodulates, decodes, and demultiplexes them to yield the original signal. Separation is possible as long as each stream induces a different spatial signature at the receiver (i.e., the channel matrix has full rank). Since most spatial equalizers use some form of channel matrix inversion, a unique solution is only possible if the number of receive antennas is greater than or equal to number of independent transmit signals. In practice, it is preferred that the number of receive antennas be greater since this leads to a better-conditioned channel matrix, and therefore more accurate channel inversion in fixed precision arithmetic. The link adaptation layer monitors the channel conditions on a per user basis and determines the optimal transmission scheme: multiplexing or diversity.

Receive Diversity and Interference Cancellation — Receive diversity is available at both the BTS and CPE due to three receive antennas. The diversity is leveraged by a maximal-ratio-combining (MRC) algorithm that coherently combines signals at multiple receivers to maximize signal-to-noise ratio (SNR). There is some natural interference suppression with MRC since it matches the spatial signature of the desired signal, not that of the interferer, which therefore gets attenuated. MRC cannot, however, suppress strong interference such as that arising from spatial multiplexing where the two streams interfere with each other, or from strong co-channel users in other cells due to aggressive frequency reuse. In this case, it is desirable to use the minimum mean square error (MMSE) algorithm that minimizes the mean square error between each desired signal and its estimate, thereby maximizing signal-to-interference-plus-noise ratio (SINR). The MMSE weights require knowledge of noise-plus-interference statistics. Therefore, it is important to detect whether the ambient environment is noise-limited or interference-limited, and to collect accurate statistics by averaging over appropriate time and frequency intervals. If the interferer is friendly (e.g., a spatial multiplexing user), the interferer's spatial signature is available to be used in the MMSE weights. For unfriendly interference from neighboring cells, second-order statistics (covariance matrices) are used to capture the spatial structure of interference.

Soft Decoding — Both MRC and MMSE algorithms yield soft signal estimates that are input to a soft decoder. The soft decisions are weighted by the estimated SINR on a tone-by-tone basis to give more weight to good tones and less weight to bad tones. Soft-decision decoding combined with SINR weighting provides significant performance gains (3–4 dB) in frequency selective channels.

Channel Estimation — The purpose of channel estimation is to identify the channel between each pair of transmit and receive antennas. The training tones transmitted from each antenna are orthogonal with respect to each other so that the channel from each transmit antenna can be identified uniquely. The training tones are spaced in frequency, with spacing less than the channel's frequency coherence so that the channel can be interpolated between training tones. The channel interpolation is optimized depending on channel delay spread, and can be further improved by time-domain filtering. In the downlink, a dedicated channel identification slot is broadcast to all users on a frame-by-frame basis. In the uplink, each slot includes both training and data tones since the traffic from the CPE can be bursty, and the channel may change between bursts.

Synchronization — Both uplink and downlink transmission are preceded by a synchronization (*sync*) slot for timing phase, timing frequency, and frequency offset estimation. The slot is structured such that data and training are transmitted over even numbered tones, and odd tones are set to zero. This introduces a repetitive pattern in the time-domain signal, which allows estimation of the above parameters. Once synchronization is obtained, fine timing estimates can be computed from the training tones.

Adaptive Modulation and Coding — The Airburst system maximizes system capacity by optimizing the link parameters available to each user. There are multiple levels of coding and modulation that can be optimized on a per user data flow basis depending on the user's SINR statistics at a particular location and time, and the user's QoS requirements. The QAM levels vary from 4 to 64, and the coding consists of a punctured convolutional code combined with a Reed-Solomon code. There are six combinations of QAM and coding levels, referred to as coding modes. The coding modes 1–6 correspond to data rates of 1.1–6.8 Mb/s obtained over a 2 MHz channel. For the downlink, the above rates are doubled when spatial multiplexing is used. Each coding mode has a different setpoint, which is defined to be the average SINR required to obtain a specified pre-ARQ packet error rate, typically in the 0.1–5 percent range. The setpoint is a function of channel characteristics: delay spread, *K*-factor, antenna correlation, Doppler, and so on. The link adaptation algorithm chooses the best coding mode per user based on SINR statistics provided by the modem.

Laboratory Performance Results

For software system simulations and laboratory performance validation purposes, a set of non-LOS channel models were developed by the IEEE 802.16 working group [6]. These models were implemented in both software and hardware to test and define the system performance. For each transceiver six multipath channels (2 × 3) had to be implemented, each with three tap delay lines. We used three TAS-Flex 500 simulators with two channels each to emulate downlink fading channels. The Airburst modem was modeled in software using Matlab/C code (*Physim*). For all channel models, bit accurate simulations of the modem were run to predict bit error rate (BER) performance vs. SNR and SIR. These results were later compared with results obtained in the laboratory using HW channel emulators and the current ASIC based product. Figure 2 shows a picture of some main elements of the product, namely a BTS chassis, a CPE board with an Airburst application-specific integrated circuit (ASIC), and CPE.

Results — Figure 3 shows a BER comparison of Physim and laboratory results for a subset of channel models and transmission modes:
- SUI-3 channel: uplink coding mode 2
- SUI-4 channel: downlink transmit diversity coding mode 3
- SUI-6 channel: downlink spatial multiplexing coding mode 3

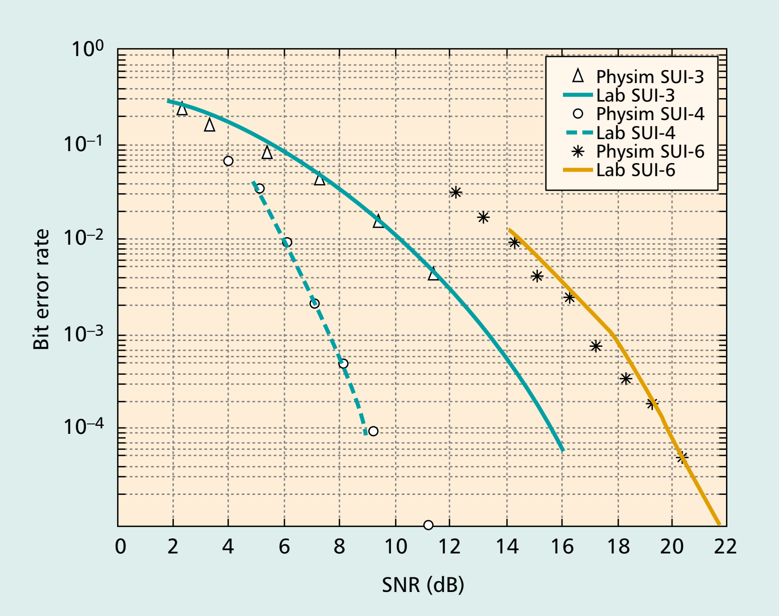


Figure 3. *Sample BER vs. SNR for several SUI models and link modes.*

It is seen that there is very good agreement between laboratory HW measurements and the *Physim* model.

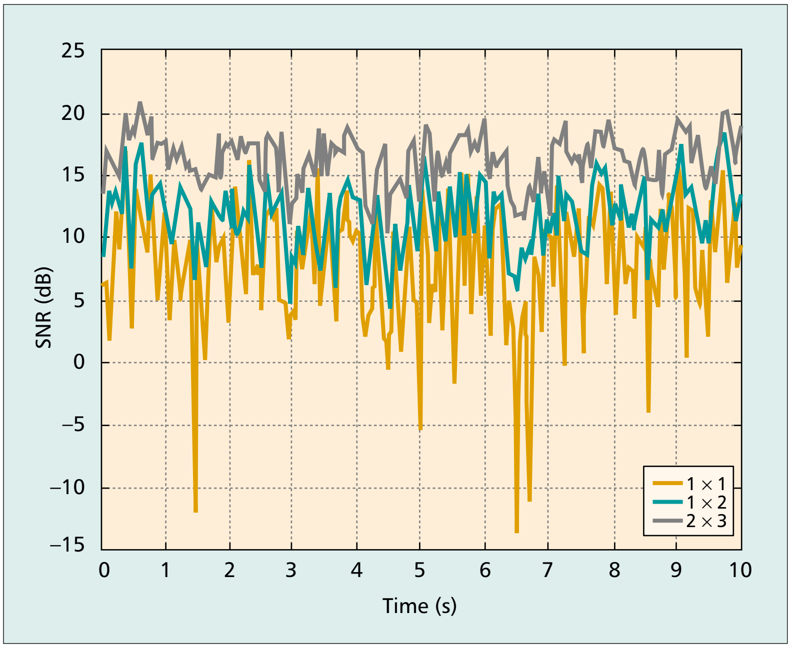
Field Trial Results

Test Setup

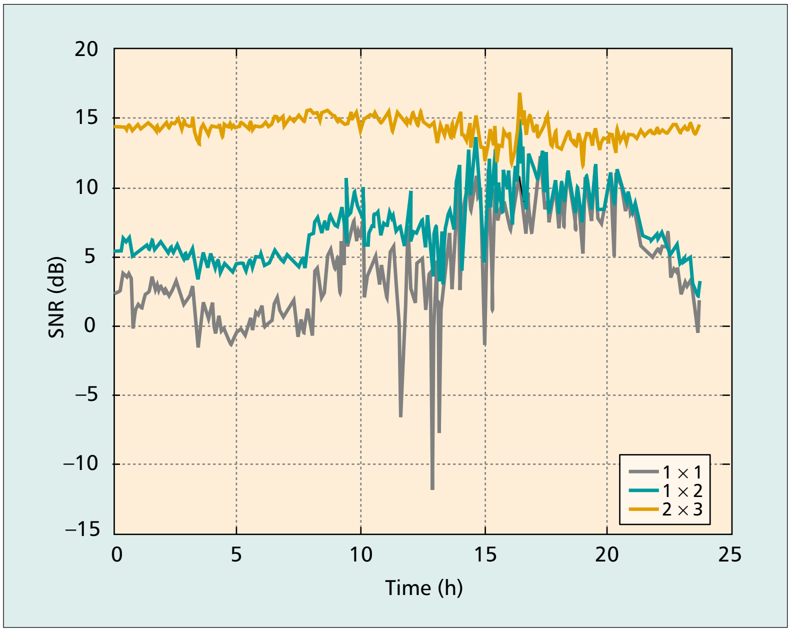
The performance of the Airburst system is currently being verified with outdoor field trials. The BTS antennas are located on the rooftop (approximately 49 ft high) of the Iospan Wireless building, and the CPEs are placed at different locations within a 3.5-mi cell radius and a 120° sector facing west of Iospan Wireless. The environment can be characterized as suburban with residential blocks (1–3 floors), commercial buildings (2–5 floors), moderate trees (30–90 ft high), and slightly hilly terrain. The total BTS transmit power and EIRP are 35.5 dBm and 51 dBm, respectively, while the CPE maximum transmit power and EIRP are 30 and 42 dBm, respectively. The downlink was operated at 2.683 GHz and uplink at 2.545 GHz center frequencies (multimegabit data service, MMDS, band), with a channel bandwidth of 2 MHz. At the BTS, the transmit and receive antennas are spaced 16 and 8 wavelengths, respectively, with a gain of 16 dBi and 3 dB beamwidth (azimuth) of 100°. At the NAU, the receive antennas are spaced up to 1.5 wavelengths, with a gain of 12 dBi and 3 dB bandwidth of 90°.

Field trials include:
- Modem performance evaluation — determining the data rates at different locations using a fully functional CPE under normal operating conditions
- Channel measurements — characterizing the wireless channel across time, space and frequency, by using the Airburst system in a test-mode.

In test mode, the BTS transmits known training signals, and the CPE samples the received signals every 50 ms in time and 72 kHz in frequen-



■ **Figure 4.** *Received SNR for a moving measurement.*



■ **Figure 5.** *Received SNR for a fixed long-term measurement at an apartment 0.8 mi from the BTS.*

cy (spanning a total of 2 MHz in bandwidth). The outdoor tests and measurements are being carried out for both fixed (short- and long-term) and moving scenarios. For the short-term measurements, the CPE is placed on a mast mounted on a mobile at approximately 9 ft above the local ground level. Fixed measurements lasting approximately 5 min each are being carried out at different distances from the BTS. In addition, long-term fixed measurements lasting from a day to several months are being carried out by monitoring fully functional CPEs in several apartments and houses at ground level. Moving measurements at low vehicular speeds are taken to cover at least 50 percent of the cell area with the CPE antennas pointed in the general direction of the BTS.

Results

In this section we report on the 2 × 3 Airburst system field test results. The results include fading margins for 99.9 percent link reliability, cell size, and data rates. The results are also compared to 1 × 2 and 1 × 1 antenna configurations (systems) by equivalently disconnecting the corresponding RF chains from the 2 × 3 Airburst system.

Fading Margins — The fading margins are a function of the Ricean *K*-factor, delay spread, and antenna correlation. Higher delay spread results in frequency selectivity that can be exploited by OFDM systems to lower the required fading margins. For Rayleigh fading channels ($K = 0$) with no delay spread and zero antenna correlation, the fading margins (including array gain) for the 99.9 percent link reliability are 10 dB, 23 dB and 35 dB for 2 × 3, 1 × 2 and 1 × 1 antenna configurations, respectively (Physim results).

Figure 4 shows a snapshot of the received SNR averaged across the receive antennas for a 1 × 1, 1 × 2 and 2 × 3 antenna configurations obtained from a moving measurement. The vehicle was moving at low speeds at a distance of 1.1 mi from the BTS. The fading margins for 2 × 3, 1 × 2, and 1 × 1 systems for 99.9 percent link reliability were computed to be 7.5 dB, 14 dB, and 21 dB, respectively. The lower fade margins for the 2 × 3 system are attributed to a higher array gain and diversity gain resulting from multiple antennas. These margins are lower than the margins reported in the previous paragraph since the measured channel has nonzero delay spread and yields an additional diversity gain.

Similarly, Fig. 5 shows the received SNR across the receive antennas for a 2 × 3, 1 × 2, and 1 × 1 system for a fixed measurement made at an apartment 0.8 mi away from the BTS. The SNR values were reported every 1 min across a 24-h period. The weather conditions were dry with wind speeds ranging from 0 to 15 mi/h. We observe that the mean received SNR and fading characteristics for the three systems are comparable to that seen in a moving measurement, albeit across a larger timescale, due to wind blown foliage. Hence, for reliable operation, a fixed wireless system needs to be designed with similar fade margins as a mobile system, even though the former exhibits orders of magnitude lower Doppler relative to mobile links.

Cell Size — For the same transmit power and 99.9 percent link reliability, when compared to the 2 × 3 system, the higher fade margins required for the 1 × 2 and 1 × 1 systems result in a smaller cell size. For example, assuming the path loss exponent of 4, 12 dB higher fade margin reduces the cell radius by half and therefore the cell area by one-fourth. Based on our test results for the given cell site and 90 percent coverage, the cell radii turned out to be 4.0 mi, 2.7 mi, and 1.6 mi for the 2 × 3, 1 × 2, and 1 × 1 systems, respectively.

Measured Data Rates — Figure 6 shows the average recorded data rates as a function of distance from the BTS for the 2 × 3, 1 × 2, and 1 × 1 systems. Data rates are higher for users closer to the BTS due to the lower path loss and therefore improved SNR. The peak data rates for the 1 × 1 and 1 × 2 systems is 6.8 Mb/s, while that for the 2 × 3 system is 6.8 * 2 = 13.6 Mb/s (two data streams with spatial multiplexing). For good link reliability, spatial multiplexing requires high receiver SNR as well as good channel matrix condition numbers. Such conditions are satisfied in non-LOS environments for distances less than 2 mi from the BTS. Approximately 80 percent of the users have data rates greater than 6.8 Mb/s and operate in the spatial multiplexing mode. At distances greater than 2 mi from the BTS, the 2 × 3 system operates mostly in a diversity mode, where the signals from all antennas are combined to lower the fading margins and therefore improve coverage (i.e., increase cell radius). The effect of multiple antennas on the measured data rate is dramatic. The mean data rate at the 1.1 mi distance from the BTS is approximately quadrupled for the 2 × 3 system when compared to the 1 × 1 system, and doubled when compared to the 1 × 2 system. As mentioned earlier, the gains are related to the spatial multiplexing capability and low fading margin of the 2 × 3 system.

CONCLUSIONS

In this article we describe the Airburst 4G broadband wireless system, laboratory test results, and recent field trial results. The laboratory test and field trial results show the encouraging performance of the MIMO-OFDM system. The results show dramatic increase in capacity, coverage, and reliability over SISO, MISO, or SIMO communication systems.

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BIOGRAPHIES

HEMANTH SAMPATH is a senior member of technical staff at Iospan Wireless Inc (2000-present). He has been working on physical layer algorithm design, development and testing of the MIMO-OFDM wireless system. He actively participated in outdoor channel measurement campaigns and field trials. He obtained the Ph.D. degree in Electrical Engineering from Stanford University in 2001, where he proposed novel transmit precoding methods to improve performance of multiple antenna systems. He has also held internship positions at the Digital Communications Research Group, Lucent Technologies, and Hughes Network Systems. He has over 10 IEEE publications and 7 patent applications. He received a B.S.E.E degree (honors) from the University of Maryland at College Park in 1996, and an M.S.E.E degree from Stanford University in 1998.

SHILPA TALWAR is a senior member of technical staff in the Physical Layer Design and Algorithms group at Iospan Wireless where he has been since 1999. Prior to joining Iospan, she worked at Philips Consumer Communications (1998–1999) and Stanford Telecom (1996–1998) as a senior systems engineer. She has worked on various projects in wireless communications such as chip design for 3G phones, satellite communications, and global positioning systems. She holds a Ph.D. in scientific computing and a Master's in electrical engineering from Stanford University (1989–1996).

JOSE TELLADO (jtellado@iospanwireless.com) is director of technology at Iospan Wireless. He joined Iospan in 1999 during its early stages as a startup, and has since been directly involved in the development of the Company's innovative MIMO-OFDM-enabled AirBurst™ technology. He is the chief designer of the physical layer, and has actively participated in the design of the wireless system architecture, the MAC layer, and the RF specification. Prior to joining Iospan, he was a research assistant at Stanford University, where he proposed new advanced methods for multicarrier modulation (DMT/OFDM) in the areas of peak to average power rRatio reduction, and multiuser transmit optimization. He has also consulted for Apple Computers Advanced Technology Wireless Group and Globalstar in the areas of WLAN and low-orbit satellite cellular systems, respectively. He received M.S. and Ph.D. degrees in electrical engineering, with an emphasis on communication theory from Stanford University in 1994 and 1999, respectively.

VINKO ERCEG received a B.Sc. degree in electrical engineering in 1988 and a Ph.D. degree in electrical engineering in 1992, both from the City University of New York. From 1990 to 1992 he was a lecturer in the Department of Electrical Engineering at the City College of New York. Concurrently he was a research scientist with SCS Mobilecom, Port Washington, New York, working on spread-spectrum systems for mobile communications. In 1992 he joined AT&T Bell Laboratories and in 1996 AT&T Labs-Research as a principal member of technical staff in the Wireless Communications Research Department where he worked on signal propagation as well as other projects related to the systems engineering and performance analysis of personal and mobile communication systems. Since February 2000 he has been working on systems, propagation, deployment, and performance issues of a MIMO OFDM communication system at Iospan Wireless Inc. as a director in communication systems.

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Combining OFDM and CDMA technologies is attractive for future wireless broadband communications and software radio realization.