A MIMO-OFDM Prototype for Next-Generation Wireless WANs

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ABSTRACT

Coupled with a robust and efficient OFDM air interface, MIMO technologies lead to a very compelling high-speed data downlink solution for future wireless systems. This article presents Nortel Networks’ MIMO-OFDM concept prototype and measured performance results. This prototype has been developed in the framework of a Nortel Networks system concept for 3G evolution systems and next-generation wide area wireless networks. The prototype is based on a shared access MIMO-OFDM physical layer in the downlink, supporting adaptive modulation and coding, with peak rates up to 37 Mb/s. The uplink is based on an enhanced UMTS WCDMA physical layer. Performance for the high-speed downlink has been measured under various emulated fading conditions. The measured performance illustrates the robustness of OFDM in frequency-selective channels and high-speed mobility channels, supporting speeds as high as 200 km/h. The prototype can also be used for over-the-air assessment of the technology.

INTRODUCTION

In recent years, multiple-input multiple-output (MIMO) wireless technologies have captured a lot of research interest, given the capacity increase achievable with such schemes [1, 2]. On the downlink, MIMO exploits multiple antennas at both the base station transmitter and the user terminal receiver. In the transmitter, the high-speed data stream intended for the user is encoded in time and space across multiple transmit antennas. In doing so, the same carrier (or spectral resource) is reused at each antenna. Signal processing is then used to decode the composite signals received at the mobile user’s terminal. The spatial antenna processing at the terminal is able to unravel the effects of complex multipath scattering, and fundamentally provides access to parallel independent propagation paths between the base station and the user. Thus, instead of having access to a single data pipe, as with conventional wireless system design, a wireless system exploiting MIMO technology is able to capitalize on the presence of multiple parallel pipes, improving both the data rate and system capacity. MIMO has now reached a certain maturity, and is being investigated in the Third Generation Partnership Projects (3GPP and 3GPP2) for the evolution of the Universal Mobile Telecommunications System (UMTS) and cdma2000 systems, respectively.

Another technology that has been considered by the industry for 3G systems evolution is orthogonal frequency-division multiplexing (OFDM). The Wireless World Research Forum (WWRF) considers OFDM the most important technology for a future public cellular radio access technology [3]. Several wireless networking (e.g., IEEE 802.11 and 802.16) and wireless broadcasting systems (e.g., DVB-T, DAB) have already been developed using OFDM technology and are now available in mature commercial products.

Since data is multiplexed on many narrowband subcarriers, OFDM is very robust to typical multipath fading (i.e., frequency-selective) channels. Furthermore, the subcarriers can easily be generated at the transmitter and recovered at the receiver, using highly efficient digital signal processing based on fast Fourier transform (FFT).

Given these interesting benefits, OFDM is currently being investigated as a potential evolution of UMTS in 3GPP [4]. In this 3GPP study, the introduction of an OFDM-based evolution in 3G is considered to fulfill potential future needs and allow a smooth transition from current UMTS systems to wider-bandwidth so-called fourth-generation (4G) systems. The goal of this activity is to help leverage operators’ investments in current Global System for Mobile Communications (GSM)/UMTS infrastructure.

Since MIMO is also considered an important building block of future wireless systems, it is important to note that OFDM is particularly well suited to MIMO technologies. Because the narrowband subcarriers in the OFDM signal experience flat fading, MIMO reception does not require complex channel equalization schemes.

Nortel Networks’ Wireless Technology Labs have built up an expertise in MIMO and OFDM...
technologies, having developed MIMO prototype based on cdma2000 technology in 2000, and a MIMO-OFDM prototype in 2001. This article presents an evolution of the MIMO-OFDM prototype, and is structured as follows. The system concept leading to this prototype is briefly presented. The prototype architecture is then described, illustrating its wide-ranging capabilities as a concept evaluation tool. A synopsis of the measured downlink performance, using radio frequency (RF) channel emulators and over-the-air setups, is provided. Conclusions on the feasibility of the proposed system concept and directions for future work are discussed at the end.

A BRIEF OVERVIEW OF THE SYSTEM CONCEPT

In the framework of 3G evolution and next-generation wireless WANs, a system concept has been developed. Aggressive targets have been set to significantly improve the cost of operating wireless packet data networks. The timescale to achieve these targets in a commercial system has been set to around 2008.¹

The improvements achieved in this system concept are based on the adoption of a number of technologies:

• A MIMO-OFDM physical layer, supporting space-time transmit diversity (STTD)² and spatial multiplexing (SM)³ modes of operation. The actual MIMO mode can be adaptively selected to suit the MIMO channel condition.
• Adaptive modulation and coding (AMC) with variable-rate turbo codes and high order modulation (quaternary phase shift keying, QPSK, 16-quadrature amplitude modulation, 16-QAM, and 64-QAM) to adapt the link to the channel conditions.
• Hybrid link-level retransmission schemes (hybrid automatic repeat request, H-ARQ).
• Shared access and advanced medium access control (MAC) scheduling for packet access, with support for quality of service.
• Multibeam MIMO antennas, with 3 beams/sector and 3 sectors/cell.
• Full frequency re-use across cell/sectors.

PROTOTYPE ARCHITECTURE

A real-time prototype has been built to evaluate the system concept described in the previous section. The prototype is based on a UMTS frequency-division duplex (FDD) framework (i.e., with a 5 MHz bandwidth and UMTS signal timing). The downlink is based on a MIMO-OFDM air interface, with two transmit and up to four receive antennas. The OFDM subcarrier spacing is 6.2 kHz. The uplink is based on an enhanced wideband code-division multiple access (WCDMA) uplink supporting peak data rates of 2 Mb/s. Although both the downlink and uplink have been implemented, the results presented in this article concentrate on high-speed downlink performance.

The downlink AMC supports up to 64-QAM modulation with rate-4/5 coding. The possible modulation and code combinations are illustrated in Table 1 for STTD and SM modes.

The prototype has been implemented using a fully reconfigurable architecture (except for the turbo decoder, which is implemented in a dedicated integrated circuit). Most of the hardware components used in the prototype are based on off-the-shelf products for the sake of implementation velocity. Modern processing functions are implemented using Texas Instruments TMS320C6x digital signal processors, while the MAC and controller functions are implemented using PowerPC™ processors, as illustrated in Fig. 1.

It is therefore easy to use this prototype to investigate new concepts in a timely fashion. Note also that the prototype is developed in a staged approach, allowing continual development and evaluation of new features. This prototype has allowed analysis of practical implementation issues related to the proposed technologies. Complexity figures have been analyzed through this prototype, leading to ongoing efforts to develop more efficient algorithms providing good complexity/performance trade-offs. Other complexity/performance trade-offs are also being investigated through this prototyping effort.

In UMTS, terminals are referred to as user equipment (UE), while the network base station is termed Node B. Both elements have been implemented, as illustrated in Fig. 1.

The Node B prototype hardware architecture is illustrated in Fig. 1a. The Node B prototype supports two transmit paths (for spatial diversity/multiplexing) and two receive paths (for receive diversity). The frequency conversions between the digital baseband and analog intermediate frequency are performed through digital upconversion (DUC) and digital downconversion (DDC) modules, equipped with high-speed digital-to-analog and analog-to-digital converters. All transmit and receive digital clocks and RF oscillators are locked to a single reference. The Node B modem is implemented on multiprocessor boards connected through a backplane to single-board computers equipped with Power PC processors for MAC and controller functions. The processors are also used to communicate with servers through a LAN connection.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Turbo coding rate</th>
<th>Peak throughput (Mb/s)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>STTD mode</td>
<td>SM mode</td>
</tr>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>2/3</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>4/5</td>
<td>6.4</td>
</tr>
<tr>
<td>16-QAM</td>
<td>1/2</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>2/3</td>
<td>10.3</td>
</tr>
<tr>
<td></td>
<td>4/5</td>
<td>12.2</td>
</tr>
<tr>
<td>64-QAM</td>
<td>2/3</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>4/5</td>
<td>18.4</td>
</tr>
</tbody>
</table>

¹ This could be compatible with the release of new spectrum at 2.5 GHz in Europe.
² This scheme was proposed by Alamouti in [6].
³ Spatial multiplexing refers here to the scheme described in [6] and related variants.
On the UE/terminal side, as illustrated in Fig. 1b, one transmit chain and up to four receive chains are implemented. The UE is scalable from two receive chains to four receive chains, to support $2 \times 2$ and $2 \times 4$ MIMO configurations, respectively. As in the Node B prototype, the baseband/intermediate frequency conversions are implemented with DUC and DDC modules. The sampling on these modules is locked to a single UE reference in order to allow downlink/uplink timing synchronization.

Baseband modem processing is implemented on a multiprocessor board connected together through a RACE++ high-speed interconnect [7]. A single-board computer with a PowerPC processor is used for higher-layer processing, and to interface with a performance monitor and/or packet-based applications. The prototype can also be used to demonstrate high-speed data services. FTP and HTTP services can be run over the prototype, as well as real-time services such as video streaming and video-conferencing.

**PERFORMANCE EVALUATION**

**TESTBED**

In this section the testbed setups for emulated RF MIMO channels and over-the-air measurements used for downlink performance assessment are described. The emulated RF MIMO channel testbed is a wired setup that allows easy replication of a wide range of channel conditions and good control over the parameters involved in the evaluation (SNR, mobile speed, channel model, etc.). Over-the-air (i.e., wireless) operation is also possible to further prove the practicality of the concept.

**Emulated RF MIMO Channel** — The emulated RF MIMO channel test-bed used for the performance evaluation is shown in Fig. 2a for a $2 \times 2$ channel. The setup is similar for a $2 \times 4$ channel, except that four receive chains are used in that case. Note that the signals are generated at the transmitter, upconverted to RF frequencies, and amplified using power amplifiers, as would normal-
ly be done in the Node B. However, the resulting RF signals, instead of being fed to antennas, go through the emulated RF MIMO channel testbed. In the RF channel emulation, the two transmit signals are faded, with or without cross-MIMO-channel correlation, and combined together to create up to four $2 \times 1$ MIMO channels. Wideband noise is then added to each path, emulating the effect of thermal noise and interference. The resulting signals are then fed to the receiver in place of the signals normally captured by the terminal’s antennas.

**Over the Air** — The over-the-air setup is similar to that used with emulated MIMO channels, except that the wired testbed is replaced by transmit and receive antennas. This setup is illustrated in Fig. 2b. The transmit antenna used for these measurements is a multi-beam MIMO antenna with dual polarization, shown in Fig. 3a.

On the terminal side, the implementation of multiple antennas is obviously an important consideration in the adoption of MIMO techniques for commercial systems. Cost-effective high-performance designs must be achieved in compact...
form factors. To evaluate the feasibility and performance of such compact antenna designs, we have prototyped both laptop (as illustrated in Fig. 3b) and personal digital assistant (PDA) form factors [8]. These antenna prototypes have also been used in MIMO propagation trials.

**Performance Results**

**Link-Level Performance** — In order to characterize the link-level performance and set up the modulation and coding adaptation rules properly, the performance of the different link modes listed in Table 1 has been comprehensively measured. Various emulated MIMO channel conditions for 2 × 2 and 2 × 4 STTD configurations have been used. The link-level performance has been measured for the International Telecommunication Union (ITU) outdoor-to-indoor/pedestrian channel models A and B (where A refers to a typical medium delay spread channel and B to a large delay spread channel) and vehicular channel model A.

These different modulation and coding combinations provide a lot of flexibility in terms of adaptation to the channel conditions. This is illustrated for the STTD mode in Fig. 4, where the throughput (defined as the data rate observed by the terminal when only error-free blocks are considered) is plotted for the different link modes as a function of the average SNR. Note that depending on the SNR, a different link mode maximizes the throughput. This allows the system to adapt the link mode to the channel conditions, thereby increasing the efficiency of the link level. In slow fading channels (e.g., pedestrian/nomadic), it is even possible to adapt the link mode based on short-term observations of channel conditions to further optimize resource utilization. This fast adaptation of the modulation and coding has also been evaluated using the prototype.

The performance of the MIMO-OFDM prototype has also been evaluated in vehicular conditions. As illustrated in Fig. 5 for the STTD mode, the prototype is very robust to high-speed mobility conditions, still offering over 10 Mb/s at a mobile speed of 200 km/h. Note that the prototype is using real channel estimation based on a scattered reference. This illustrates the practicality of an OFDM-based interface for high-speed mobility.

**The Impact of Correlation in MIMO Channels** — In practical systems, the performance of MIMO techniques depends on the correlation observed by the receiver across the different MIMO channels. To characterize typical urban macrocellular environments, we conducted extensive MIMO propagation trials in 2001 in central London at a carrier frequency of about 2 GHz. These MIMO channel measurements were performed using our antenna prototypes for PDA and laptop form factors, with up to four receive antennas.

MIMO correlation models have been derived from these trials, showing that higher average correlations are experienced in outdoor-to-indoor than outdoor-to-outdoor scenarios. To evaluate the impact of MIMO channel correlation on the prototype performance in these outdoor-to-indoor scenarios, high-level and medium-level correlation profiles for outdoor-to-indoor/pedestrian-A have been derived from our correlation models. These correlation profiles have been replicated using RF channel emulators.

The impact of such correlation profiles on the prototype performance for outdoor-to-indoor/pedestrian-A 2 × 2 STTD is illustrated in Fig. 6. These results show that even with worst-case correlation in MIMO channels, the impact on performance is limited. Note also that since outdoor-to-indoor/pedestrian-A is a quasi-flat fading channel with very little multipath diversity, correlation between the different paths affects performance more significantly than for higher delay spread channels (e.g., outdoor-to-indoor/pedestrian-B).
Following the development of a system concept for future wide-area macrocellular wireless networks, a prototype has been built to evaluate its feasibility and investigate the implementation of MIMO and OFDM technologies. This prototype has been used to evaluate performance in different conditions typical of macrocellular wireless networks. The results obtained from these tests indicate very good performance for the MIMO-OFDM prototype. The proposed MIMO-OFDM concept is proving to be very robust in highly-dispersive channels (e.g., outdoor-to-indoor/pedestrian-B) and high-speed mobility channels (supporting speeds as high as 200 km/h).

New features continue to be added to this MIMO-OFDM prototype. The cost reduction of MIMO terminals is being investigated, through techniques such as MIMO receive antenna selection.

CONCLUSIONS

The authors wish to thank the people involved in the Mid-Term 3G Evolution system concept team from Nortel Networks’ Wireless Technology Labs, and in particular the physical layer development team, the antenna and propagation team, and the prototype team. The authors are also grateful to the reviewers for their fruitful comments.

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BIographies

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IEEE Communications Magazine • December 2004

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Figure 6. Impact of correlated channels in outdoor-to-indoor scenario (outdoor-to-indoor/pedestrian-A, 3 km/h, 2 × 2 STTD).

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