Technologies and Performance for Non-Line-of-Sight Broadband Wireless Access Networks

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ABSTRACT

This article presents emerging technologies for upcoming non-line-of-sight fixed or stationary broadband wireless access systems. We describe design trade-offs for overall maximization of the radio capacity and coverage of FWA in multicell interference- and fading-prone environments. We characterize quantitatively the impact of key emerging radio technologies on the overall performance.

INTRODUCTION

The demand for broadband Internet access is continually growing. Announced delays in the deployment of third-generation (3G) high-speed wireless networks — wideband code-division multiple access (WCDMA) is unlikely to be truly widely available before 2003 — as well as slow progress in satisfying demands for wired solutions such as digital subscriber line (xDSL) and cable modems place high expectations on alternative last mile technologies such as fixed wireless access (FWA). The aim of such access systems is to provide wireless high-speed Internet access, and in relevant markets voice services, to fixed or nomadic residential customers and small offices/home offices (SOHO) located within reach of an access point or base transceiver station (BTS). Mainstream Internet applications are targeted such as Web browsing and email, but also more demanding services such as real-time conferencing and/or voice. To maintain reasonably low RF costs as well as good penetration of the radio signals, mass market FWA systems typically use sub-5 GHz bands, examples of which are the so-called multipoint multichannel distribution services (MMDS) band (2.5–2.7 GHz) in the United States and the 3.5 GHz band in international markets. The subscriber unit, sometimes referred to as customer premises equipment (CPE) is currently typically installed on a rooftop and communicates wirelessly to a BTS several miles away. However, as line-of-sight (LOS) requirements are to be mitigated in the future, the CPE may be installed on the outside wall of the house or placed inside on a desktop. Future broadband access systems can also be envisioned to support portability and serve stationary lightweight unit users located anywhere within the coverage area. In any case, ubiquitous FWA networks must be able to cope with widely varying terrain features (flat, hilly, varying tree densities), urbanization levels, and user densities (rural, suburban, dense urban).

A careful radio design, and clever exploitation of the subscriber access unit's stationarity while in use and the (limited) directionality of the unit's antenna can allow for an order of magnitude improvement over other advanced mobile digital wireless systems such as 3G, in terms of data rates, access quality/reliability, and spectrum efficiency. In fact, upcoming FWA systems should offer performance comparable to wired technologies such as xDSL and cable modems to be truly attractive. Advantages of FWA include rapid deployment, high scalability, lower maintenance and upgrade costs compared to cable and DSL, and granular investments to match market growth. Nevertheless, a number of important issues including spectrum efficiency, network scalability, easily installable CPE antennas, and above all reliable non-LOS (NLOS) operation need to be resolved before FWA can penetrate the market successfully.

This article describes how selected design features at the physical and link layers such as the use of multiple antennas at both ends of the wireless link (multiple-input multiple-output, MIMO, technology), adaptive modulation, automatic repeat request (ARQ) and fragmentation (ARQF) protocols, and more contribute to achieving these goals. We further consider emerging radio technologies that turn multipath delay spread into a benefit such as MIMO-based spatial multiplexing technology and coded orthogonal frequency-division multiplexing (OFDM).

The remainder of this article is organized as follows. The next section addresses design challenges in NLOS-FWA systems. We then summarize the high-level requirements of next-generation NLOS-FWA emphasizing radio performance. We recall the definition of the key system metrics and present simple design tradeoffs. Next, we address NLOS high-performance-enabling radio technologies and describe their impact on system design. The article goes on with a characterization of the overall performance for an NLOS-FWA system incorporating such technologies using multilayer simulations. We address both optimum performance and robustness issues such as antenna pointing errors at the user's side. The last section provides some conclusions.

Design Challenges

Current FWA solutions are based on the existence of an LOS link between the subscriber unit and the access point. Finely pointed directional high-gain antennas are typically used at the subscriber side. Maintaining LOS and using narrow-beam antennas are ways to protect the radio link from sources of interference and disturbance with which it is unable to cope. These impairments typically include intersymbol interference and fading caused by delay-spread and multipath propagation and, to a smaller extent, intercell co-channel interference caused by frequency reuse. In near-LOS conditions (Ricean factor of 10 dB or more), the link budget typically accounts for only moderate fade margins, and the modem does not require the use of complex equalizers because multipath components are suppressed by a highly directional subscriber antenna (provided the antenna is carefully pointed). Reliance on LOS conditions, however, places unacceptable limits on the scalability and ubiquity of the technology. For example, in a typical urban or suburban deployment scenario as low as only 30 percent of the subscribers will actually experience an LOS connection to the BTS. In addition, for most of those users LOS is obtained through rooftop positioning of the antenna and requires very accurate pointing, thereby making the installation both time- and skill-consuming. Moreover, necessary periodic upgrades of the cell layout (cell splitting) are made very challenging due to the necessity of repointing the subscriber antennas. It is worth mentioning that the LOS condition could be otherwise realized through the deployment of smaller overlapping cells; however, this solution comes at the cost of a higher number of BTS per unit of area and hence high infrastructure costs. Eliminating the reliance on LOS has several key advantages. First, broader antenna beams (or even in certain relevant applications omnidirectional antennas) can be used at the subscriber side without incurring unwanted multipath. This in turn improves user friendliness since installation by the user himself or an unskilled worker becomes possible, and reduces deployment and upgrade cost. It also allows for higher coverage and penetration, opening the door for some form of portability support. For this to be possible it is essential to make the radio link (layers 1 and 2 combined together) able to cope with a particularly severe channel environment including fading, multipath delay spread, and interference.

Figure of merit	Requirement
Aggregate rates	6 Mb/s
Spectral efficiency	≈ 2 b/s/Hz/BTS
Coverage	6 mi rooftop, 3 mi wall, 2 mi indoor
Latency	Comparable to DSL
Link reliability	.999

Table 1. *Typical NLOS-FWA requirements.*

Requirements for NLOS-FWA

In order to respond to the challenges above while successfully carrying their future share of the access traffic, advanced FWA systems must provide both *user friendliness* and a *high level of performance*. A key to user friendliness is the degree of self-installability and robustness with respect to signal distortions in NLOS operation. Advanced FWA systems will furthermore require low network and subscriber costs. Among others, this can be achieved through high coverage performance in initial rollouts and high user capacity in mature deployments; hence, network economics are therefore tightly coupled to performance. Specific hardware/development cost issues are not addressed here.

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There are several relevant figures of merit for radio performance, including *aggregate data rates* (averaged across users and across time), *spectrum efficiency*, *coverage*, *bit and packet error rates*, *latency*, and *link reliability*. Generic requirements for an NLOS-FWA system are shown in Table 1. The next section defines these figures of merit in greater detail. Overall radio performance is usually expressed in terms of *coverage and spectrum efficiency* that have to be optimized under minimum acceptable access link quality constraints such as error rates, latency, and reliability specified by the service provider and the application.

Performance Parameters of Wireless Access Systems

In this section we discuss performance metrics for NLOS-FWA systems. We choose to characterize wireless network performance by the two aforementioned metrics (spectrum efficiency,

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SE, and coverage), both key indicators of infrastructure cost in different stages. Coverage is critical in early rollout stages because it governs the number of BTSs needed per unit of area to cover an initially sparse population of subscribers. As the number of subscribers grows, SE becomes the dominant performance metric since it determines the number of users any given cell site will be able to serve simultaneously per unit of spectrum.

SPECTRUM EFFICIENCY

The spectral efficiency (downlink or uplink) in bits per second per Hertz per BTS is measured as

$$SE = \frac{rM}{KB},$$

where M is the aggregate (average) coded throughput for one RF channel, and r is the forward error correction (FEC) code rate. Hence, rM is the *effective* throughput a user sees when having (temporarily) sole access to the medium. The effective throughput is defined by the link layer payload throughput offered to the network (e.g., IP) layer, and takes radio and MAC overhead into account. This value is averaged over all possible channel conditions experienced across the cell/sector area and at all times. The aggregate throughput is a function, among others, of the physical layer performance and link budget, and hence takes into account link limitations such as path loss, maximum transmit power, noise level, and so on. K is the well-known spatial reuse factor and is given by the number of BTSs in a cluster where a given RF frequency is used only once. Finally, B is the channel bandwidth including guardbands and rolloff effects. The SE is typically evaluated for a specific cell size.

The number of sectors deployed per BTS is captured implicitly in the SE expression. Increasing the number of sectors with separate RF channels improves the SE through a potential increase of channel throughput (because, e.g., interference is reduced and higher antenna gain is obtained). Note that the improvement will in general not be proportional to the number of sectors. In this article we focus on the downlink SE, which is considered the bottleneck in many Internet applications. We note that a similar approach may be taken to evaluate the uplink performance.

COVERAGE AND RELIABILITY CONSTRAINTS

Coverage is defined as the *cell size* for which the system can *reliably serve the cell users*. Reliability constraints are of two kinds and can be expressed as follows:

- **Coverage reliability**: A certain prescribed large percentage (e.g., 90 percent) of cell locations must be served with minimal required link reliability constraints.
- **Link reliability (LR)**: This quantity is expressed in terms of a maximum outage probability with typical numbers being 1–0:999 or less (the number of 9s can vary with the provider).

An outage is declared if the packet error rate goes above a prescribed threshold for a determined amount of time. With TCP/IP being the typical transport/network protocol for Internet access systems, LR can alternatively be defined in terms of latency statistics for IP packet or file delivery. We refer the interested reader to [1] for an overview of TCP performance in NLOS-FWA systems.

PERFORMANCE OPTIMIZATION

The coverage and capacity performance are tightly coupled to the physical layer performance for which an essential indicator is the signal-to-noise-plus-interference ratio (SINR) *set point*. The radio set point is defined as the level of SINR required at any one of the receiver's antennas in order to meet the LR target at a specified level of throughput (typically the lowest acceptable in terms of service). The system set point is a function of the fading channel model (Rayleigh, Ricean, RMS delay spread, etc.) and therefore includes a fade margin. If the physical layer includes some form of diversity combining, the margin will be reduced by the so-called *diversity gain*.

Conveniently, we can identify two main approaches to increase the performance of any radio system:

- **To decrease the set point for a fixed throughput:** This allows optimization of both coverage and reuse factor K by making the system able to deal with lower levels of carrier-to-noise ratio (C/N) and carrier-to-interference ratio (C/I).
- **To increase the throughput for a given set point:** This yields a higher value of rM for a given coverage performance.

Both strategies can be pursued simultaneously to obtain maximum SE (minimize K and maximize rM). This is the key to a sensible design.

TECHNOLOGIES FOR ADVANCED FWA SYSTEMS

A number of emerging radio technologies are instrumental in realizing the high performance requirements of next-generation NLOS-FWA systems, at both the medium access control (MAC) and physical (PHY) layers. At the PHY layer, diversity signaling, spatial multiplexing exploiting multi-antenna capability, and delay-spread-robust modulation help the modem deal with severe channel impairments. At the MAC layer, link layer retransmission and adaptive modulation help deal with both high and widely varying error rates.

We note that the use of such techniques is in general not restricted to fixed access systems. In fact, advanced proprietary FWA systems can showcase technologies which will find their way into global wireless standards later on. In the following, we discuss both qualitatively and quantitatively the impact of the above mentioned technologies on system performance. A technology summary is given in Table 2.

AUTOMATIC RETRANSMISSION AND FRAGMENTATION

At the link layer an acknowledgment and retransmission algorithm is implemented between the subscriber unit and the BTS using the ARQ protocol. Typically, in addition to the retry mechanism the MAC layer will perform fragmentation of IP packets going over the air into "atomic" or elementary data units (ADUs). Typically, an IP packet will span a few tens of ADUs with the limit on fragmentation being imposed by the increased overhead per payload bit. We refer to the combination of fragmentation and retransmission as ARQF. The advantage of ARQF over simple IP-based ARQ is that only small portions of the erroneous data (the ADUs) are retransmitted, instead of the full IP packet. A technique complementary to coding, ARQF only introduces redundancy during the fraction of time when data gets corrupted. A finite bufferization mechanism makes ARQF efficient in dealing with short as well as long fades. ARQF removes packet errors at the cost of only moderate additional link latency. Thanks to the ARQF mechanism, FWA systems can be designed to operate at significantly higher post-coding bit error rate (BER) levels, typically one or two orders of magnitude higher depending on the channel characteristics, while still providing satisfactory TCP/IP performance in terms of throughput and latency (see a later section). The higher target error rates translate into a reduction of the set point by 4–7 dB in a fading channel scenario. ARQF can also be viewed as an effective time diversity technique for dealing with the slowly varying FWA channel.

Adaptive Modulation

The use of adaptive modulation (AM) and coding makes the adaptation of a user's data rate as a function of the channel conditions (SINR, fading rate, etc.) possible, and has been popularized in the EDGE[1] cellular standard [2]. AM is becoming a key feature of wireless data systems. Efficient AM schemes must incorporate:

- **Robust transmission modes** with low modulation efficiency such as binary phase shift keying (BPSK) and quaternary PSK (QPSK) and small code rates in order to be able to extend the reach of the BTS and increase robustness to interference.
- **High data rate modes** with high modulation efficiency such as 64-quadrature amplitude modulation (QAM) or 256-QAM and high code rates in order to improve spectrum efficiency.

Typically, the use of AM yields substantial improvement in system performance by exploiting margins of SNR available at any time/location. In comparison, current non-adaptive FWA systems are deployed using either a conservative modulation/coding mode to preserve coverage and frequency reuse performance or high order modulation to guarantee high data rates at the expense of coverage and spectrum efficiency. The switching points between different modulation and coding modes have to be computed from a set of channel (SINR) and error (BER, packet error rate) statistics. Fine field-based tuning is required to determine the switching rules.

Another advantage of AM besides increased SE and improved coverage is facilitated installation and rate provisioning at the CPE. This is due to the fact that the need for trying to find the best spot for CPE antenna(s) on the customer's house is eliminated. In any case searching the best spot is a futile operation in most cases given that the propagation conditions at all locations are subject to (even slow) changes. For the same reason self-adaptivity to even very slowly changing channel conditions by the CPE is a key requirement to reach higher customer satisfaction.

Technology	Impact (qualitative)
ARQF	Set point ↓
Adaptive modulation	Data rate ↑
Diversity (space)	Set point ↓
Diversity (frequency)	Set point ↓
MIMO-spatial muxing	Date rate ↑

Table 2. *Layer 1 and 2 technologies for advanced NLOS-FWA.*

Smart Antennas

Smart antennas refer to the use of multiple antenna elements, together with intelligent signal processing and coding. Although their use is more popular at the BTS side, smart antennas can be implemented at the CPE as well, on either the receive or transmit side. There are several possible uses for smart antennas in FWA. Here, we focus on spatial diversity, interference canceling, and so-called spatial multiplexing aspects.

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Spatial Diversity — The basic idea of spatial diversity (SD) is that multiple antennas exhibiting uncorrelated fading are much less likely to fade simultaneously than a single antenna element. Diversity signaling techniques increase the average SNR by means of coherent combining (array gain), but more important, the SNR statistics are improved. The use of SD can reduce the system set point by as much as 10–15 dB with just two or three antenna elements [3] and is thus very powerful. This leverage can be exploited to both extend coverage and tighten frequency reuse. Moreover, lower set points reduce power amplifier costs and prolong battery life in future portable units. Note that when combined with AM, the set points of all modulation/coding levels are reduced, thereby resulting in higher aggregate throughput.

Several measurement campaigns for FWA, including those conducted by Iospan Wireless Inc. and AT&T for the FWA market, suggest that 0:5–1 wavelengths antenna spacing suffices to ensure high SD gain at the user's side. For a carrier frequency of 2.5 GHz, for example, this means 6–12 cm antenna spacing. Even lower antenna spacing requirements can be satisfied by using dual-polarized antennas [4]. At the BTS side more spacing is needed because paths tend to impinge with a smaller angular spread.

At the receiver, whether up- or downlink, the antennas are combined on a priori estimation of the channel. Maximum ratio combining offers optimal performance within the class of

[1] *Enhanced Data Rates for GSM Evolution, a 2.5G standard.*

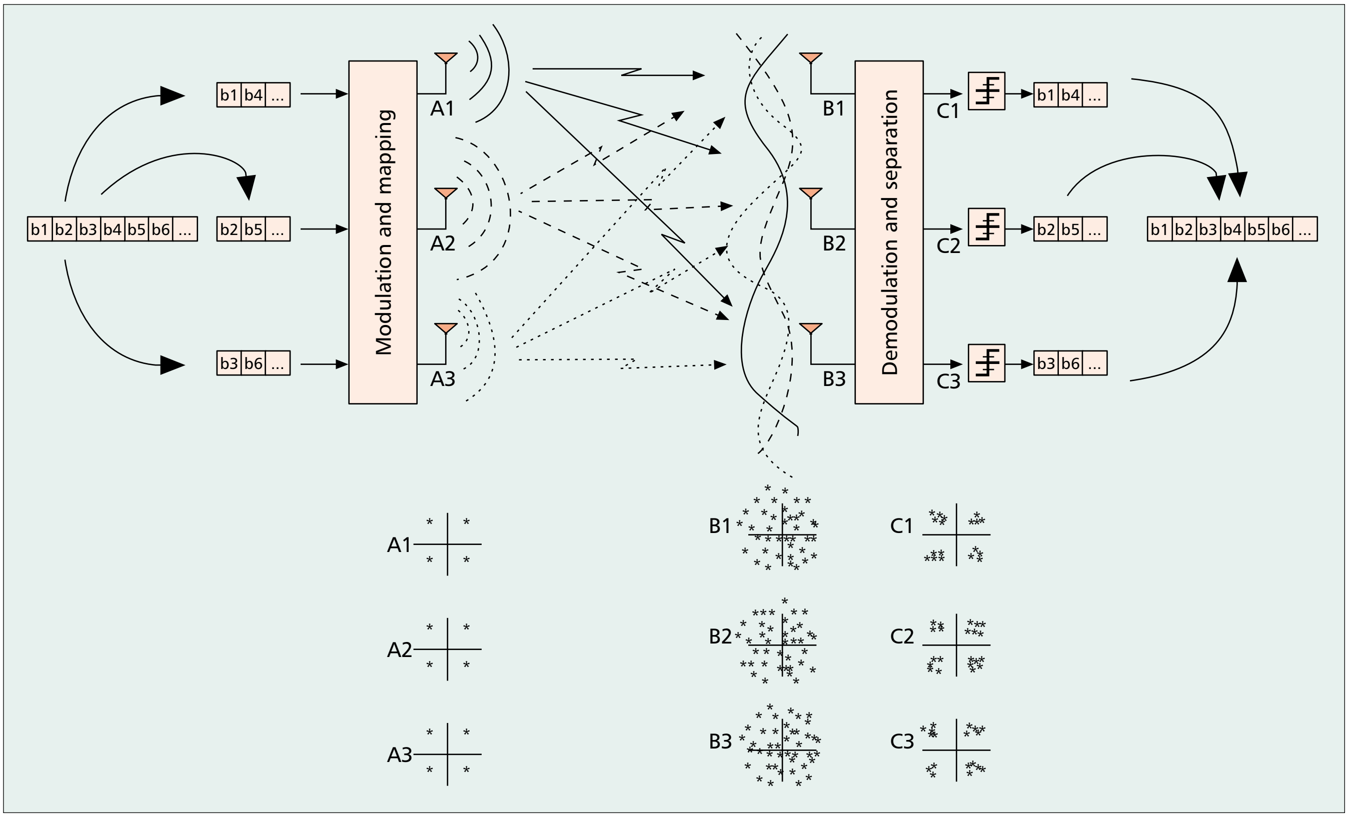

Figure 1. *A basic spatial multiplexing scheme with three transmit and three receive antennas yielding threefold improvement in SE.*

low-complexity linear combiners. At the transmitter, combining is impaired by the absence of accurate knowledge of the channel, especially in frequency-division duplex (FDD) systems. Space-time coding is a particularly attractive approach to realizing transmit diversity gain without requiring channel knowledge in the transmitter [5]. A precursor to space-time codes is a technique called delay diversity in which each transmit antenna sends a delayed version of the same signal, effectively converting spatial selectivity into frequency selectivity, which can readily be exploited through the use of coded OFDM (see a later section for more details).

Spatial Multiplexing — Employing multiple antennas at both ends of the wireless link (leading to the so-called MIMO techniques) can dramatically increase the bit rate [6, 7]. The idea behind MIMO is that the use of multiple antennas at both the transmitter and the receiver create a matrix channel with the possibility of transmitting over several independent spatial "dimensions" or "modes" within the same time frequency slot at no additional power expenditure. This technique is referred to as *spatial multiplexing* (SM) and allows linear (in the number of antennas) capacity increase provided rich enough scattering is present. The use of SM thus seems particularly interesting in the case of FWA, where a very high data rate is required and space for a few antenna elements at both sides of the radio link is easily affordable. Figure 1 shows the schematic of a spatial multiplexing system. A high-rate signal is multiplexed into multiple bitstreams, which are then transmitted simultaneously using multiple antennas. The signals are mixed in the channel since they occupy the same time and frequency resource. At the receiver, the individual data streams are separated and demultiplexed to yield the original high-rate signal. The separation is made possible by the fact that each transmit antenna "sees" a very different channel because of rich multipath. In practice, the individual streams are encoded jointly in order to maximize the performance gain. SM increases the throughput for a given SINR level and therefore contributes to a higher *rM*. We note that in general not all cell locations will be able to benefit from this transmission mode. Users closer to the BTS are more likely to experience channel conditions that make the use of SM possible assuming that scattering remains rich enough. For channels less amenable to SM (e.g., for near-LOS users or large distance between transmitter and receiver), the system will rather use spatial diversity (space time coding). In that case, the diversity mode exploits joint transmit-receive antenna diversity, which is a particularly robust form of SD. For these reasons SM and space-time coding must be viewed as complementary rather than competitive approaches to using multiple antennas. The intelligence for mode switching between SM and space-time coding is located in the link adaptation module, as an extension of the AM algorithm.

Interference Canceling — Multiple antennas can also be used to perform interference canceling (IC), which is useful in dealing with strong sources of co-channel interference arising from tight frequency reuse deployment.

Very tight reuse factors (e.g., 1 or less) can be deployed in IP-based bursty traffic FWA networks (unlike voice-centric networks) because the average activity factor of individual users is generally very low. Simultaneous activity of co-channel users in neighboring cells will cause short peaks of interference that can be handled by IC. The amount of channel state information required by the IC algorithm typically depends on performance needs and the specifics of the training architecture. In NLOS links, IC algorithms cannot rely on angle of arrival information for the interferer or target user's channel. In this case, the antenna weights can be computed from channel statistics to make them as orthogonal as possible to the strongest interferer's signature(s).

Frequency Diversity: Turning Delay Spread into a Benefit

Broadband transmission over multipath channels usually introduces frequency-selective fading. Since data rate requirements can be expected to increase even further in the future, this effect is likely to amplify. In single-carrier (SC) modulation frequency selectivity is typically mitigated through the use of an equalizer. The complexity of the equalizer quickly grows as a function of data rate. Therefore, in practice the computational complexity of SC equalizers and the complexity required for equalizer adaptation can pose limits on the performance of SC systems in the high delay spread and/or high data rate case. In multicarrier modulation (OFDM), frequency selectivity is handled by transmitting over a set of parallel narrowband orthogonal subcarriers. OFDM is implemented using low-complexity fast Fourier transform (FFT), which explains the growing popularity of this approach. In addition frequency diversity can be realized through coding and interleaving across subcarriers. Because information bits are spread equally over many subcarriers, the effect of fading occurring at particular discrete frequencies can be mitigated. As a consequence, in coded OFDM systems the presence of frequency selective fading actually improves the set point performance over the case of frequency at fading. Depending on the code rate and interleaving depth, gains (in terms of set point performance) of up to 2–3 dB can be achieved at locations experiencing significant delay spread.

Time Diversity

Time diversity refers to a set of techniques used, especially in mobile wireless (where the access unit is actually moving), which consist of coding and interleaving the transmitted information over data blocks that span multiple time slots experiencing independent channel fading. In FWA, however, the channel varies slowly (often below 1 Hz Doppler). Therefore, it is difficult to realize time diversity benefits through coding and interleaving across time while meeting latency constraints. Instead of coding and interleaving across time, FWA systems can use ARQF to extract time diversity gain. In essence, ARQF relies on the hope that a failed packet transmission will not coincide again with a fade when the packet is resent later. The advantage of ARQF as a time diversity technique is that the extra latency incurred to get information through during longer fade periods is limited to those rare events when the longer fades occur, thus offering a good overall error performance/latency compromise.

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Performance of Non-LOS FWA

In this section we summarize briefly our findings regarding the quantitative impact of the aforementioned features on the performance of NLOS-FWA systems. The evaluation is carried out using a multilayer simulator. The following global figures of merit are used to evaluate performance:

- Spectrum efficiency in bits per second per Hertz per cell
- Coverage in square miles per BTS
- Robustness to antenna pointing as an indicator of ease of installation

The performance measurement is done under coverage and link reliability constraints such as those discussed in a previous section. We target 90 percent coverage and 99.9 percent link reliability with an outage being declared after 3 s spent with over 50 percent link layer packet error rate. These settings turn out to provide acceptable IP throughput[2] [1].

We choose to evaluate downlink performance following an incremental technology development where each of seven stages includes an additional feature taken from the following list: ARQF, adaptive modulation, space diversity with the number of antennas going from[3] 1×1 to 1×2 to 2×3, frequency diversity, and interference canceling. Note that the sequence is arbitrary and does not necessarily reflect the best technology development path.

System Assumptions

We consider a generic IP-based FWA system with 2 MHz wide FDD channels in the 2.5 GHz band. The cell towers are 30 m high and communicate with 4 m high wall mounted subscriber units over mostly NLOS Ricean fading channels. The distribution of Ricean factors is based on measurement-based models reported in [8]. The link budget is determined assuming the well-known Cost-Hata path loss in suburban terrain. More specific models for FWA can be used, such as those reported in [9], that will give more accurate results in terms of absolute performance evaluation. The transmit power is 35 dBm. Each BTS has three 120° sectors. To illustrate the robustness to antenna directionality, we consider a wider than usual beam (90°) for the subscriber antenna. The trade-offs for the antenna beamwidth will be examined as well.

Air Interface — IP packets are fragmented into 50-byte data units over the air. The downlink employs Weighted Fair Queuing (WFQ) scheduling, the uplink is based on ALOHA type contention followed by slot reservation. The physical layer uses coded OFDM modulation. The presence of frequency diversity is simulated

[2] 1 Mb/s for an end-to-end RTP of 100 ms at 70 percent channel loading.

[3] The format is $M_T \times M_R$ with M_T and M_R denoting the number of transmit and receive antennas, respectively.

The use of MIMO techniques carries the greatest advantage in terms of coverage and data rates. The reason for this is that MIMO technology offers the flexibility to use the multiple antennas as degrees of freedom for either diversity or rate increase purposes at each user location.

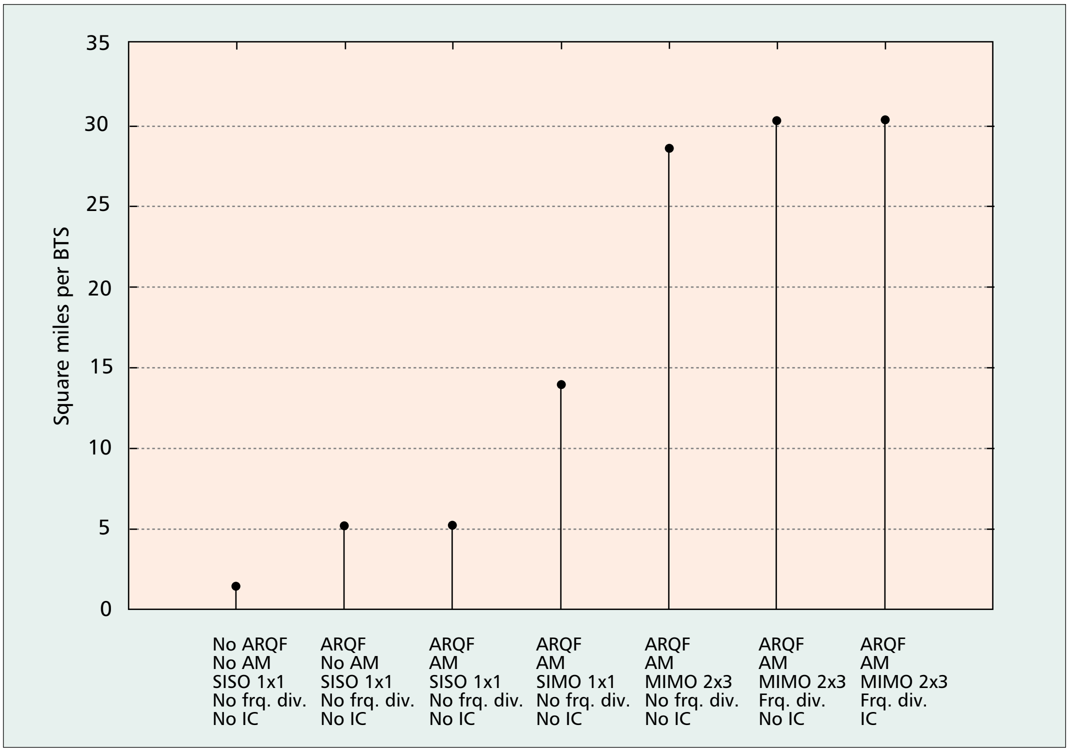


Figure 2. *Estimated coverage performance for various technology stages.*

by artificially varying the amount of multipath delay spread. For SD, we use a combination of delay diversity on the transmit side and maximum ratio combining (MRC) (equivalent to a spatial matched filter) on the receive side. In this example, both the MIMO SM and the IC algorithm are based on a minimum mean square error (MMSE) approach.

Simulator — The results rely on a combination of system-level and protocol/link-level simulations. Using an integrated TCP/MAC/PHY link simulation (the platform used was the Berkeley ns software), we determine the BER level which gives an acceptable link reliability and TCP/IP throughput (see above). For example, we find that a system with ARQF can operate at 10e-3 BER pre-ARQF over a fading channel with no line of sight component. In comparison, 10e-4 BER was found to be required without ARQF to achieve the same performance. Next, the required BER is converted into a target SINR (set point) for each desired level of data rate. The set points are a function of the diversity order (space and frequency). The assumed system has 6 different coding/modulation levels yielding efficiencies between 1 b/s/Hz and 6 b/s/Hz, those values are doubled when MIMO-SM is activated. In the non-AM case, we only use the conservative 1 b/s/Hz level. Finally, the set points are stored as lookup tables used by a system-level simulator, which returns the coverage, frequency reuse K, and spectrum efficiency performance. For the coverage performance we assume no interference (sparse deployment).

The spectrum efficiency is computed assuming a fixed 4 mi cell radius with maximum possible reuse K for each system, under the two reliability constraints.

We emphasize that the simulation finds its value in the relative comparison of system stages. Absolute performance values will vary with the detailed design assumptions, some of which are not disclosed here.

NLOS-FWA Performance Results

The *coverage performance* is shown in Fig. 2. Combined together, ARQF and SD were found to improve the coverage set point by 20 dB, which explains why they contribute to the largest coverage gains.

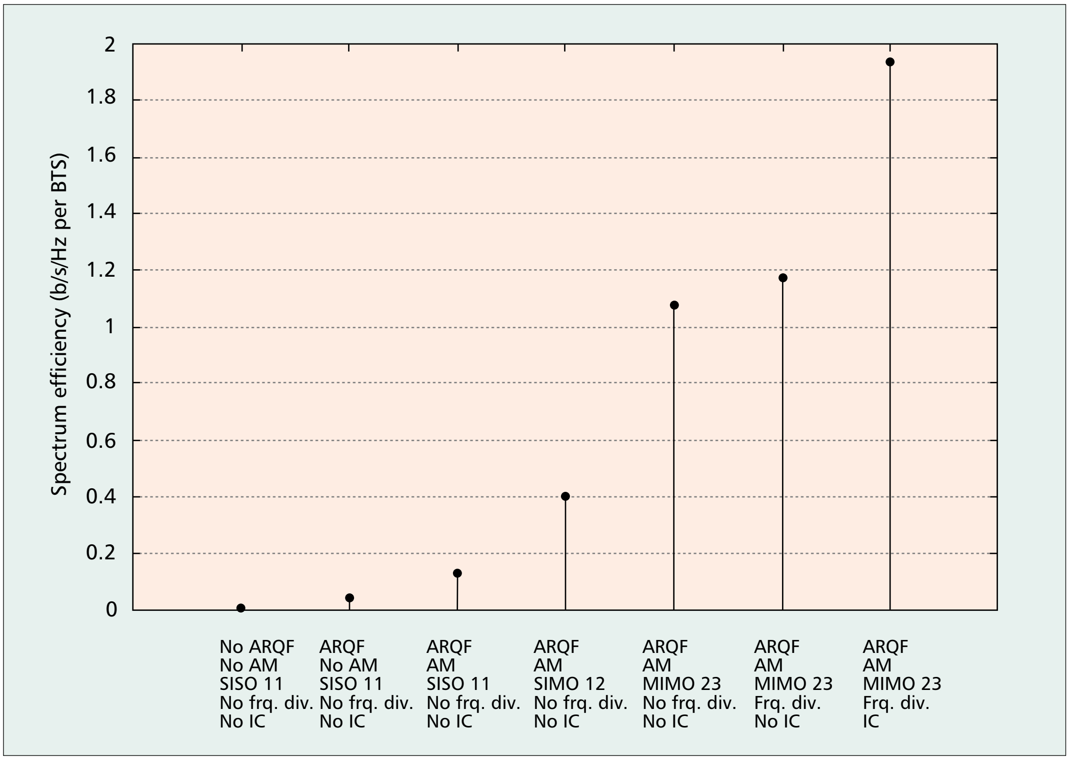
The *spectrum efficiency performance* is depicted in Fig. 3. We can see that the spectrum efficiency is dramatically improved by SD techniques allowing the various modes of the adaptive modulation scheme to be kicked off more easily, as well as SM. Third, the reduced set point results in a much higher tolerance to interference. For example, in the absence of any of the mentioned features, the achievable reuse factor is only 23, leading to extremely small efficiency.

Higher tolerance to interference is also achieved by employing IC. The allowable reuse factor in the different stages improves dramatically, from 23 to 1, as more features are added. In particular, we find that in the 2×3 setup IC permits reuse 1 even at full channel loading.

Overall, the use of MIMO techniques carries the greatest advantage in terms of coverage and data rates. The reason for this is that MIMO technology offers the flexibility to use the multiple antennas as degrees of freedom for either diversity or rate increase purposes at each user location.

Robustness to Pointing

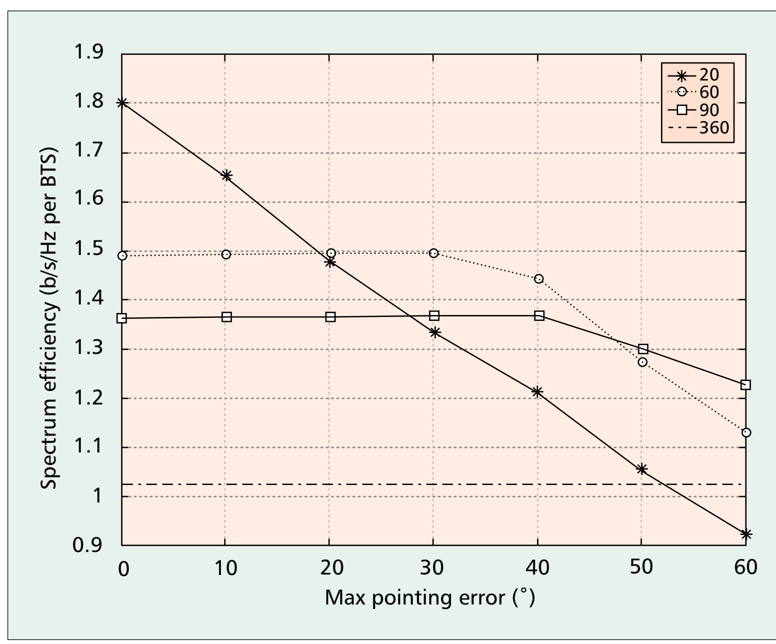
Besides pure performance, self-installation is among the most desirable features of future FWA systems. The use of large subscriber



■ **Figure 3.** *Estimated spectral efficiency for various technology stages.*

antenna beamwidths as discussed above is a simple solution to meet the corresponding requirements. The downside with broader beams from more traditional narrow-beamed antennas is lower nominal boresight gain (20 dB for 20° vs. 12 dB for 90°). In addition, broader beams also incur more intersymbol and co-channel interference, which constitutes a problem for PHY layer technologies not well equipped to deal with these types of distortion. In the cases of coded OFDM and MIMO, however, more multipath means better performance, to a certain extent, due to frequency diversity gain and increased multiplexing gain. In addition, narrow-beam antennas will suffer from a gain reduction in rich multipath environments because energy tends to be scattered in angle (although usually not uniformly) around the subscriber unit and is picked up only through weak side-lobes. This energy would otherwise be captured by a wider-beam or omnidirectional antenna. This loss can be modeled by introducing a gain reduction factor (GRF) that acts as a loss subtracted from the antenna's nominal gain. The GRF tends to compensate for some of the performance price paid for using wider-beam antennas because those experience lower GRF levels. Extensive measurements of GRF have been carried out [10] from which it is possible to model the relation between GRF and beamwidth, as shown in Table 3.

Our simulation attempts to measure the combined effects above. In Fig. 4, we measure the progressive impact of mispointing by evaluating the efficiency when the antenna is pointed toward the BTS with an error uniformly distributed over x degrees. We vary x from 0 (accurate pointing) to 90°. In Fig. 5, we assume that



■ **Figure 4.** *Spectrum efficiency vs. pointing error at the subscriber side for various antenna beamwidths.*

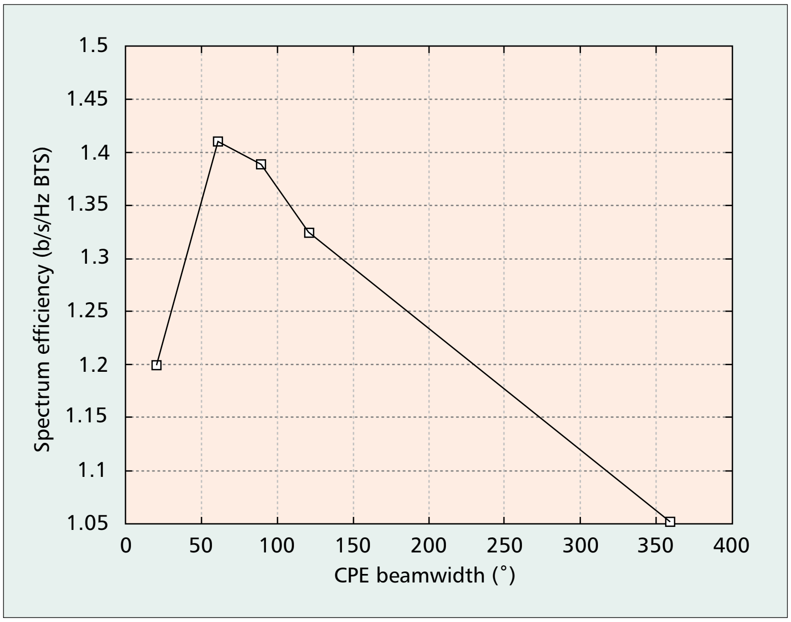
no pointing at all is possible in the sense that the antenna is just fixed on the best side[4] of the house, pointing away from the wall at 90°, in which case the random orientation of the house determines the error.

Although the 20° antenna gives highest performance in the best case scenario (accurate pointing), it can be seen that antennas with 60–90° beams provide the desired robustness to pointing errors while giving close to maximum system performance in NLOS environments.

[4] *In the sense of received power level.*

Antenna BW (–3 dB)	GRF (dB)
10˚	9 dB
20˚	6 dB
30˚	5 dB
50˚	3.5 dB
70˚	2.5 dB
90˚	1.5 dB
150˚	1 dB
200˚	0.5 dB
360˚	0 dB

■ **Table 3.** *Gain reduction factor vs. antenna beamwidth in NLOS-FWA.*



■ **Figure 5.** *Spectrum efficiency vs. subscriber antenna beamwidth.*

Omnidirectional antennas at the subscriber unit are also possible, at the cost of some performance loss.

Conclusion

Performance requirements for NLOS-FWA were discussed and the impact of key radio technologies was illustrated via end-to-end system simulations. We found that MIMO diversity and spatial multiplexing combined with adaptive modulation techniques and interference canceling are efficient ways to reach the high performance levels expected from these systems. Coded OFDM turns multipath delay spread into additional gain whenever available. We furthermore concluded that accurate pointing needs can be eliminated and self-installation facilitated at negligible cost in performance, through the use of wider-beam antennas at the subscriber side. The extra multipath caused by using such antennas is handled efficiently by a combination of ARQF and diversity techniques.

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Additional Reading

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