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

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Abstract— **This paper presents emerging technologies for upcoming non-line-of-sight fixed or stationary broadband wireless access (FWA) systems. We describe design tradeoffs for overall maximization of the radio capacity and coverage of FWA in multi-cell, interference and fading prone environments. We characterize quantitatively the impact of key emerging technologies on the overall performance.**

Keywords— **Broadband wireless, fixed access, Internet, smart antennas, MIMO, diversity, adaptive modulation, ARQ, performance analysis, spectrum efficiency.**

I. Introduction

The demand for broadband Internet access is continually growing. Announced delays in the deployment of third generation high speed wireless networks (WCDMA is unlikely to be truly widely available before 2003), as well as slow progress in satisfying demands for wired solutions such as x-DSL and cable modems place high expectations in alternative last mile technologies such as fixed wireless. 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 application are targeted such as web browsing, email, but also more demanding services such as real time conferencing and/or voice. To maintain reasonably low RF costs as well as a good penetration of the radio signals, mass market FWA systems typically use sub-5GHz bands, examples of which are the so-called MMDS[1] band in the U.S and the 3.5GHz band in international markets. The subscriber unit (sometimes referred to as Customer Premises Equipment or CPE) is currently typically installed on rooftop and communicates wirelessly to a BTS several miles away. However as line of sight requirements are being mitigated in the future, the CPE may be installed on the outside wall of the house or placed inside on a desk top. Future broadband access systems can also be envisioned to support portability, serving stationary light-weight 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, the clever exploitation of the subscriber access unit's stationarity while in use and of the (even 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 a 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, easy-install CPE antennas, and above all reliable non-line-of-sight (NLOS) operation need to be resolved before FWA can penetrate the market successfully.

This paper 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 (MIMO technology), adaptive modulation, ARQ, and more conribute to achieving these goals. We furthermore describe emerging radio technologies which turn multipath delay spread into a benefit such as MIMO-based spatial multiplexing technology and coded 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 putting emphasis on radio performance. We recall the definition of the key system metrics and we present simple design trade-offs. 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 a NLOS-FWA system incorporating such technologies using multi-layer simulations. We address both optimum performance and robustness issues such as pointing errors at the user's side. The last section provides some conclusions.

II. Design Challenges

Current FWA solutions are based on the existence of a 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

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[1] Multipoint Multichannel Distribution Services, close to 200 MHZ of spectrum in the 2.5 to 2.7 GHz band.

radio link from sources of interference and disturbance it is unable to cope with. These impairments typically include intersymbol-interference and Rayleigh fading caused by delay-spread and multipath propagation and to a smaller extent intercell co-channel interference caused by frequency reuse. In LOS (or near LOS[2]) conditions, the link budget typically accounts only for 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 30 percent only of the subscribers will actually experience a 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 a time and skill consuming operation. Moreover, necesary periodic upgrades of the cell lay out (cell splitting) are made very challenging due to the necessity of repointing most of subscriber's antennas. It is worth mentioning that the LOS condition could be otherwise realized through the deployment of many additional overlapping sectors in every coverage area. But 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 pure LOS has several key advantages. First broader antenna beams (or even in certain relevant applications ommni-directional) can be used at the subscriber's side wihtout fear of picking up unwanted multipath. This in turn improves user friendliness as installation by the user himself or an unskilled worker becomes possible, 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 (layer 1 and layer 2 combined together) able to cope with a particularly severe channel environment including fading, multipath delay spread, and interference.

III. 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.* User friendliness will be measured by the degree with the technology lends itseld to self installability and can cope with various signal distortions caused by 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.

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

IV. Performance of FWA systems

In this section, we discuss performance metrics for NLOS-FWA systems. We choose to characterize wireless network performance by two key metrics, namely *spectrum efficiency (SE)* and *coverage*, both being key indicators of infrastructure cost in different stages. Coverage is critical in early rollout stages as it governs the number of BTS 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 as it determines the number of users any given cell site will be able to serve simultaneously per unit of spectrum.

A. Spectrum Efficiency

The spectral efficiency (downlink or uplink) in Bit/Sec/Hz/BTS is measured as

$$SE = \frac{rM}{KB} \tag{1}$$

where M is the aggregate (or average) coded throughput for one RF channel, and r is the forward error correction (FEC) code rate. Hence, rM is the *effective*[3] throughput a user sees when he has (temporarily) sole access to the RF medium. This value is averaged over all possible channel conditions experienced across the cell/sector area at all times. The aggregate throughput is function of both the physical layer performance and the link budget hence must take into account link budget limitations such as path loss, maximum transmit power, noise level.

K is the well known spatial reuse factor and is given by the number of BTS in a cluster where a given RF frequency is used only once. Finally, B is the channel bandwidth including guard-bands and roll-off 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 spectrum efficiency through a potential increase of channel throughput (because, for example, interference is reduced or higher antenna gain is obtained). Note that the improvement will in general not be proportional to the number of sectors.

In this paper, we focus on the downlink spectrum efficiency which is usually considered the bottleneck in many

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[2] A near LOS condition is normally assocated with a Ricean fading K-factor of 10dB or more.

[3] The effective link layer throughput is defined by the payload throughput offered to the network (e.g. IP) layer and takes all radio and MAC overhead into account.

Internet applications. We note that a similar approach may be taken to evaluate the uplink performance.

B. 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 (say e.g. 90 percent) of cell locations must be served with minimal required link reliability constraints. Link Reliability (LR): This is expressed in terms of a maximum outage probability with typical numbers being $1-0.999$ or less (the number of 'nines' can vary with the provider). An outage is declared if the packet error rate drops below 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 [7] for an overview of TCP performance in NLOS-FWA systems.

C. Performance Optimization

The coverage and capacity performance is 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 radio system performance:

- *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 C/N and 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 spectrum efficiency (minimize K and maximize rM). This is the key to a sensible design.

V. 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, both at the medium access control (MAC) and physical (PHY) layers. At the PHY, diversity signaling, spatial multiplexing exploiting multi-antenna capability, delay-spread-robust modulation are helping the modem deal with severe channel impairment. At the MAC, 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 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 II.

A. Automatic Retransmission and Fragmentation (ARQF)

At link layer level an acknowledgment and retransmission mechanism is implemented between the subscriber unit and the BTS. The MAC layer performs fragmentation of IP packets going over-the-air into 'atomic' or elementary data units (ADU). 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. Only erroneous 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, while still providing satisfactory TCP/IP performance in terms of throughput and latency. The higher target error rates translate into a reduction of the set point by 4 to 7dB in a fading channel scenario. ARQ can also be viewed as an effective time diversity technique for dealing with the slowly-varying FWA channel.

B. Adaptive Modulation

The use of adaptive modulation (AM) and coding makes the adaption of a user's data rate as a function of the channel conditions (e.g. SINR, fading rate, etc.) possible, and has been popularized in the EDGE[4] cellular standard [6]. AM is becoming a key feature of wireless data systems.

Efficient AM schemes must incorporate

- *robust transmission modes* with low modulation efficiency such as BPSK and 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 64QAM or 256QAM 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 of the switching algorithm is usually required to determine the switching rules.

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

Another advantage of AM besides increased spectrum efficiency 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 the 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 for reaching higher customer satisfaction.

C. Spatial Diversity and Interference Canceling

Spatial Diversity (SD) is obtained through the use of multiple antennas at either the BTS and/or the CPE. The basic idea of 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 importantly the statistics of SNR fading are improved. The use of SD can reduce the system set point as much as $10-15$dB with just 2 or 3 antenna elements and is thus very powerful. This leverage can be exploited both to extend coverage and to tighten frequency reuse. Moreover, lower set points reduce power amplifier costs and prolong battery life in the case of portable units. Note that when combined with AM, the set points of all modulation/coding levels are reduced, thereby resulting in a higher aggregate throughput. SD gain can be obtained both at the transmitter and the receiver, both at the subscriber and BTS side. Several measurement campaigns for FWA, including those conducted by Iospan, ATT 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 2.5GHz for example, this means $6-12$cm antenna spacing. Even lower antenna spacing requirements can be satisfied by using dual-polarized antennas [5]. At the BTS side more spacing is needed because paths impinge with a smaller angular spread.

At the receiver, whether up- or down-link, the antennas are combined upon a priori estimation of the channel. Maximum Ratio Combining offers optimal performance within the class of 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. There the recently developed space-time codes [8] are particularly attractive since they realize transmit diversity gain without requiring channel knowledge in the transmitter. Another alternative is delay diversity which effectively converts spatial selectivity into frequency selectivity. The transmit SD gain is then picked up by a frequency coded modulation such as coded OFDM (See par. E).

Multiple antennas can also be used to perform interference canceling (IC) and are hence useful in dealing with co-channel interference (CCI) arising from a spectrally efficient hence tight frequency reuse deployment.

Very tight reuse factors (such as 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 in general very low. Simultaneous activity of co-channel users in neighboring cells will cause short peaks of interference which can be handled by IC. The amount of channel state information required by the IC algorithm typically depends on the performance needs and the specifics of the training architecture. In NLOS links, IC algorithms can not rely on angle of arrival information for the interferer or the target user's channel. In this case, the antenna weights can be computed from channel statistics such that they are as orthogonal as possible to the strongest interferer's signature(s).

D. MIMO-based Spatial Multiplexing (SM)

Employing multiple antennas at both ends of the wireless link (Multiple In Multiple Out or 'MIMO') can dramatically increase the bit rate [1], [2]. The basic idea is that the use of multiple antennas at both the transmitter and the receiver opens up multiple parallel spatial data pipes within the same bandwidth and allows linear (in the number of antennas) capacity increase provided rich enough scattering is present. The use of spatial multiplexing thus seems particularly interesting in the case of FWA, where a very high data rate is required. Fig. 1 shows the schematic of a spatial multiplexing system. A high rate signal is multiplexed into multiple bit streams 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 that are closer to the BTS are more likely to experience channel conditions that make the use of SM possible assuming the scattering remains rich enough.

For channels with poor scattering the system will rather use SD signaling than SM. In that case, the SD mode exploits joint transmit-receive antenna diversity which is a particularly robust form of SD. The intelligence for mode switching between SM and SD is located in the link adaptation module, as an extension of the AM algorithm. SM is particularly well suited for NLOS-FWA because, compact multi-element subscriber units can be designed with 2 or 3 elements.

E. Frequency Diversity: turning delay spread into a benefit

Broadband transmission over multipath channels usually introduces frequency-selective fading. As data rates are expected to increase much over next generation FWA, this effect is likely to amplify. In single carrier (SC) modulation frequency selectivity is 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 FFTs 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 is 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-flat fading. Depending on the code rate and interleaving depth gains of up to 2-3dB can be achieved at locations experiencing significant delay spread.

F. Time Diversity

Time diversity refers to a set of techniques used especially in mobile wireless (where the access unit is actually moving) that consist of coding and interleaving the transmitted information over data blocks that span multiple time slots experiencing independent channel fading. In fixed FWA, however, the channel varies slowly (often below 1Hz 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 ARQ 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 overall.

VI. Performance of Non-LOS FWA

In this section, we illustrate numerically the 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: (i) spectrum efficiency in Bits/Sec/Hz/Cell, (ii) coverage in square miles per BTS, and (iii) 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 section III. We target 90% coverage and 99.9% link reliability with an outage being declared after 3 seconds spent with over 50% link layer packet error rate. These settings turn out to provide acceptable IP throughput[5] [7].

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[6] 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.

A. System Assumptions

We consider a generic IP-based FWA system with 2MHz-wide FDD channels in the 2.5GHz band. The cell towers are 30m high and communicate with 4m high wall-mounted subscriber units over mostly NLOS Ricean fading channels. The distribution of Ricean factors is based on measurement-based models reported in [10]. The link budget is determined assuming the well known Cost-Hata path loss in suburban terrain[7]. The transmit power is 35dBm. Each BTS has three 120deg sectors. To illustrate the robustness to antenna directionality, we consider a wider-than-usual beam (90 degrees) 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 FIFO scheduling, the uplink is based on contention (ALOHA type) followed by reservation. The physical layer uses coded OFDM modulation. The presence of frequency diversity is simulated by artificially varying the amount of multipath delay spread. For SD, we use a combination of delay diversity on transmit and MRC combining on receive. IC is based on a generic minimum mean-square error (MMSE) approach.

Simulator: The results rely on a combination of system level and protocol/link level simulations. Using an integrated[8] TCP/MAC/PHY link simulator 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-ARQ over a fully fading channel. In comparison, $10e-4$ BER is required without ARQF to achieve the same performance. Next, the required BER is converted into a target SNR (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 Bit/Sec/Hz and 6 Bits/Sec/Hz, those values are doubled when MIMO-SM is activated. In the non-AM case, we only use the conservative 1 Bits/Sec/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).

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[5] One Mb/s for an end to end RTP of 100ms at 70% channel loading.

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

[7] More specific models for FWA can be used, such as those reported in [12] that will give more accurate results in terms of absolute performance evaluation.

[8] The Berkeley-NS TCP simulator is used as platform.

The spectrum efficiency is computed assuming a fixed 4 mile cell radius with maximum possible[9] reuse K for each system.

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.

B. NLOS FWA Performance results

The *coverage performance* is shown in Fig. 2. Combined together, ARQF and SD improve the coverage set point by up to 20dB and thus contribute to large 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. Thirdly, the reduced set point results in a much higher tolerance to interference. 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 one at even 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.

C. Robustness to Pointing

Besides pure performance, *relaxed pointing requirements* and *decreased installation time* are among the most desirable features of future FWA systems. The use of large subscriber antenna beamwidths as discussed above is a simple solution to meet these requirements. The downside with broader beams compared to more traditional narrow-beamed antennas is lower nominal boresight gain (20 dB for 20deg vs. 12 dB for 90deg). In addition, broader beams also pick up more intersymbol and co-channel interference which constitutes a problem for physical layer technologies not well equipped to deal with these types of distortion. In the case 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 omni-directional antenna. This loss can be modeled by introducing a gain reduction factor (GRF) which 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 [11] out from which it is possible to model the relation between GRF and beamwidth, as shown in Table III.

Our simulation attempts to measure the combined effects above. In Fig. 4 and 5, the system's spectrum efficiency was evaluated for different subscriber antenna beamwidths and for two installation scenarios: (1) The antenna is pointed toward the BTS but pointing is done with an error uniformly distributed over x degrees. We vary x from 0 (accurate pointing) to 90deg. (2) The antenna is fixed on the best side[10] of the house with no attempt to point precisely at the BTS.

Although the 20deg antenna gives highest performance in the best case scenario (accurate pointing), it can be seen that antennas with 60 to 90 degree beams provide the desired robustness to pointing errors while giving close to maximum system performance in NLOS environments. Omni-directional antennas at the subscriber unit are also possible, at the cost of some performance loss.

VII. 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 can be 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 ARQ and diversity techniques.

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[9] under the two reliability constraints

[10] In the sense of received power level. The antenna is pointing away from the wall at 90deg.

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TABLE I

Typical NLOS-FWA requirements

Figure of Merit	Requirement
Aggregate Rates	6 Mb/s
Spec. Eff.	≈ 2 Bit/Sec/Hz/BTS
Coverage	6mi rooftop, 3mi wall-mounted
Latency	Comparable to DSL
Link Rel.	.999

TABLE II

Layer 1,2 technologies for advanced NLOS FWA.

Technology	Impact (qualitative)
ARQF	Set point ↓
Adapt. Mod.	Data Rate ↑
Diversity (space)	Set point ↓
Diversity (frequency)	Set point ↓
MIMO-Spatial Muxing	Date rate ↑

TABLE III

Gain Reduction factor vs. antenna beamwidth in NLOS FWA.

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

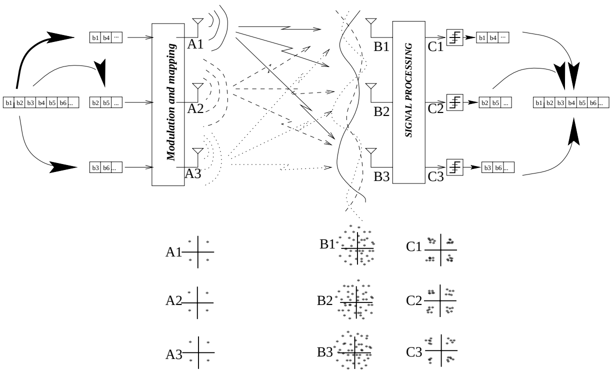

Fig. 1. Basic spatial multiplexing (SM) scheme with 3 transmit and 3 receive antennas yielding three-fold improvement in spectral efficiency.

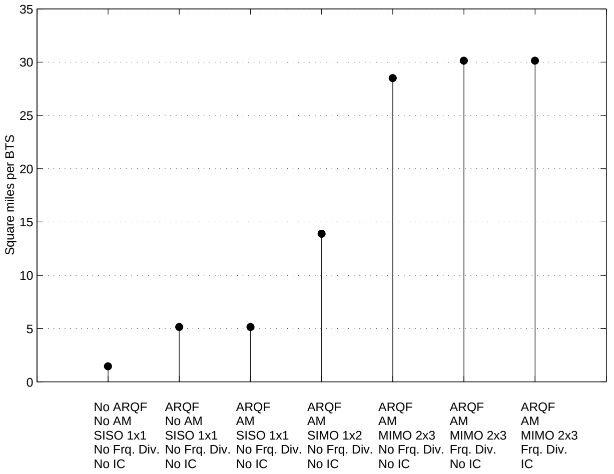

Fig. 2. Estimated coverage performance for various technology stages.

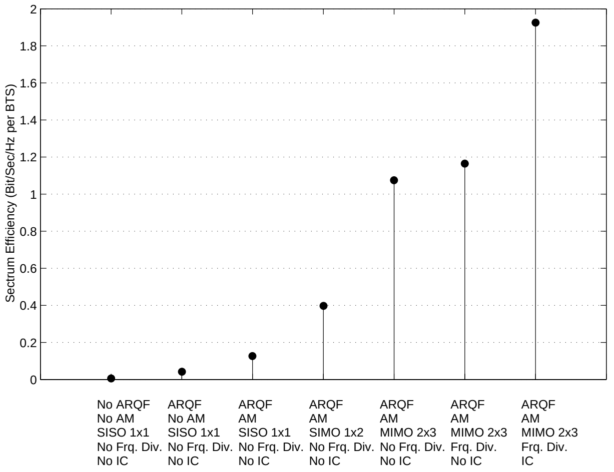

Fig. 3. Estimated spectral efficiency for various technology stages.

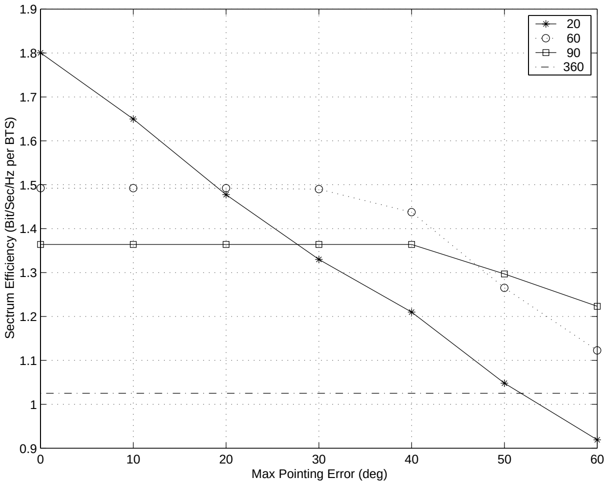

Fig. 4. Spectrum Efficiency vs. Pointing error at the subscriber side for various antenna beamwidths.

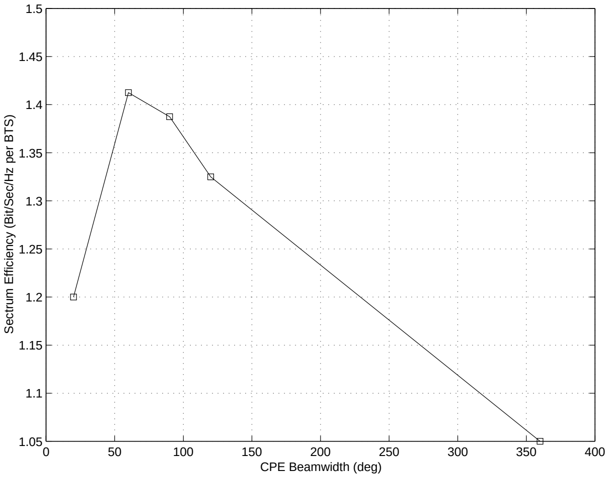

Fig. 5. Spectrum Efficiency vs. Subscriber antenna beamwidth.