REPORT ITU-R M.2040

Adaptive antennas concepts and key technical aspects

(Question ITU-R 224/8)

(2004)

1 Introduction

This Report identifies the key adaptive antenna concepts and describes their technical aspects. The traditional approach to the analysis and design of wireless systems has generally been to address antenna systems separately from other key systems aspects, such as:

– propagation issues;

– interference mitigation techniques;

– system organization (access techniques, power control, etc.);

– modulation.

Adaptive antenna technologies are best implemented with an overall system approach, where all the system components, including the antenna system, are integrated in an optimal way, leading to substantial coverage improvements (e.g. larger coverage area, reduced "holes" in coverage) for each cell, vastly superior mitigation of interference problems, and substantial system capacity improvements.

This Report reviews the various concepts of adaptive antennas, including the concept of "spatial channels", provides a theoretical analysis of the potential of the technology and identifies the key characteristics. Attached as Annex 1 is a glossary of relevant terminology for adaptive antenna systems.

1.1 Related Recommendations

The following ITU-R Recommendations may be useful in that they address mobile systems to which the concepts considered here may be considered appropriate to a greater or lesser degree:

Recommendation ITU-R M.622:	Technical and operational characteristics of analogue cellular systems for public land mobile telephone use
Recommendation ITU-R M.1032:	Technical and operational characteristics of land mobile systems using multi-channel access techniques without central controller
Recommendation ITU-R M.1033:	Technical and operational characteristics of cordless telephones and cordless telecommunication systems
Recommendation ITU-R M.1073	Digital cellular land mobile telecommunication systems
Recommendation ITU-R M.1074:	Integration of public mobile radiocommunication systems
Recommendation ITU-R M.1221:	Technical and operational requirements for cellular multimode mobile radio stations

Recommendation ITU-R M.1457:	Detailed specifications of the radio interfaces of International Mobile Telecommunications-2000 (IMT-2000)
Recommendation ITU-R M.1678:	Adaptive antennas for mobile systems
Recommendation ITU-R SM.856:	New spectrally efficient techniques and systems.

2 Antennas and adaptive antenna concepts

2.1 Antennas and coverage

Adaptive antennas may be defined as an array of antennas and associated signal processing that together are able to change its radiation pattern dynamically to adjust to noise, interference and multipath. Adaptive antennas are used to enhance received signal-to-interference noise ratios (SINR) and may also be considered as forming beams for transmission. Likewise, switched beam systems use a number of fixed beams at an antenna site. The receiver selects the beam that provides the greatest signal enhancement and interference reduction. Switched beam systems may not offer the degree of performance improvement offered by adaptive systems, but they are much less complex and are easier to retro-fit to existing wireless technologies. Finally smart antennas are similarly defined as systems that can include both adaptive antenna and switched beam technologies. A glossary of relevant adaptive antenna terms is provided in Annex 1; this section provides further discussion on the terminology and its general usage.

The reader is cautioned that there is some variation in terminologies here; for example, non-adaptive or non-switched systems are sometimes termed smart simply due to the incorporation of masthead RF electronics, and often the terms adaptive and beam-forming are used rather loosely or narrowly. (For example, Recommendation ITU-R SM.856, seemingly the only other ITU-R Recommendation that mentions any aspect of adaptive antennas, uses the term adaptive rather than fully adaptive correctly, but briefly describes an example of a very narrow and specific interpretation of this as used in an earlier system at VHF.) Further, care is needed when the term adaptive is applied in discussing land mobile systems, but used alone without a further descriptor e.g. as applied to dynamic control of modulation or of bandwidth resources or of coding, power or other attributes of an air interface protocol.

Adequate for simple RF environments where no specific knowledge of the user's location is available, the omnidirectional approach scatters signals, reaching target users with only a tiny fraction of the overall energy radiated into the environment (or, conversely, for emissions from the users towards the base station (BS)).

Given this limitation, omnidirectional strategies attempt to overcome propagation challenges by simply boosting the power level of the signals. In settings where numerous users (hence, interferers) are relatively close to each other, this makes a bad situation worse in that the vast majority of the RF signal energy becomes a source of potential interference for other users in the same or adjacent cells, rather than increasing the amount of information conveyed by the link.

In uplink applications (user to BS), omnidirectional antennas offer no gain advantage for the signals of served users, limiting the range of the systems. Also, this single element approach has no multipath mitigation capabilities.

Therefore omnidirectional strategies directly and adversely impact spectral efficiency, limiting frequency reuse.

A single antenna can also be constructed to have certain fixed preferential transmission and reception directions: today many conventional antenna systems split or “sectorize” cells. Sectorized antenna systems take a traditional cell area and subdivide it into “sectors” that are covered using multiple directional antennas sited at the BS location. Operationally, each sector is treated as a different cell. Directional antennas have higher gain than omnidirectional antennas, all other things being equal, and hence the range of these sectors is generally greater than that obtained with an omnidirectional antenna. Sectorized cells can improve channel reuse by confining the interference presented by the BS and its users to the rest of the network, and are widely used for this purpose. As many as six sectors per cell have been used in commercial service.

2.2 Adaptive antenna systems and diversity

Understanding diversity is an important element in this context. As noted by Winters [1], the three primary cellular wireless system impairments may be grouped under three categories *viz*. multipath fading, delay spread and co-channel interference. As explained later, multiple antennas, M in number, can generally provide increased gain of M and additionally effect diversity gain against multipath fading. The gain M may be considered as the reduction in required receive power for a given average output S/N (independent of the environment) whereas the diversity gain component (only possible with multipath evident) is the reduction in required average output S/N for a given error rate in the presence of fading. So space diversity antenna systems incorporate two or more antenna elements whose physical separation is used to combat the negative effects of multipath.

Diversity offers an improvement in the effective strength of the received signal by using one of two methods:

– *Switched diversity*: Assuming that at least one antenna will be in a favourable location at a given moment, this system continually switches between antennas (connecting each of the receiving channels to the most favourably located antenna) to select the antenna with the maximum signal energy. While reducing signal fading, switched diversity does not increase gain since a single antenna is used at any time, and does not provide interference mitigation.

– *Diversity combining*: This approach coherently combines the signals from each antenna to produce gain: Maximal ratio combining systems combine the outputs of all the antennas to maximize the ratio of combined received signal energy to noise.

In contrast to switched diversity systems, diversity combining uses all antenna elements at all times for each user, creating an effective antenna pattern that dynamically adjusts to the propagation environment. Diversity combining is not guaranteed to maximize the gain for any particular user, however. As the algorithms that determine the combining strategy attempt to maximize total signal energy, rather than that of a particular user, the effective antenna pattern may in fact provide peak gain to radiators other than the desired user (e.g. co-channel users in other cells). This is especially true in the high interference environments that are typical of a heavily loaded cellular system.

2.3 Antenna systems and interference

More sophisticated antenna systems can mitigate the other major limiting factor in cellular wireless systems: co-channel interference. For transmission purposes, the objective is to concentrate RF power toward each user of a radio channel only when required, therefore limiting the interference to other users in adjacent cells. For reception, the idea is to provide peak gain in the direction of the desired user while simultaneously reducing interference from other co-channel and adjacent channel users. This assumes an antenna system with instant beam steering capabilities: This can be achieved with phased array technology, in particular with digital beam-forming techniques.

In addition, using a larger number of simple antenna elements gives a new dimension to the treatment of diversity as well.

2.4 Smart antenna systems

The advent of powerful and low-cost digital signal processors, general-purpose processors and application-specific integrated circuits (ASICs), as well as the development by several companies and research entities of software-based signal-processing techniques have made advanced adaptive antenna systems a practical reality for cellular communications systems: arrays of multiple antennas, combined with digital beam-forming techniques and advanced low cost baseband signal processing open a new and promising area for enhancing wireless communication systems. Useful reference material on adaptive antennas will be found in § 12.

At the heart of an adaptive antenna system is an array of antenna elements (two or more, typically four to 12), whose inputs are combined to adaptively control signal transmission and/or reception. Antenna elements can be arranged in linear, circular, planar, or random configurations and are most often installed at the BS site, although they may also be implemented in the mobile terminal. When an adaptive antenna directs its main lobe with enhanced gain to serve a user in a particular direction, the antenna system side lobes and nulls (or directions of minimal gain) are directed in varying directions from the centre of the main lobe. Different switched-beam and adaptive smart antenna systems control the lobes and the nulls with varying degrees of accuracy and flexibility. This has direct consequences in term of system performance.

2.4.1 Switched-beam antenna

Switched-beam antenna systems form multiple fixed beams with heightened sensitivity in particular directions. These antenna systems detect signal strength, choosing from one of several predetermined, fixed beams, based on weighted combinations of antenna outputs with the greatest output power in the remote user's channel, and switching from one beam to another as the mobile moves through the sector. These choices are driven by RF or baseband digital signal processing techniques. Switched beam systems can be thought of as a "micro-sectorization" strategy.

2.4.2 Adaptive array antenna

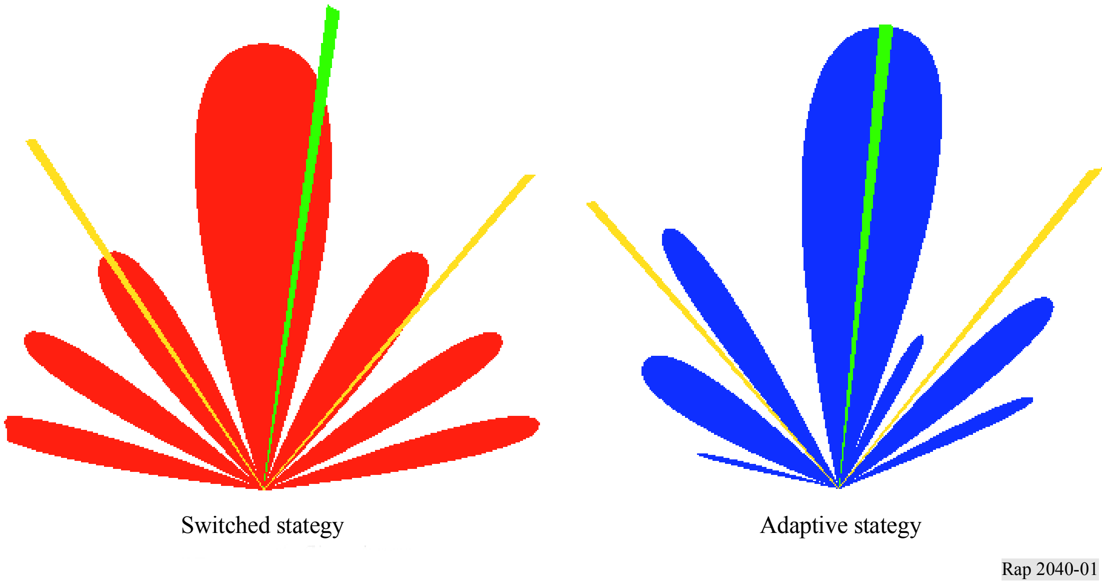
Adaptive antenna technology represents the most advanced and productive approach to date for significant improvements to spectrum efficiency. Using a variety of signal-processing algorithms, an adaptive system effectively identifies and tracks all the relevant signals and interferers present in order to dynamically minimize interference and maximize reception of the signals of interest. In the same manner as a switched-beam system, an adaptive system will attempt to increase gain based on the user's signal as received at the various elements in the array. However, only the adaptive system provides optimal gain while simultaneously mitigating interference. Diversity combining also continuously adapts the antenna pattern in response to the environment. The difference between it and the adaptive antenna method is fundamentally in the richness of the models on which the two systems' processing strategies are based. In a diversity system, the model is simply that there is a single user in the cell on the radio channel of interest. In the adaptive system, the model is extended to include the presence of interferers and, often, temporal history regarding the user's propagation characteristics. With this second model, it is possible to discriminate users from interferers, even at low SINR, and provide reliable gain and interference mitigation.

The adaptive antenna systems approach to communication between a user and the BS in effect takes advantage of the spatial dimension, adapting to the RF environment – including the constellation of users and other emitters – as it changes, according to predefined strategies. This approach continuously updates the BS system's radiation and reception patterns, based on changes in both the desired and interfering signals relative configuration. In particular, the ability to efficiently track users through antenna main lobes and interferers through nulls ensures that the link budget is constantly maximized. By implementing the smart antenna strategies digitally, it is possible for the BS to support a separate, tailored, strategy for each active channel in the system via a single array and set of radio electronics.

The difference between the two approaches – adaptive and switched beam – is illustrated in Fig. 1, which shows how the adaptive algorithms behave with respect to interferers and the desired signal.

FIGURE 1

Difference between switched beam and adaptive beam



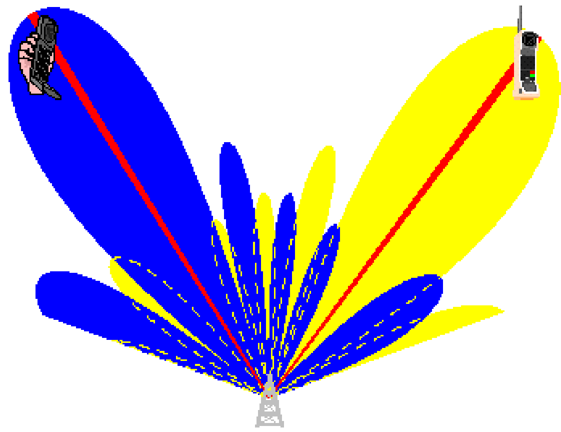
2.4.3 Spatial processing: the fully adaptive approach

Utilizing sophisticated algorithms and powerful processing hardware and microprocessors, "spatial processing" takes the frequency reuse advantage resulting from interference suppression to a new level. In essence, spatial processing (spatial division multiple access. (SDMA)) dynamically creates a different notional beam structure for each user and assigns frequency/channels on an ongoing basis in real time. Spatial processing maximizes the use of multiple antennas to usefully combine signals in space, through methods that transcend the "one user-one beam" methodology.

Depending on the details of the air interface and the service definition, so-called "spatial channels" can be robustly created via spatial processing whereby each conventional temporal channel (e.g. frequency and time-slot or code combination) may be reused within the cell, achieving reuse factors less than one. Figure 2 depicts such a situation for two users. Spatial channels, or intra-cell reuse (SDMA), are used operationally today in commercial cellular systems in several countries. While the concept of intra-cell reuse may seem unfamiliar, it is readily supported so long as adequate spatial selectivity is available in the distribution and collection of radio energy from the cell. For instance. depending on the air interface, as little as 10 dB of spatial selectivity or isolation for different locations in the cell may be adequate. Dependent on the air interface details, even terminals which are collinear (truly radial) with respect to the BS, may be distinguished, even collinear with two adjacent such stations. In this section we refer to reuse factors, R, that are now sub-unity, which cannot be achieved in normal cellular systems (where $R > 1$).

FIGURE 2

A two user spacial channels strategy, reuse = 0.5



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3 Theoretical analysis of adaptive antenna enhancements

3.1 Introduction

This analysis estimates the maximum capacity or spectral efficiency of a cell as a function of the frequency reuse factor in the network. The "uplink" or "reverse link" SINR in the cellular network are first calculated via computer simulations that may include empirically derived adaptive antenna processing gains at the BS. (In this analysis user terminals are considered to only have conventional antenna systems.) The theoretical capacity is then derived using Shannon's law, modified to include various "coding gaps"[1].

3.2 Definition of the model used in this analysis

3.2.1 Methodology

Given a fully loaded network (all communication resources used), and a fixed number of users, N, per BS, for a given allocated network bandwidth, B, the problem is to select the frequency reuse factor R, which will maximize the capacity of the network, hence its spectral efficiency. The trade-off is as follows: the lower the frequency reuse factor, the higher the bandwidth available per user, b, but the higher the interference per user.

The user's available bandwidth is:

$$b = B/(NR)$$

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[1] Coding gap is the difference (usually expressed dB relative to S/N) between the operational channel capacity and the Shannon limit (which assumes the use of infinite length block codes). If the Shannon limit is $\log_2(1 + S/N)$ bit/s/Hz and the actual throughput is $\log_2(1 + a \times S/N)$ bit/s/Hz, $a \leq 1$ where a is the coding gap.

Following the evaluation of the available SINR after the adaptive antenna processing, Shannon's law gives the user's available capacity:

$$b \times \log_2(1 + a \times \mathrm{SINR}(R))$$

where a represents the coding gap (typically in the range of −3 to −6 dB).

The aggregate cell capacity is then $(B/R) \times \log_2(1 + a \times \mathrm{SINR}(R))$ and the network spectral efficiency is: $\eta = (1/R) \times \log_2(1 + a \times \mathrm{SINR}(R))$, usually expressed in bit/s/Hz/cell. Clearly the SINR depends on a number of system design and implementation factors, not only R.

The reuse factor which maximizes the total BS capacity, hence the network's system spectral efficiency, is to be found from the behaviour of η as a function of R and the coding gap, a, and depends on the specific implementation of the receiver.

3.2.2 The cellular model

The cellular model which has been selected in this analysis is the so called "concentric circular cellular geometry", where all cells have equal areas, and the cell of interest is also circular, located in the centre of all surrounding cells [2]. Three tiers are included in the analysis with 8, 16 and 24 cells respectively each, as sources of co-channel interference for the central cell.

User terminals are placed uniformly in their respective cells. We assume they are fitted with conventional omnidirectional antennas.

3.2.3 Propagation model

The interference of the surrounding cells into the cell of interest is evaluated with a typical path loss exponent of 3.5. At this stage, the dispersion in path losses is not taken into account, although it is anticipated to have an impact on the capacity. This impact is more important at high reuse factors, as, with the number of interferers decreasing, averaging effects are reduced.

3.2.4 Limitations of the model

The methodology presented above might be improved upon, for instance by adopting different parameter values, e.g. number of array elements, more elaborate propagation models, or more detailed cellular models. The model does not include multipath effects. Unequalized multipath can be approximately considered as reducing the SINR.

The analysis also considers the uplink only. To the extent that downlink SINRs differ from those of the uplink, the analysis should be considered approximate. There are many factors that determine the relative performance of uplink and downlink adaptive antenna processing, including the following:

– air interface specifics, duplexing method in particular (time division duplex (TDD) vs. frequency division duplex (FDD));

– propagation environment;

– service definitions including data rates, user mobility and so on;

– smart antenna processing algorithms.

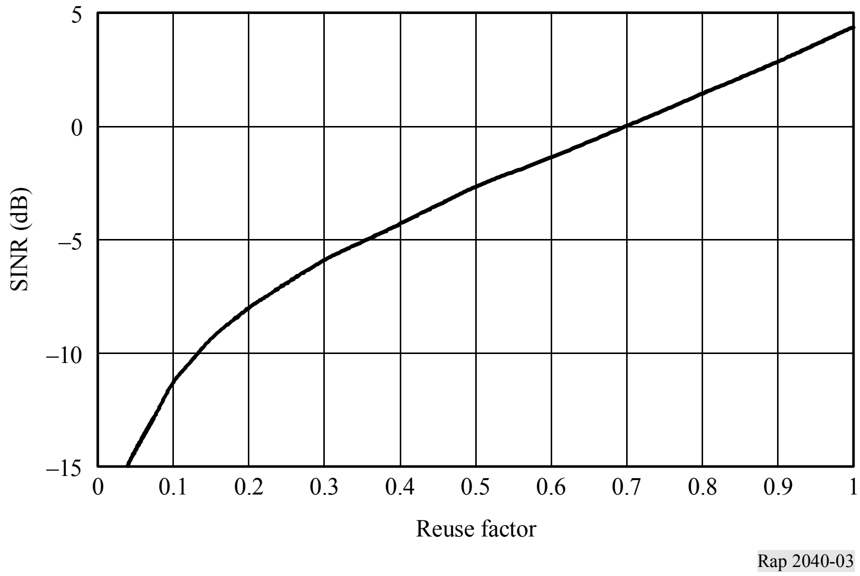
3.3 Results and comparisons

3.3.1 Example with a single element antenna

A simulation of a single element antenna is performed, to provide a reference for the SINR enhancements provided by adaptive antennas. Figure 3 gives an example of the potential SINR available at the output of the antenna, as a function of the reuse factor and includes many implementation specific parameters.

FIGURE 3

SINR versus reuse factor (one antenna)



The low reuse factor region (approximately unity) may correspond to the case of typical code division multiple access (CDMA) systems; and in this case the SINR is computed before application of the "de-spreading processing gain". For high reuse factors, (e.g. 3, 6, 7, 9 …...) the loss dispersion effects mentioned in § 3.2.3 may mean that the mean SINR values presented in the plot are optimistic.

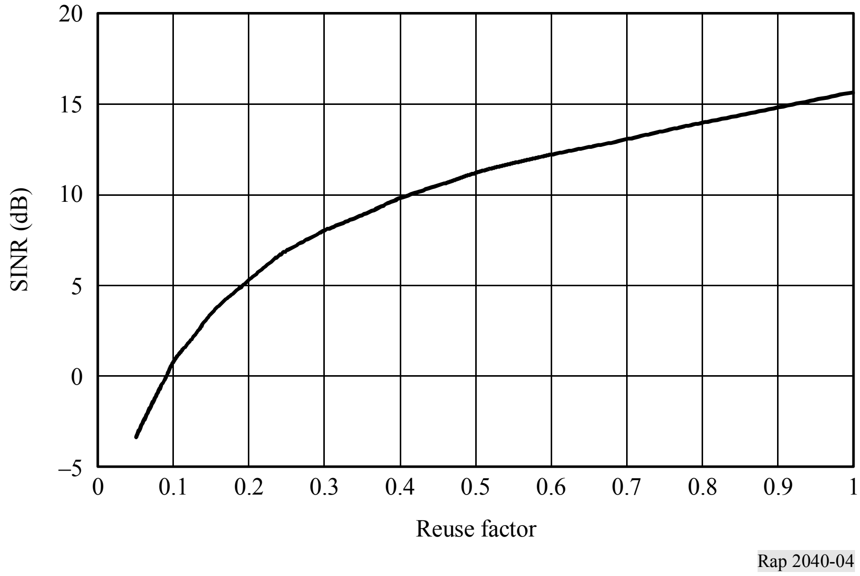
3.3.2 Example of adaptive antenna array with 12 elements

Figure 4 represents the potential uplink SINR for a specific implementation of a 12-element array adaptive antenna, after processing. The results are obtained through special simulation software, adapted from actual adaptive antenna processing software and system models. This software aims at maximization of the SINR, by increasing the antenna gain for the user of interest whilst simultaneously attempting to minimize gain for interfering signals.

Smaller (less than one) reuse factors which can be obtained in the case of fully adaptive arrangements (spatial channels or SDMA, see § 2.4.3) demonstrate how significant can be the improvement effected by use of adaptive antenna technology, although the results attained depend on many factors (see especially § 9.2). It is simply not possible to attain sub-unity reuse figures without use of adaptive antennas, although as shown above the reuse figures can in any case generally be significantly improved from the conventional case.

FIGURE 4

SINR versus reuse factor for 12-element array smart antenna

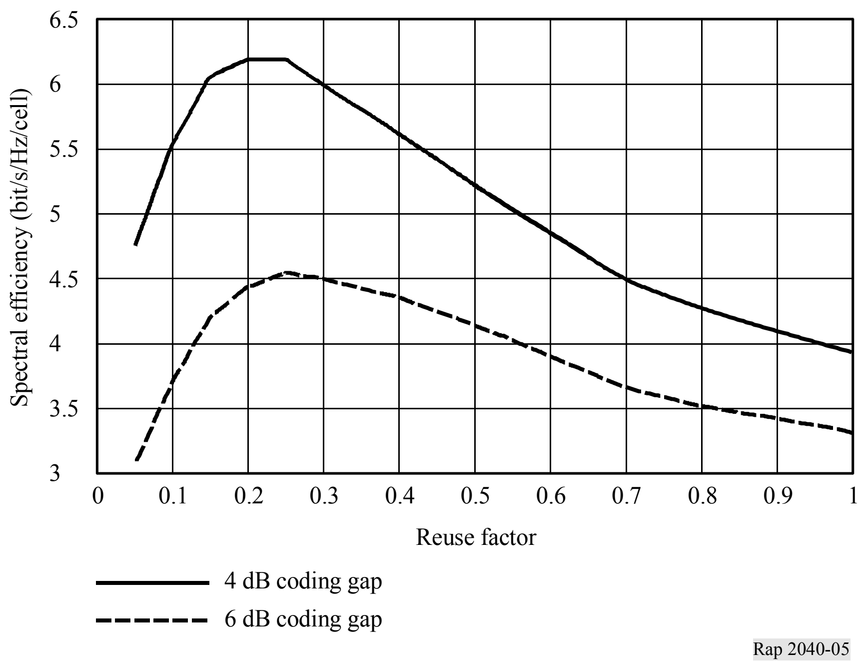


3.3.3 Resulting spectral efficiency

The above results are the basis for defining the spectral efficiency as a function of the reuse factor, for different values of the "coding gap". The results are shown in Fig. 5. They show SINR values, after adaptive antenna processing, in terms of spectral efficiency in bit/s/Hz/cell, and demonstrate the considerable potential of adaptive antennas in this CDMA example context.

FIGURE 5

Spectral efficiency for adaptative antenna versus reuse factor for 4 and 6 dB coding gap



The analysis shows that a network spectral efficiency of 4 to 6 bit/s/Hz/cell is achievable. In contrast, most 2G cellular systems today operate at a spectral efficiency of approximately 0.1-0.2 bit/s/Hz/cell. Additionally, one adaptive antenna based new system operating in the region of 2 GHz exhibits an efficiency as high as 8 bit/s/Hz/cell. For this, both simulation and practical results reveal consistent average reuse figures of 1/3 in this SDMA, TDD-based system example.

Rather confusingly, this efficiency metric is also sometimes referred to as “net system capacity” or even “net system capability”, in Mbit/s/MHz/cell. In general the overall improvement depends on many factors; see § 9.2.

The spectrum efficiency, η, can be simply calculated as:

$$\eta = N_c\, R_d \,/\, (B_c\, R)$$

where:

N_c: number of time slots/carrier

R_d: user data rate per slot

B_c: carrier bandwidth, and

R: reuse figure as before.

Then for a representative PCS 1900 system we have:

$$\eta = (8 \times 13.3 \text{ kbit/s/slot}) \,/\, (200 \text{ kHz} \times 7) = 0.08 \text{ bit/s/Hz/cell}$$

Section 9.1 provides such figures for a range of practical systems, including FWA as well as mobile systems. This metric is a most useful measure when considering spectrum usage and comparing potential deployment scenarios. This explains the great significance of the reuse factor R, which in turn depends on many factors as explained here and later (see § 9.2).

3.3.4 Resulting system performance

Adaptive antennas have been successfully applied by manufacturers and design houses to several existing air-interfaces and deployed commercially, as well as applied to air interfaces in development.

Published and unpublished results from system deployments, field-testing or desk system studies demonstrate that, although most of these (circuit-switched) systems were developed without any consideration being given to adaptive antennas, if not armed with features that are antithetical with adaptive antenna inclusion, substantial overall performance improvements can nonetheless be obtained. This analysis shows that if adaptive antenna system requirements are integrated from the outset in the overall creation of air interfaces, substantial additional performance improvements and overall higher spectral efficiencies can be obtained.

This analysis also alludes that, in the case of existing packet-switched systems, it is difficult to make general statements on the performance improvements that might be derived from the inclusion of adaptive antennas. But in order to meet the performance benchmarks yielded by the model, such systems must fundamentally be designed from the outset with due consideration given to adaptive antenna requirements.

4 Key technical aspects for adaptive systems

The implementation of an adaptive antenna system is a relatively complex system problem, involving trade-offs amongst many parameters. The following have been identified as key technical aspects from an overall performance standpoint, although implementation aspects should be considered as key parameters as well:

- number of antenna elements in the array;
- services aspects:
  - voice circuit versus data packet;
  - wideband or narrow-band services.
- system aspects:
  - FDD versus TDD;
  - access techniques: CDMA versus TDMA;
  - modulation: multi-carrier versus single carrier;
  - system organization:
    - protocols;
    - power control;
    - pilot signals;
    - synchronization;
    - training information;
  - radio propagation characteristics;
  - use of other interference mitigation techniques;
- design flexibility: add-on feature or new overall system design.

4.1 Number of array elements

The number of elements in antenna array is a fundamental design parameter, as it defines the degrees of freedom available to the system in creating optimal patterns, and the additional gain the array will provide. One direct consequence is that it may readily be shown that use of n antennas can afford the ability to provide $(n - 1)$ instantaneous nulls for interference mitigation. This parameter n is commonly in the 4 to 12 range, the upper-limit being dictated on one hand by economical considerations, and on the other hand by practical considerations regarding implementation, installation or increasingly, environmental issues. Useful results are also feasible when n is equal to 2.

The achievable improvement in system spectral efficiency increases with the number of elements in the array.

4.2 FDD and TDD systems

Adaptive antenna systems generally discriminate and identify emitters based on the relative phases and amplitudes of a given emitter’s signal at the various elements in the array. This collection of complex numbers is called the “spatial signature” of the emitter. On the uplink, the signature is directly measured by the BS, which develops its subsequent processing strategy for the uplink signals. On the downlink, however, in the absence of any additional information regarding the propagation channel from the BS to the user, an estimate or extrapolation of the downlink signature must be generated. Since the estimate of the downlink signature is less exact than that of the uplink signature, downlink adaptive antenna performance tends to be less than that on the uplink. Here, there is a clear-cut difference between FDD and TDD systems:

– Due to the frequency separation in up and downlinks, FDD systems exhibit uplink and downlink propagation characteristics that are not well correlated on a short-term basis, whereas in TDD systems the uplink and downlink channels can be considered more reciprocal. Normally the channels are separated temporally over periods much less than the reciprocal of the fading rate.

– Independent of the de-correlation issue mentioned above, the fact that the uplink and downlink are at different frequencies for an FDD system introduces the additional complexities of frequency scaling and more elaborate equipment calibration to map uplink signatures to downlink signatures.

The practical effect is that the capacity, and to a lesser extent downlink gain, improvements provided by adaptive antennas in FDD systems are generally less than those provided in TDD systems due to the greater relative mismatch of uplink and downlink performance in the former. It should be stressed, however, that significant gains for FDD systems are nevertheless realizable.

4.3 Service aspects

The type of service to be provided also impacts on the downlink extrapolation problem mentioned above: In a circuit-switched system, there is some short-term persistence in the way the system resources are utilized. Thus, there is the same persistence in the interference environment, and some correlation between uplink and downlink interference characteristics. Adaptive antenna systems can exploit this correlation of the interference environment in performing their downlink processing. In a packet-switched system, where the uplink and downlink interference environments may be quite different and where user transmissions are “bursty”, the correlation between the uplink and downlink interference environments may be quite different.

Therefore adaptive antenna techniques will behave differently in packet data systems and voice circuit systems.

4.4 Design flexibility

The benefits of adaptive antenna technologies will also vary depending on whether they are implemented as an add-on (or appliqué) to an existing system air interface – or whether they are incorporated from the outset in an air interface design.

4.5 Propagation environment

The algorithms used in adaptive antennas may also help handle some multi-path effects by taking advantage of space diversity, and in fact adaptive antennas mitigate multipath problems, although achievable performance will ultimately depend on the complexity of the radio environment.

The focused reception (or transmission) patterns generated by the array tend to reduce the amount of multipath that must be compensated for in the BS (or terminal) receivers, reducing the complexity of temporal equalization through "spatial equalization". This property will be increasingly valuable as systems evolve towards higher symbol rates and higher order modulation schemes. On the other hand, this spatial equalization process consumes some of the degrees of freedom in the effective pattern generation, which can reduce the level of interference mitigation performance.

4.6 Access techniques

Two main access techniques need to be considered: CDMA and frequency division multiple access (FDMA). The selection of one or the other may have an influence on the performance of the adaptive antenna system, all else being equal. Intuitively, CDMA lends itself better to combating interference, and this can be taken into account in the adaptive antenna algorithms design strategy. However, in a CDMA system which transmits many channels in parallel over a larger bandwidth, each user signal is confronted with a large number of interferers, which the antenna system cannot individually reduce to zero; thus, a dynamic interference-nulling strategy is not viable in this instance, and other beam-forming criteria must be implemented.

4.7 Other system considerations

The implementation of adaptive antenna techniques involves many system considerations and trade-offs. In addition to those mentioned above, the following points also deserve due consideration:

- factors having an impact on the downlink signature de-correlation with respect to the uplink signature:
  - frame length in TDD;
  - duplexing distance and uplink/downlink delay in FDD;
  - modulation bandwidth;
  - interaction with power control functions;
  - user mobility;
- factors having an impact on algorithm complexity:
  - modulation and equalization requirements;
  - service requirements (packet versus circuit);
  - protocols design for packet systems;

– factors having an impact on efficiency trade-offs;
  – use of other interference mitigation techniques;
  – frequency planning and/or frequency reuse policy;
  – system functions which cannot use spatial channels:
    – broadcast functions;
    – paging functions.

Adaptive antenna systems will have an impact on both the cost and complexity of the networks in which they are deployed. The cost analysis should consider the impact on a per BS basis and at an overall network level. With respect to complexity, there are additional issues to be considered when deploying them in existing networks.

4.7.1 Other considerations

There are a number of less commonly appreciated adaptive antenna technology advantages. For example, the inevitable re-distribution of RF power amplification elements for adaptive antenna systems commonly leads to lower total amplifier cost than is the like case with conventional technology. From a deployment viewpoint, it is sometimes attractive to utilize adaptive antennas in only a proportion of the BSs in the overall infrastructure in an area, and similarly the interference mitigation advantages may be particularly beneficial for such situations as cross-border coordination arrangements.

As noted in § 2.2, delay spread can be an important impairment in many cellular systems. It may be shown theoretically [3] that adaptive antennas can eliminate delay spread over $(M-1)/2$ symbols or cancel $(M-1)$ delayed signals over any delay. But it is commonly necessary that most or all of the processing capability is not used for countering temporal distortion at the expense of spatial processing, so temporal equalizers have an important part to play here, and dependent on the air interface and environment, the overall digital signal processing (DSP) can be complex, often with several levels of heuristic adaptation (see also § 7).

5 Enhancing CDMA systems

5.1 Introduction

This section describes several of the more significant aspects of capacity and coverage, and their relationship to the number of antenna elements for CDMA systems. Additionally some consideration is given to transmit diversity usage, where both up and downlinks are thereby improved, and to the additional benefits provided by adaptive antennas through active interference mitigation on the downlink and active interferer suppression in the uplink.

Two digital cellular radio interfaces are considered here to show it is possible to obtain significant performance improvements from the application of adaptive antenna systems.

Section 5.2 presents an analysis of the first order effect of adaptive antennas on ANSI-95 CDMA network capacity and coverage. The results of this analysis are exemplary of the level of improvements that can be expected when adaptive antennas are used on some of the digital cellular networks shown in Recommendation ITU-R M.1073.

5.2 CDMA (ANSI-95) systems

5.2.1 Introduction

The following analysis covers the effect of adaptive antennas on CDMA network capacity and coverage. This analysis applies to all of the existing CDMA-based networks and shows general, first-order effects.

The analysis in this Report does not take diversity effects into consideration. The fading on the channels to each of the antennas is assumed to be completely correlated. In a real system, depending on how the antennas are configured and the propagation environment, there is usually some decorrelation between the channels of the different antennas. In the uplink, such decorrelation between receive channels gives additional uplink capacity and coverage beyond what is presented here. In the downlink, decorrelation between the transmit channels can be exploited by combining a transmit diversity scheme with adaptive antennas to give additional downlink capacity and coverage beyond what is presented here. The antennas at the BS can be configured to maximize the benefits from both adaptive antennas and receive and transmit diversity.

Furthermore the analysis here does not take into consideration the effect of active interferer suppression in the uplink and active interferer mitigation in the downlink. This will also increase capacity and coverage, especially when the network includes high data rate users.

5.2.2 Uplink capacity and coverage

As a basis for the analysis of the effect of uplink capacity of coverage we can use the following formula for the received bit energy per power spectral density of the thermal noise plus interference, E_b/I_0 [4]:

$$\frac{E_b}{I_0} = MG \frac{S}{FN_{th}W + \alpha(1+\beta)(N-1)S} \tag{1}$$

where:

- E_b: bit energy
- I_0: power spectral density of thermal noise plus interference
- F: BS noise figure
- N_{th}: power spectral density of the thermal noise
- S: received signal strength per antenna
- G: processing gain
- α: voice activity factor
- β: intercell interference factor
- N: number of users in the cell
- W: system bandwidth
- M: number of antennas.

We can use equation (1) to express the capacity of the cell as

$$N = N_{pole} - \frac{FN_{th}W}{\alpha(1+\beta)S} \tag{2}$$

where N_{pole} is the *pole capacity* defined by:

$$N_{pole} = \frac{MG}{\alpha d(1+\beta)} + 1 \tag{3}$$

and where d is the required E_b/I_0. Note that the pole capacity is proportional to the number of antennas. The pole capacity is the theoretical maximum capacity if the mobiles have infinite transmit power available, i.e. the capacity in the limit where coverage is no longer a concern and interference alone limits capacity. In practice the mobiles do not have infinite power. The practical capacity is therefore typically a fraction of the pole capacity. Typical values are 50-60% of the pole capacity [4]. Depending on how close we are operating to the pole capacity, the required received signal power per antenna, S, will differ. From equation (2), the required received signal energy per antenna may be expressed as:

$$S = \frac{FN_{th}W}{N_{pole}\,\alpha(1+\beta)(1 - N/N_{pole})} \tag{4}$$

Assuming that the user terminals have a limited power, P_t, and assuming path loss with a path loss exponent of γ, we can express the cell radius, R', as:

$$R' = r_0 \left(\frac{P_t}{S}\right)^{1/\gamma} \tag{5}$$

where r_0 is a constant. Given that the area, A, of the cell is proportional to the cell radius squared, and using equations (4) and (5) we can derive the relation:

$$A^{-\gamma/2} = k \frac{1}{N_{pole} - N} \tag{6}$$

where k is a constant. If we approximate N_{pole} as being proportional to M (i.e. neglecting the "1" in equation (3)), assuming a nominal pole capacity of 1 when $M = 1$ and absorbing the constant k into a normalized coverage area, we can rewrite equation (6) as:

$$A^{-\gamma/2} = \frac{1}{M - N} \tag{7}$$

We can now express the uplink normalized capacity, N, as a function of the normalized coverage area, the number of antennas at the BS, and the path loss exponent:

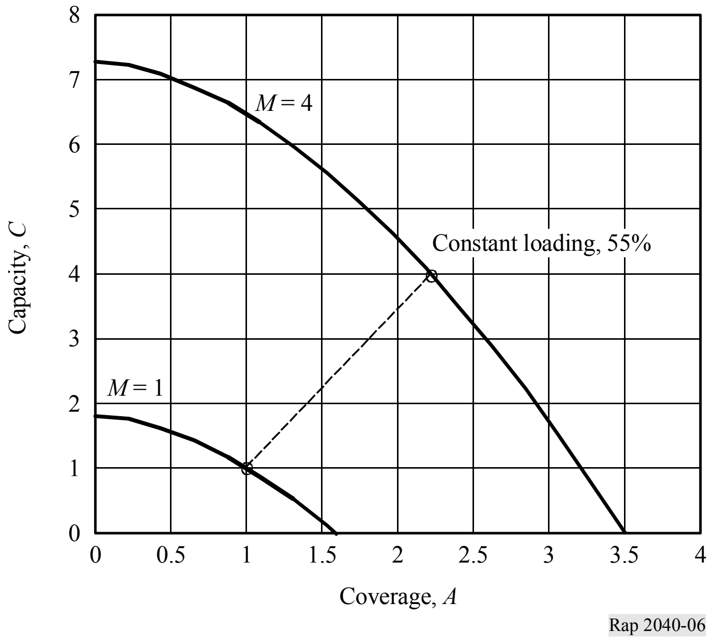
$$N = M - A^{\gamma/2} \tag{8}$$

For a given number of antennas and a given path loss exponent there is thus a trade-off between coverage and capacity. Figure 6 plots these trade-offs for one and four antennas with a path loss exponent of 3.5.

The $M = 1$ curve represents the capacity-coverage trade-off when a single antenna is used and the $M = 4$ curve represents the capacity-coverage trade-off when an adaptive antenna with four antennas is performing beam-forming without nulling. Also illustrated are the points where the loading equals 55% of maximum capacity (pole capacity). With the adaptive antenna, keeping the same relative loading, we simultaneously increase capacity by a factor of 4 and coverage by a factor of 2.2.

FIGURE 6

**Capacity-coverage trade-offs for one and four antennas.
Path loss exponent γ = 3.5**



As mentioned above, a CDMA system is normally operated at a certain fraction of its maximum capacity (the pole capacity). Figure 6 illustrates how capacity and coverage increase when the fractional loading is held constant when going from a single- to multiple-antenna BS. In Fig. 6 both axes are normalized, so that the capacity improvement factors and coverage improvement factors are shown in relationship to each other for the one and four antenna array cases ($M = 1$, 4 respectively). With constant fractional loading and with the assumption that the pole capacity is proportional to the number of antennas, the increase in capacity is of course:

$$\text{Constant load capacity gain} = M \tag{9}$$

To see how the coverage area increases we can divide equation (8) by M, introduce the per-antenna loading factor, $\mu = N/M$, and rewrite it as:

$$A = (1 - \mu)^{2/\gamma} M^{2/\gamma}$$

Now, as μ remains constant, the coverage area gain for constant loading is given by:

$$\text{Constant loading coverage area gain} = M^{2/\gamma} \tag{10}$$

Both of the gains in uplink capacity and uplink coverage area in equations (9) and (10) can thus be achieved simultaneously, as illustrated in Fig. 6.

5.2.3 Downlink capacity and coverage

A slightly different analysis is required to estimate the effect of adaptive antennas on downlink capacity.

Let us assume that we can express an average SINR for the user terminal as:

$$SINR_{avg} = \frac{P_{delivered,avg}}{N_{thermal} + P_{base}(1-\eta_{avg})(1+\beta_{avg})\rho_{avg}} \tag{11}$$

where:

- $P_{delivered,\,avg}$: average power delivered to the user terminal
- $N_{thermal}$: thermal noise power
- P_{base}: total power transmitted by the BS
- η_{avg}: average orthogonality factor
- β_{avg}: average inter- to intra-cell interference ratio
- ρ_{avg}: average path loss for interference.

We can further model the average delivered power to the user terminal as:

$$P_{delivered,avg} = k\frac{P_{base}}{MN}M^2R^{-\gamma} = k\frac{P_{base}}{N}M \;\; R^{-\gamma} \tag{12}$$

We have here divided the total available BS power among the N users and the M antennas, multiplied it with the coherent power combining gain which is potentially M^2 (see implementation factors in § 9.2) and multiplied it with the path loss factor $R^{-\gamma}$, R being the cell radius and γ being the path loss exponent. The constant k is for normalization.

Among the variables in the denominator of equation (11), the only variable that depends on the radius of the cell is the average path loss for the interference, ρ_{avg}, which we can model as:

$$\rho_{avg} = \rho_0\left(\frac{R}{R_0}\right)^{-\gamma} \tag{13}$$

where ρ_0 and R_0 are constants. Using equations (12) and (13) we can rewrite equation (11) as:

$$SINR_{avg} = \frac{kR_0{}^{-\gamma}P_{base}MR^{-\gamma}/N}{R^{-\gamma}N_{thermal} + P_{base}(1-\eta_{avg})(1+\beta_{avg})\rho_0R^{-\gamma}} \tag{14}$$

For instance, using equation (14) we can make the following observations.

If we increase the number of BS antennas by a factor of M, keep the total BS power constant, and keep the cell radius constant, then we can increase the number of users by a factor of M. (This assumes perfect downlink beam-forming. In reality the factor of M is somewhat reduced due to imperfect downlink beam-forming.) When we have increased the number of user per BS we cannot increase the radius of the cells. That would lower the S/I ratio at the user terminals.

However, if we increase the number of BS antennas by a factor of M, keep the total BS power constant, and keep the number of users constant, then we can increase the cell radius by at least a factor of $M^{1/\gamma}$. It can actually be increased more as the interference in the denominator is reduced.

If we increase the number of antennas by a factor of M and increase the total power of the BS by a factor of M (i.e. we keep the same power amplifiers), then we can simultaneously increase the number of users by a factor of M and increase the radius of the cells by a factor of $M^{1/\gamma}$.

The downlink coverage area gains are of course given by the square of the gains in cell radius.

The purpose here has been to show the more important relationships between the parameter sets, and the comments in § 9.2 on implementation factors are relevant. In practice, the adaptive antenna benefits may be taken in different permutations of these simple examples discussed, sometimes on different BS in the same area deployment.

5.2.4 Summary of results for CDMA systems

We summarize the impacts of adaptive antennas on the capacity and coverage of a CDMA system as follows:

– If we increase the number of uplink antennas by a factor of M, then the uplink capacity and coverage area increase by a factor of M and $M^{2/\gamma}$, respectively. These gains are achieved simultaneously.

– If we increase the number of downlink antennas by a factor of M but keep the total BS power constant, then we can either increase the downlink capacity by a factor proportional to M (M de-rated due to imperfect downlink beam-forming) or we can increase the downlink coverage area by a factor slightly higher than $M^{2/\gamma}$ (M de-rated due to imperfect downlink beam-forming).

– If we increase the number downlink antennas by a factor of M and increase the total power of the BS by a factor of M (i.e. keep the same power in the power amplifiers), then we can simultaneously increase the downlink capacity by a factor proportional to M (M de-rated due to imperfect downlink beam-forming) and increase the downlink coverage area by a factor proportional to $M^{2/\gamma}$ (M de-rated due to imperfect downlink beam-forming).

Although not analysed here, it can be shown that TDMA (e.g. GSM and ANSI-136) systems exhibit similar improvements in performance when adaptive antenna technologies are exploited.

6 Transmit diversity, interference handling

The above capacity and coverage effects do not include additional benefits that can be achieved from diversity. In the uplink, de-correlation among receive channels results in additional uplink capacity and coverage. In the downlink, de-correlation among transmit channels can, if adaptive antennas are combined with a transmit diversity scheme, improve downlink capacity and coverage. The antennas at the BS can be configured in order to maximize the benefits from both adaptive antennas and receive and transmit diversity.

The above capacity and coverage effects neglect the effect of active interferer suppression in the uplink and active interferer mitigation in the downlink. This will also increase capacity and coverage, especially when the network includes high data rate users.

7 Duplexing and algorithms

Unpaired or disaggregated frequency can be used by TDD only, and here the implications of TDD *per se* are very advantageous so long as the antenna weights are determined and updated sufficiently fast or the terminal is not moving excessively fast, since uplink and downlink use the same frequency channels. FDD frequency arrangements are generally more common historically, and it is anticipated that in the future greater use of TDD systems will be made to take advantage of the greater affinity of adaptive antenna systems to TDD and also to reflect the fact that traffic asymmetry may thereby be better accommodated.

There are a wide range of algorithms for implementing adaptive antennas, and recent advances in DSP technologies have been most advantageous in providing the ability to cope with various approaches to the eigen-vector problem. In the more sophisticated systems now deployed commercially the algorithms themselves are adjusted automatically over time, i.e. they learn/adapt to a lesser or greater extent [5].

8 Terminal applications

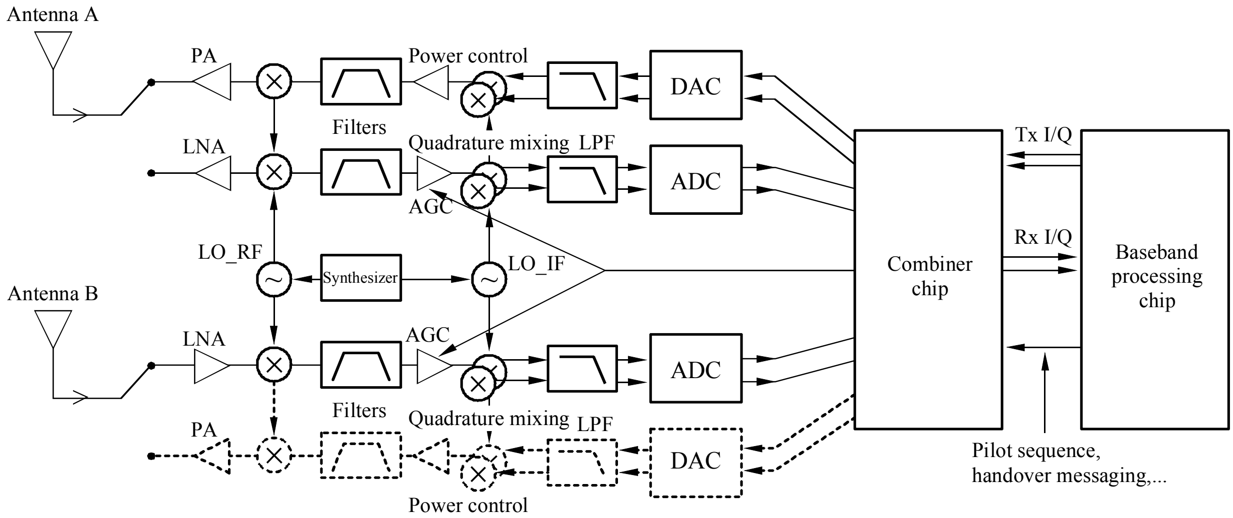
Many of the user terminals targeted are somewhat larger than customary handsets designed primarily for voice and limited data applications. For example many terminals will be laptop computers or similarly sized personal digital assistants and thus can more readily enable multiple antennas to be incorporated. However, it is possible with relatively small terminals to provide enough electro-magnetic separation and/or polarization de-correlation to make such designs feasible. A major design challenge is integrating the additional RF and control requirements to a significantly lower volume cost than is required for the BS case. This section describes one supplier's generic technology as applied to terminals, and is termed smart terminals.

The additional hardware components comprise: antenna, receiver chain, smart terminal technology chipset. Enabled only during call time and/or when there is a significant decrease in the quality of the call (lower FER), the addition of another receive chain increases the total power consumption of the terminal by only 2-3%. The power consumption of the additional chipset is negligible. Good results have been obtained with a mere 0.2 λ spacing (at 1.9 GHz) between two co-polarized (aligned) antennas. These results can be enhanced by having different types and/or polarization of antennas.

Figure 7 shows an example of a CDMA handset arrangement using this basic approach. Here the integration of the smart terminal solution has no impact on the protocols messaging, and there is no requirement to modify the current standards. The simple arrangement shown should not be taken as the only possible solution, however.

FIGURE 7

Handset example for CDMA



ADC: analogue to digital converter
AGC: automatic gain control
DAC: digital to analogue converter
LNA: low-noise amplifier
LO-IF: local oscillator – IF
LO-RF: local oscillator – RF
LPF: low-pass filter
PA: power amplifier

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The chipset needs to have access to some information from the baseband chip: pilot code, handover messaging, indication of the burst type, etc. In principle, any current air interface can be accommodated by this general approach, but it may be desirable to make minor changes/upgrades to software, RF chip sets etc. for best overall integration of the smart terminals.

This approach could be implemented not only on the receive side but also on the transmit side, bringing higher uplink data rate and improved battery life.

9 Spectral efficiency and deployment

9.1 Spectral efficiency and capacity gains

Overall the spectral efficiency as defined as bit/s/Hz/cell may commonly be increased by some 2 to potentially 15 times in practical deployed systems through use of adaptive antennas. Globally over 0.1 million adaptive antenna based BS have already been deployed for microwave terrestrial cellular mobile systems. Adaptive antenna systems may also be used for fixed applications such as fixed wireless access (FWA). Commonly some FWA systems use mobile-derived technologies, and even where deployed in spectrum formally allocated as FS, the accommodation of non-line-of-sight conditions is very important.

From the point of view of coverage estimations in RF cell planning procedures, it is worth remarking here that in this context it is the envelope (aggregation) of the cell/sector active antenna instantaneous patterns that is used rather than any particular selection of the latter. It is also most efficient for the RF link budgets for up- and downlinks to be arranged to be balanced, and for this it is of course necessary to properly take account of the appropriate values of diversity gain and spatial processing gain as described above and not just the passive gains of the antennas for each link.

Hitherto, standardization activities internationally have taken almost no account of the use, or optional use, of adaptive antennas, but this situation is expected to change rapidly in the near future since adaptive antennas appear to constitute a viable route to mitigating the very significant spectrum shortages likely for mobile services. Whereas such techniques as dynamic frequency selection and power control, different modulation schemes (including orthogonal frequency division multiplexing), software define radio (SDR) technology[2] and different system architectures are all useful, adaptive antennas can have a far more dramatic effect on total spectrum utilization, as shown in the following Table:

System	Capacity gains
PHS	2× to 15×
GSM/GPRS/EDGE	2× to 6×
CDMA/IS-95	2× to 8×
W-CDMA	2× to 8×

The right-hand column illustrates the gain in delivered capacity in the same, unmodified spectrum as that specified in the corresponding standard. As noted earlier, in most cases it is possible to integrate adaptive antenna technology into systems without recourse to modification to the extant standard in any way. However, especially for more complex systems, it can be advantageous to consider the incorporation, or potential incorporation, of such technology into the standardization preparation process at the earliest stage.

9.2 Implementation factors

In general the actual capacity gains and other benefits depend on the nature of the precise algorithms used and such factors as number of antenna elements; the element spacing and/or orientation; use of fully adaptive or switched beam arrangements; the loading; the degree of concentration and relative disposition of users across the area (inter-cell as well as intra-cell); the clutter and multipath scenario; the speed of travel of the users; whether TDD or FDD; for FDD, the duplex frequency separation; the implementation details of the DSP arrangements; whether of fixed (pre-defined) algorithm/s design, or having a degree of autonomous (dynamic) or operator-introduced learning to refine them, etc., see also § 4.7.

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[2] Many adaptive antenna designs today already utilize SDR approaches.

It should be understood that for the reasons given, it is not possible to set down benchmarks or relative criteria since there are many variables involved. The purpose of the figures tabulated is simply to illustrate that the implications of using adaptive antenna technology can be quite significant in some cases. In the more advantageous cases, frequency reuse figures can be as low as one third, and in this case of such fractional reuse some use the term "personal cell" or "spatial domain" to describe the notion of this degree of spatial selectivity.

10 Coexistence example (TDD/FDD)

The direct effect of adaptive antenna technology on coexistence is due to the fact that the RF energy radiated by transmitters is focused in specific areas of the cell and is not constant over time. This characteristic plays a major role in determining the likelihood of interference in coexistence scenarios. While an absolute worst case may look prohibitive, the statistical factor introduced by the use of adaptive antenna technology determines the percentage of time that the worst case happens. If this percentage is satisfactorily small, coexistence rules may be relaxed, thus helping the economics of the deployment. The example description presented here assumes that only the TDD BS use adaptive antennas.

10.1 Methodology

The following interference scenarios for coexistence of FDD and TDD systems would need to be considered.

Deterministic analysis:

1 FDD BS <-> TDD BS

2 TDD UE <-> FDD UE

Monte Carlo simulation:

3 TDD UE <-> FDD BS

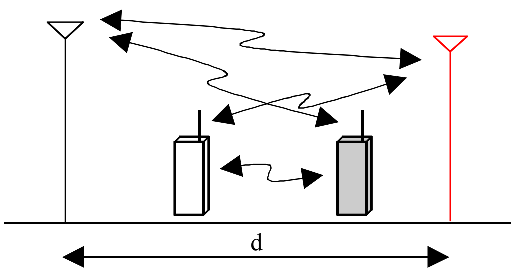
4 FDD UE <-> TDD BS

5 TDD UE <-> FDD UE

The scenarios are also depicted in Fig. 8. This Report addresses only the BS-BS scenario and does not take into consideration the affects of multipath.

FIGURE 8

Coexistance scenarios



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The analyses reported here are mostly done for the BS-BS macrocell case in both rural and urban areas, since previous analyses reported that the macro TDD BS-macro FDD BS interference was the most problematic case. The results are, however, easily extendable to micro and picocell cases involving BSs and user equipment (UE).

The adjacent channel effects are taken into consideration using adjacent channel interference ratio (ACIR).

$$ACIR = 10\log\left[\frac{1}{\frac{1}{ACLR}+\frac{1}{ACS}}\right] \qquad \text{dB}$$

where:

$ACLR$: adjacent channel leakage power ratio

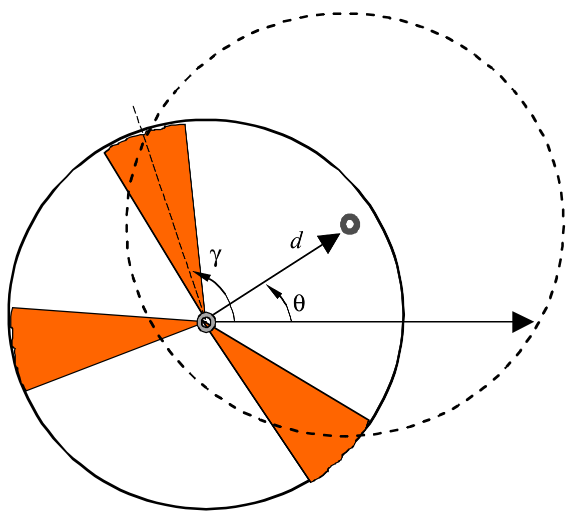
ACS: adjacent channel selectivity.

10.1.1 Statistical analysis

As described above, implementation of adaptive antenna technology at the BS requires statistical analysis. Therefore, scenario 1 is dealt with through Monte Carlo simulation. The statistical simulation of the adaptive antenna technology case is performed at a snapshot in time. The basic set up for the simulation in the horizontal plane is shown in Fig. 9.

FIGURE 9

Basic set up for the simulation horizontal plane



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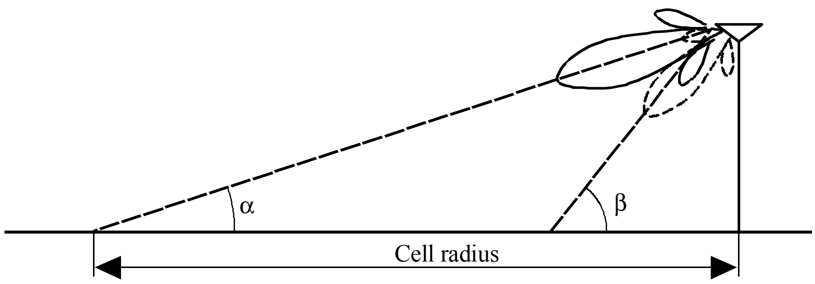
It is being assumed that during any given time slot on any carrier, one beam at the TDD BS with adaptive antennas illuminates each sector, thus affecting the victim FDD BS or UE, or vice versa, the FDD BS, shown in red, radiates its energy in space, thus affecting the TDD BS or UE. The distance between the two BS is set to be smaller than the larger of the two cell radii, presumably the FDD cell radius. It is assumed that the TDD BSs with adaptive antennas are located at random points within the FDD cell area, thus having a random distance *d* and angle θ to the FDD BS. The UEs are assumed to be uniformly distributed within the cell area. In Fig. 9, γ is the angular offset of the adaptive antennas' main beam relative to the same reference direction as that of angle θ.

In vertical plane, it is assumed that the adaptive antenna beams are distributed in the angular area between α and β as shown in Fig. 10. α is determined by cell radius and transmitter height while β is assumed as 45°. Both vertical and horizontal beam width of the adaptive antennas are assumed to be equal to 10°.

FIGURE 10

Basic set up for the simulation vertical plane



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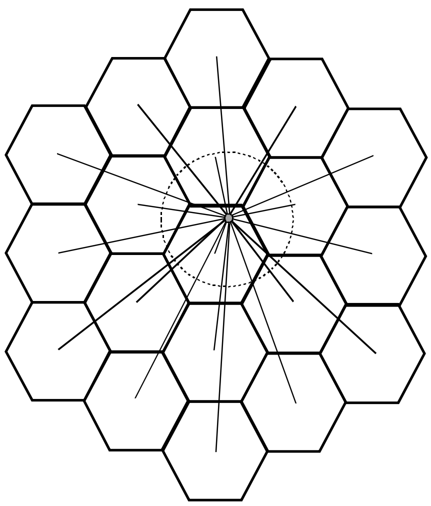
10.1.2 Network of cells

For the purpose of demonstrating the impact of adaptive antenna technology on coexistence, a network of 19 cells has been considered. Figure 11 depicts the network of 19 cells built around an interfering station.

FIGURE 11

Network of 19 interfering cells



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The BS density is based on [6]: cell radii of 4 km for rural/macro and 1.5 km for urban/macro have been assumed. Some comparative simulations were also performed with cell radii as low as 500 m and as high as 9 km. The contribution from interferers beyond the closest 19 is considered to be insignificant. The likelihood of interference is observed by assuming that at least 95% of the time the victim is protected (5% interference threshold).

10.1.3 Power control

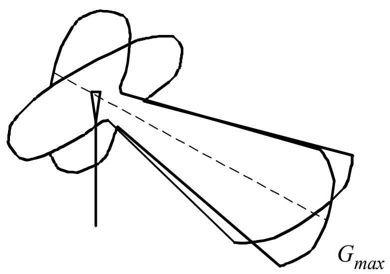
In all cases, the effect of perfect downlink and uplink power control is taken into consideration. In the downlink, this is implemented by lowering the transmit power of a TDD BS beam as the user moves closer to the BS to take advantage of reduced path loss. For simulations involving FDD network of cells, random values within the power control dynamic range of the FDD BS, as specified in [6], have been assumed. In the uplink, power control is implemented by lowering the transmit power of the UE as it moves closer to the BS.

10.1.4 BS antenna gain

Throughout, FDD BSs are considered to have a maximum gain of 15 dBi with a degree of down tilt such that the gain towards the horizon is reduced by 3 dB. For the TDD BSs utilizing adaptive antenna technology, however, each beam is modelled in E-plane and H-plane according to Fig. 12.

FIGURE 12

E-plane and H-plane cross-sections of the adaptive antenna beam



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10.1.5 UE beam-forming

With beam-forming capabilities, the amount of interference to/from other stations is reduced. Recent studies [7], [8] suggest that with two antenna positions at the UE, it is possible to create 90° beams with about 5.5 dBi gain and 10 dB front-to-back ratio. This produces significant gain in E_c/I_0 and if enhancing the link budget (coverage) is the goal, E_c improvement of up to 7 dB and received signal strength indicator improvement of up to 2.5 dB have been measured due to handset beam-forming [7].

10.2 Results

10.2.1 TDD BS -> FDD BS

Corresponding ACLR and ACS values for 5 MHz channel spacing are being used for interference from TDD BS to FDD BS and vice versa. It was determined that with acceptable interference threshold of –106 dBm to –114 dBm (rural areas) being met at least 95% of the time, using adaptive antenna technology at the BS causes the safe coexistence distance to be reduced significantly from 9.5 km to under 3 to 5 km.

10.2.2 FDD BS -> TDD BS

Using the interference protection criterion, safe coexistence is determined feasible at least 90% of the time for both urban and rural cells.

10.2.3 Summary of BS-BS case

The following Table summarizes the interference numbers for macro BS-BS case. It is evident that the use of adaptive antenna technology reduces the required additional isolation. The following Table shows the additional isolation required in less than 2% of the time in rural and urban areas using a dual-slope propagation model. The additional isolation, if necessary, can be easily achieved by coexistence-friendly site engineering practices.

Macro BS-BS interference

Scenario	Total interference power at 2% threshold (dBm) for rural (1)	Additional isolation required less than 2% of the time (dB) for rural(2)	Total interference power at 2% threshold (dBm) for urban(1)	Additional isolation required less than 2% of the time (dB) for urban(3)
TDD BS to FDD BS	–101	5 to 13	–86	9 to 14
FDD BS to TDD BS	–88	18 to 26	–81	14 to 19

(1) Assuming a dual-slope propagation model.

(2) Assuming –114 to –106 dBm maximum tolerated interference level.

(3) Assuming –100 to –95 dBm maximum tolerated interference level.

10.3 Conclusions from coexistence analysis

This implementation example indicates the potential for significant reduction in BS-BS interference through use of adaptive antenna technology, so that some coexistence cases otherwise impossible become potentially feasible. The additional isolation, if necessary, may be achievable by coexistence-friendly site engineering practices.

11 Overall summary

This Report has outlined many of the most important aspects of the use of adaptive antennas in cellular systems, together with specimen examples, and in particular:

– provided a model and analysis estimating the maximum capacity or spectral efficiency of a cell as a function of the frequency reuse factor in the network;

– illustrated the significant improvements that are possible in terms of coverage, interference mitigation and overall spectrum efficiency;

– described the several types of adaptive antenna types, and shown that even sub-unity reuse figures are possible;

– described how these techniques are now to be used in user terminals as well as BSs;

– noted the advantages of TDD over FDD in terms of obtaining spectrum efficiency;

– noted the potential benefits in terms of minimizing or eliminating cross-border coordination difficulties;

– noted that extant standards can be used without modification, and that selective, partial deployment of such base stations may be used mixed into larger conventional deployments.

12 References

This is not intended to be a comprehensive references set, but rather a selected set containing the most relevant material for this context.

[1] WINTERS, J. H. [February 1998] Smart antennas for wireless systems. *IEEE Personal Comm.* p. 23-7.

[2] ETSI TS 25 104 V4.2.0 (2001-9).

[3] RAPPAPORT, T. S. [1996] *Wireless Communications.* Prentice Hall.

[4] KIM, K. *et al.* [2000] *Handbook of CDMA system design, engineering and optimization.* Prentice Hall.

[5] TSOULOS, G. (ed.) [2001] *Adaptive antennas for wireless communications.* IEEE Press (this is an extensive, annotated collection of reprints).

[6] ERICSSON, M. *et al.* [September 2001] Capacity study for fixed multi-beam antenna systems in a mixed service WCDMA system. PIMRC 2001, International Symposium on Personal, Indoor and Mobile Radio Communication, San Diego, United States of America.

[7] EL ZOOGHBY, A. [October 2001] Potentials of smart antennas in CDMA systems and uplink improvements. *IEEE Ant. & Prop.*, Vol. 43, **5**.

[8] GORANSSON, B. *et al.* [September 2000] Advanced antenna systems for WCDMA: Link and system level results. PIMRC 2000, International Symposium on Personal, Indoor and Mobile Radio Communication, London, United Kingdom.

Bibliography

Array Comm. [18-19 October 2001] Adaptative antennas in evolving IMT-2000 and complementary systems. 3GPP Future Evolution Workshop, Helsinki, Finland.

BRANKA, V. and JINHONG, Y. [April 2003] *Space-Time Coding.* John Wiley & Sons Ltd.

International Engineering Consortium, On-line Smart Antenna Tutorial, http://www.iec.org/online/tutorials/smart_ant/.

JANANASWAMY, R. [2001] Radiowave propagation and smart antennas for wireless communications. Kluwer Academic Pub.

LAIHO, J. *et al.* [2002] *Radio network planning and optimization for UMTS.* Wiley.

LIBERTI, J. C. and RAPPAPORT, T. S. [1999] *Smart antennas for wireless communications.* Prentice Hall.

Practical Subscriber Unit Adaptive Antenna Array Feasibility and Performance for Use with DMM Mode, 3GPP2-C50-20001204-031, December 2000.

Proposal for Differential Measurement Metric (DMM) Multiplexed into Forward Power Control Sub-channel, 3GPP2-C50-20001204-030, December 2000.[3]

QI BI, *et al.* [January 2001] Wireless mobile communications at the start of the 21st Century. *IEEE Comm. Magazine.*

Annex 1

Glossary of relevant adaptive antenna terminology

– *Adaptive antenna system:* An array of antennas and associated signal processing that together is able to change its antenna radiation pattern dynamically to adjust to noise, interference and multipath. NOTE – Adaptive arrays form an infinite number of patterns (scenario-based) that are adjusted in real time.

– *Adaptive spatial processing:* An advanced signal processing technique that integrates a higher level of measurement and analysis of the scattering aspects of the RF environment to maximize the use of multiple antennas, combining signals in space in a method that transcends a one user-one beam methodology.

– *Diversity combining:* A technique of coherently combining the signals from multiple antennas to produce a gain. NOTE – Diversity combining uses all antenna elements at all times for each user, creating an antenna pattern that dynamically adjusts to the propagation environment.

– *Multi-beam antenna:* An antenna system that uses multiple beams at an antenna site for transmission and/or reception. NOTE – Multi-beam systems may or may not be adaptive.

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[3] The Third Generation Partnership Project 2 (3GPP2) is a collaborative third generation (3G) telecommunications standards-setting project comprising North American and Asian interests developing global specifications for ANSI/TIA/EIA-41 "Cellular Radiotelecommunication Intersystem Operations network evolution to 3G, and global specifications for the radio transmission technologies (RTTs) supported by ANSI/TIA/EIA-41. This and other 3GPP2 documents are available free by e-mail request to: secretariat@3gpp2.org.

– *Multiple input multiple output (MIMO):* A technique that utilizes multiple antennas on both ends of the transmit-receive path, i.e. at both the BS and the terminal in a wireless network.

– *Signal gain:* The increase in the desired signal strength resulting from combining inputs from multiple antennas to optimize available power required to establish given level of coverage.

– *Smart antennas:* A smart antenna system combines multiple antenna elements with a signal-processing capability to optimize its radiation and/or reception pattern automatically in response to the signal environment. NOTE – The two major categories of smart antennas, based on the choice of transmit strategy, are adaptive antennas and switched-beam antennas.

– *Space-time coding:* A transmit diversity technique that takes advantage of the spatial dimension by transmitting a number of data streams using multiple co-located antennas and uses various coding structures that exploit multipath effects in order to achieve very high spectral efficiencies.

– *Spatial diversity:* The composite information from the antenna array that is used to minimize fading and other undesirable effects of multipath propagation.

– *Spatial division multiple access (SDMA):* The use of smart antenna technology which employs advanced processing techniques to, in effect, locate and track fixed or mobile terminals, adaptively steering transmission signals toward users and away from interferers. NOTE – This scheme can adapt the frequency allocations to where the most users are located and achieves superior levels of interference suppression, making possible more efficient reuse of frequencies than the standard fixed hexagonal reuse patterns.

– *Steered-beam antenna system:* An approach that utilizes phased-array antennas, with multiple columns of antenna elements in pairs or equally spaced, to create a narrower beam directed only to the intended mobile on the forward link and steered with the mobile as it moves. NOTE – Steered-beam antenna systems are one form of adaptive antenna systems.

– *Switched-beam antenna system:* An antenna system that creates a number of fixed beams at an antenna site, allowing the receiver to select the beam that provides the greatest signal enhancement and interference reduction. NOTE – Switched beam systems form a finite number of fixed, predefined patterns or combining strategies (sectors).

– *Switched diversity:* A technique of switching the receive channel to one of multiple antennas to select the antenna with the maximum signal energy.