

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 multi-path 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

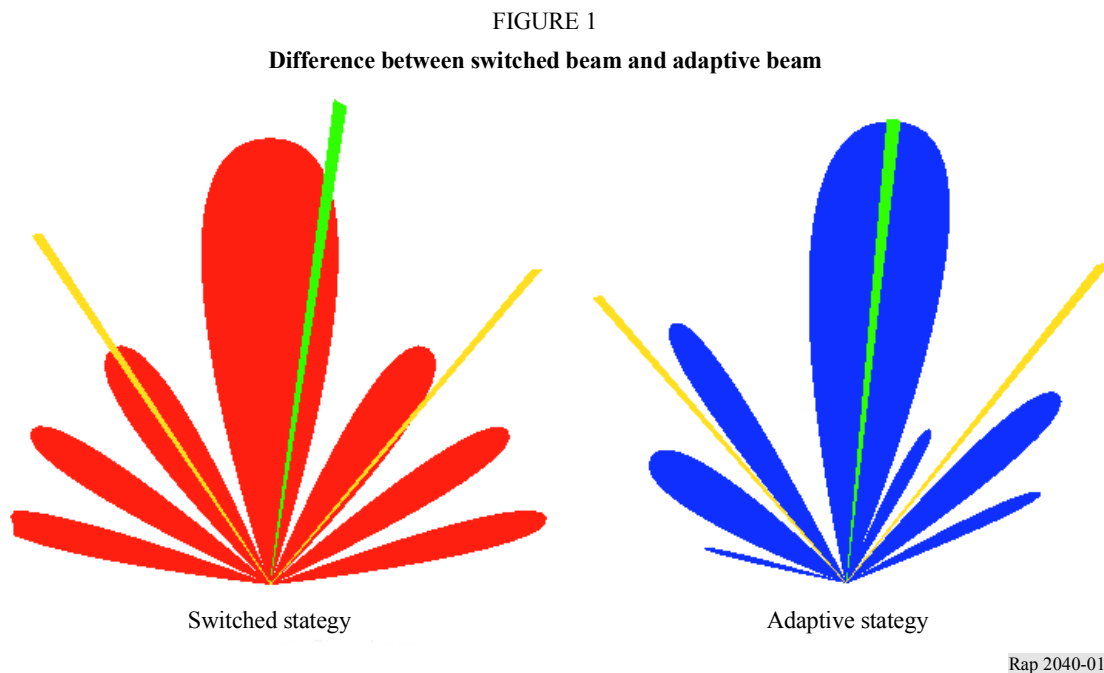
Switched-beam antenna systems form multiple fixed beams with heightened sensitivity in particular directions. These antenna systems detect signal strength, choosing from one of several predetermined, fixed beams, based on weighted combinations of antenna outputs with the greatest output power in the 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.



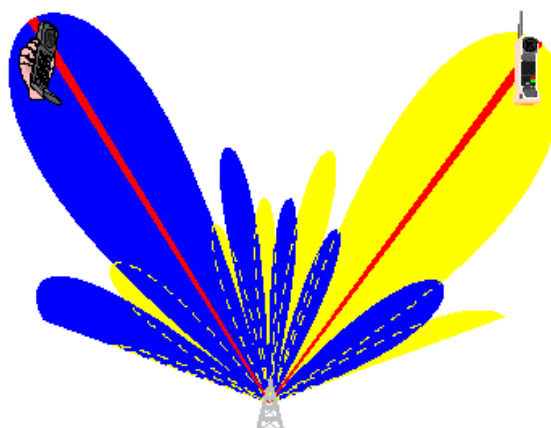
2.4.3 Spatial processing: the fully adaptive approach

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:

$$b = B/(NR)$$

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:

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

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

The aggregate cell capacity is then $(B/R) \times \log_2(1 + a \times \text{SINR}(R))$ and the network spectral efficiency is: $\eta = (1/R) \times \log_2(1 + a \times \text{SINR}(R))$, 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.

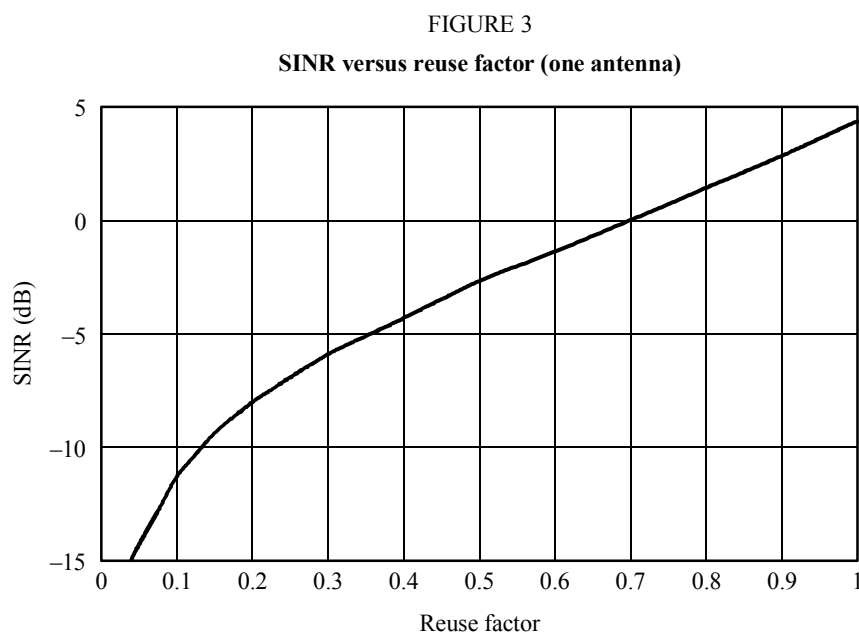
The analysis also considers the uplink only. To the extent that downlink SINRs differ from those of the uplink, the analysis should be considered approximate. There are many factors that determine the relative performance of uplink and downlink adaptive antenna processing, including the following:

- 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.



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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.

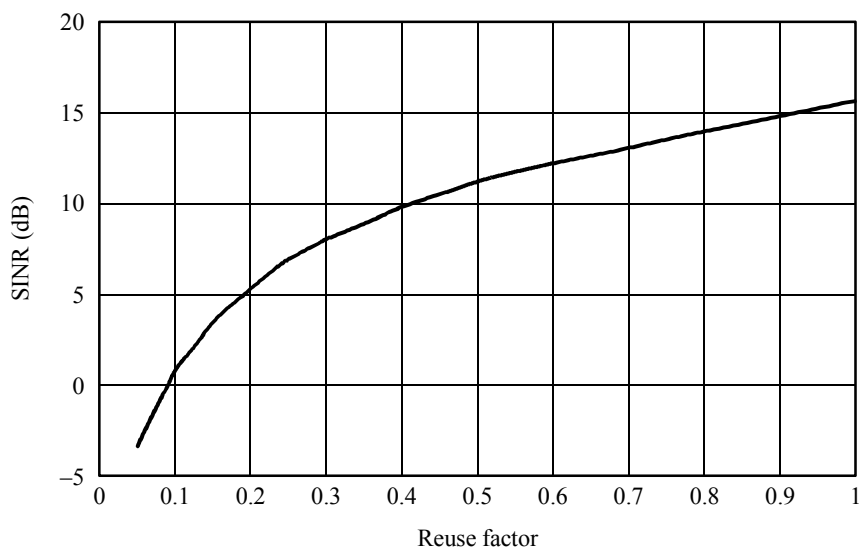
3.3.2 Example of adaptive antenna array with 12 elements

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



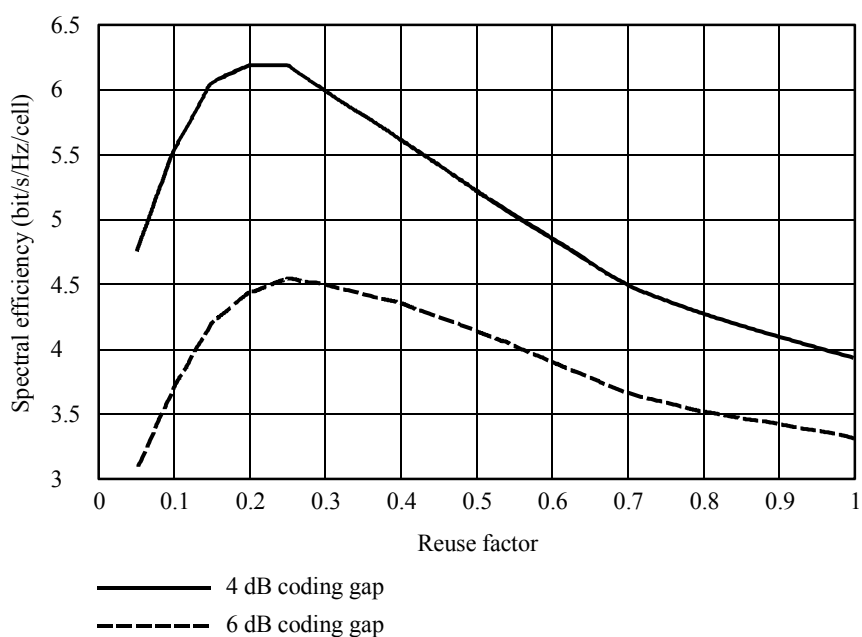
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3.3.3 Resulting spectral efficiency

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



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