Adaptive antennas

Veli Voipio 1900-02-14 10:12

HUT, IRC/Radio Laboratory

Table of contents

Abstract

In mobile communications there is a need to increase the channel capacity. The adaptive antenna has an intelligent control unit, so the antenna can follow the user, adapt to varying channel conditions and minimize the interference. Therefore there can be several users in the same channel in the same cell.

The concept of the adaptive antenna in communication systems is quite new, and requires a new way of thinking: the adaptive antenna is not merely a component any more. It is a system, made of an antenna array, receivers after antenna elements, and of a signal processing unit. It can be and integrated part of a multiuser receiver.

Fully adaptive antennas are not generally available yet, so this discussion about adaptive antennas tends to be quite theoretical, explaining what an adaptive antenna can do.

1. Introduction

In mobile communications there is a need to increase the channel capacity. One way is to direct the radiation pattern towards the desired signal. Therefore other signals in the same channel are separated if they come from other directions. Therefore the adaptive antenna provides spatial separation, or spatial filtering. Some sources are talking of space division multiple access. The term space division was originally used in wired telephone switching systems.

In addition to that, there is a possibility to reduce the interference coming from other directions by forming nulls in the radiation pattern towards the interferers.

Adding intelligent control, the antenna can follow the user, adapt to varying channel conditions and minimize the interference. The ultimate result is that there can be several users in the same channel in the same cell without disturbing each other.

The definitions in Kraus [21] page 497 are complicated, but a good to look at: "An *adaptive antenna* can steer the beam towards the existing signal and generate nulls towards undesired signals. Also, by suitable processing, performance may be further enhanced, giving *simulated patterns* of higher resolution and lower sidelobes (these exist only in the signal processing domain). In addition, by appropriate sampling and digitizing the signals at the terminals of each element and processing them with a computer, a very intelligent *smart antenna* can be built. Digital beamforming antennas can simultaneously direct *multiple* beams."

In this paper I am using the word "adaptive" in a wide sense, covering the definitions above: The adaptive antenna can do various kinds of antenna beam steering and beam shaping operations in order to improve the received input signal. In addition to that an adaptive antenna can track the direction of the desired signal coming to the antenna and simultaneously attenuate the interferences coming from other directions. An adaptive antenna may even separate two transmissions different directions, or even in the same direction, frequency and time slot at different spatial distances, or can it can put multipath propagation into positive use.

Still another definition: an adaptive antenna is a group of sensors and a signal processing system with an optimal combiner for a diversity receiver. This is a signal processing expert's view, but the ultimate result is the same.

The adaptive antenna has several advantages compared to ordinary antennas. The improvement of the spectral efficiency in cellular systems is widely appreciated. Spectral efficiency improvement up to three times while having minimal impact on the UMTS standard has been reported by Bull in [2]. Less transmitting power is needed, both uplink and downlink, so there is less interference on

others. The antenna also often gives an improved gain, and an extended range, as suggested by Flügel in [2] and Tsoulos [35].

Normally the adaptive process is applied to the uplink (from the mobile to the base station) signal reception only. In that case the mobile unit consumes less transmission power, and the operational time of the battery is extended. But the benefits of adaptation are very limited, if no beamforming is applied in the downlink transmission (from the base station to the mobile).

Physically an adaptive antenna looks very much like an ordinary antenna, but has built-in electronics and control software. It co-operates with the receiver's adaptive control system in real time. It may also communicate interactively with the cellular radio network control system.

Smart antenna and intelligent antenna are often used just as synonyms for the adaptive antenna. Commercial ads use the term "smart" quite liberally, and a "smart antenna" may not be anything else than an antenna with several narrow switched beams.

Adaptive antennas are easiest to implement in land mobile base stations and in vehicle installed units. Handheld systems have size limitations. A handset can have two antennas, and it may help – compare that two ears has an advantage over one in hearing acoustic signals. And the ears are relatively close to each other compared to the wavelengths we hear!

The future satellite systems could make use of the digital beamforming antennas, both in satellites [2] and in land fixed and mobile units [18]. In the LEO satellite systems the array antenna with signal processing could compensate the changes of the direction of the communication caused by the movements of the satellites and the mobile [26]. The interference canceling function may not need be implemented.

Little information has been published about the early use of the adaptive antennas, since the main applications were intended for the military use. The main goal was to reduce the malevolent interferences during the cold war. The earliest systems stand from 1930s and they were large, complex and expensive installations based on the vacuum tube technology.

The research for communication applications has been active in 1990s. But there are probably only provisional applications in use in cellular systems.

2. Antenna system aspects

2.1 Mechanical structure

All the modern systems are based on antenna arrays. The element amplitudes and phases are adjusted (weighted), electronically to generate desired radiation patterns. A phase frontier is generated by a linearly changing the phase differ-

ence in the elements in the array. Actually, for wideband arrays a delay-controlled array is better than a phased array, otherwise different frequencies go to different directions, see page 1206 in [12].
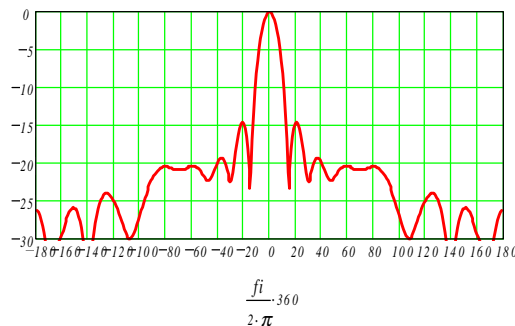
Direction of the wavefront
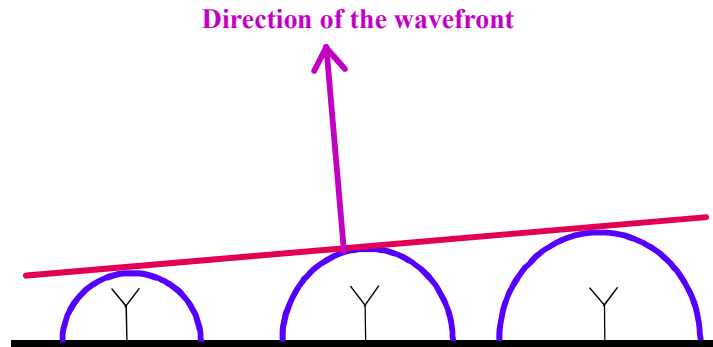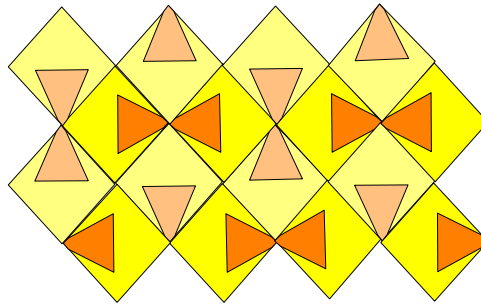
Phasing and wavefront illustrated

The radiation pattern has sidelobes, nulls in addition to the main beam. If the element spacing is over half wavelength, then grating lobes and grating nulls may appear.
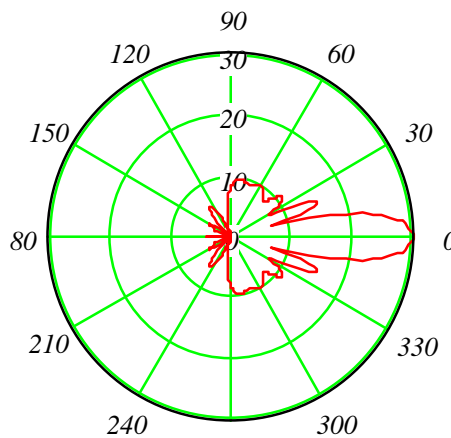
Radiation pattern in a polar plot

$$\frac{fi}{2 \cdot \pi} \cdot 360$$

Radiation pattern in a rectangular plot

An example of special kind of array, made of triangular patch elements in a square ground plate, 2x4 array, 2 polarizations

2.2 Diversity

Diversity is an inherent part of an adaptive antenna, therefore it is shortly mentioned here:

The multipath propagation causes correlated interference that produces fading. Diversity helps to overcome the effects of fading by providing two or more uncorrelated received signals of the transmitted signal. Some of the diversity types are:

- Space or antenna diversity: the antenna elements cover a large area, up to $40 \cdot \lambda$.

- Direction or angle (of arrival) diversity: reception from different directions.

- Polarization diversity: reception of two orthogonal polarizations. This diversity scheme might become important in the mobile handsets.

- Time diversity: for example interleaving over the timeslots in GSM.

- Macrodiversity means that several base stations communicate with the mobile.

- Spread spectrum systems (frequency hopping or direct-sequence type) provide frequency diversity.

Diversity reception requires appropriate combination. Selection combining is the simplest one. Equal gain combining and is also common. Maximum ratio combining is practically same as an adaptive antenna. Channel equalization can be seen as implicit multipath diversity combining. RAKE receiver multipath reception can be used in CDMA spread spectrum systems to alleviate the effects of frequency selective fading within the bandwidth.

2.3 Beamforming: pointing and nulling

The electronic beam steering (beam pointing) does the same as the beam switching. Beamforming is a more advanced process: the antenna can generate one ore more beams towards the desired signal paths, and nulls toward the undesired signal directions. In that sense it is also a spatial filter.
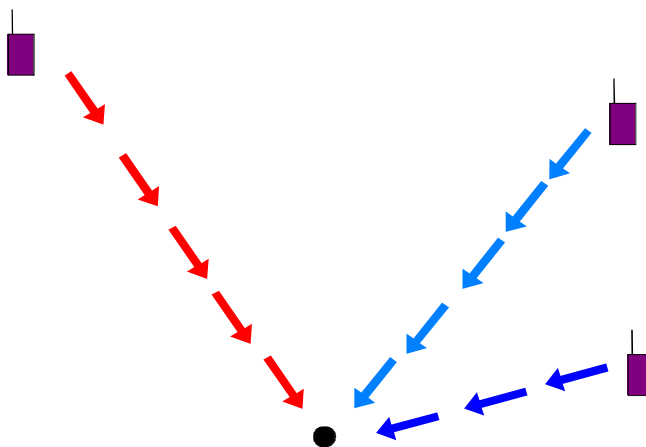
A situation where beam pointing and nulling can be used

In some cases the antenna may have an omnidirectional pattern and just form nulls when necessary. This will make null forming easier but increases the thermal noise level.
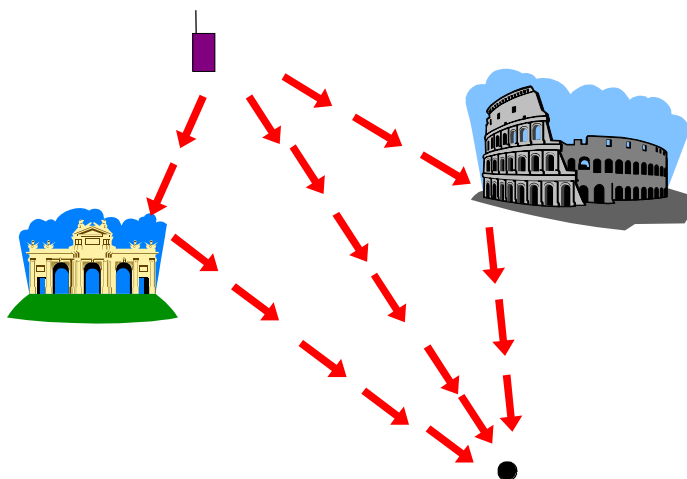
Multipath reception: selecting one beam or combining beams

Theoretically possible adaptive antenna radiation patterns for multipath reception and interference canceling The antenna can produce a pattern that has several main lobes, according to the multipath components. The problem is that the incoming signals may cancel each other. Better, but also more complex, is to make separate

patterns for each path and then combine the signals with an equalizer or RAKE receiver.

Customarily the nulls in an antenna radiation pattern are quite narrow. That does not help if the path spread is wide. In order to attenuate interference coming from a widespread angle the antenna can set several narrow-angle nulls side by side. In the mobile communications the angular path spread is about 10°. Attenuating it may require 3..5 narrow nulls. If N is the number of elements, it means that N-1 narrowbeam interferers can be canceled. But when wide angles are attenuated with multiple nulls, then there are less nulls available for the rest of the interferers.

One problem is that the position of the nulls in a phased array changes with frequency, which is a problem in wideband systems.

The beamforming in the array is controlled by modifying the amplitude and phase of the elements, and the beamforming network combines the signals. There are two types of beamforming networks: The element-space network generates radiation patterns for each receiver input. The beam-space processing generates beams that are used by the receiver in a selective way through weights [27].

Superresolution is a digital signal processing (DSP) technique. The beam is like an inverted null, and that kind of beam is very narrow. The disadvantage is that it is sensitive to noise, and also to unknown sensor gain and phase variations across the array aperture [8].

Superdirectivity or supergain could be considered in mobile sets. In that case the antenna group is small. But it requires accurate driver units to control the currents in the elements, and some currents are very high, so the power consumption rules out the use of superdirectivity in practice [21].

2.4 Adaptability

The adaptive antenna uses all parameters available coming from antennas, seen as arbitrarily positioned sensors. It can be seen as beamforming, but also as optimal combining of the signals received by different antenna elements. **The goal of the antenna system is to minimize the bit error rate using digital signal processing**. The processing goes as follows:

The detector after the antenna and the RF amplifier circuits are phase-sensitive, normally of the I/Q type and therefore the baseband signal retains the phase information in addition to the amplitude information. After A/D conversion the signal can be processed any desired way by using software algorithms, provided the processor is fast enough. The output is a combination of the antenna inputs in amplitude and phase. *Once the input is in digital form, it is available to several beamformers and receivers without loss of the signal quality.*

In addition to the antenna electronics, there are other parts in the reception system contributing to the antenna functions. An equalizer or a RAKE receiver provide recovery of the multipath components on the temporal axis. The receiver module gives the bit error rate information for the control unit as a feedback. The control unit optimizes the antenna elements input by modifying the received amplitude and phase. The control unit can make use of other available system information, like network traffic statistics, known user behavior etc., to enhance the basic adaptive antenna control.

The adaptive antenna can select one of the multipath components for reception. On the other hand, the adaptive antenna can constructively use multipath signals coming from different directions at different timepoints. It generates several antenna beams for one user channel. An equalizer or a RAKE receiver are also needed.

In CDMA systems the users are separated by code. It means that the interference cancellation and multiuser detection techniques can be used to cancel the interference caused by other users. Spatial interference cancellation means that if a strong interference is coming in the same direction as the desired signal and if the interfering signal is simultaneously coming from a different direction, it can be used to cancel itself. Therefore the detection of the desired signal becomes easier. Man-made noise, like the interference by other mobile units tends to be directional [22]. Thus the direction of an unknown or undetected signal can be used to identify the interference.
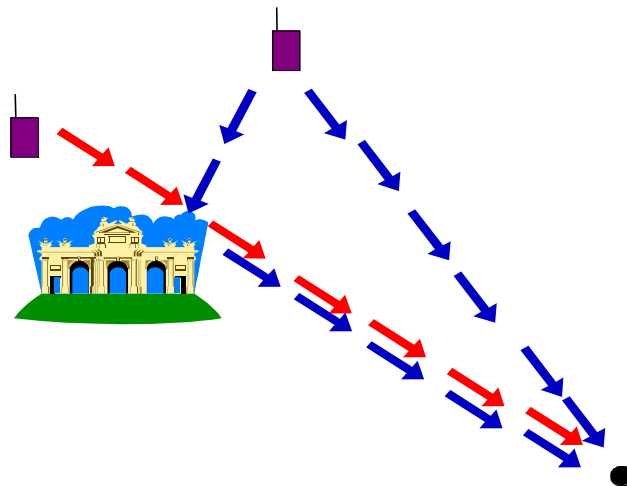
Canceling the interference from the desired signal

The adaptive base stations also improve reliability of the network in failure situations, since closely situated base stations are able to cover the faulty one in between them to some extent without special arrangements.

The interfering units move and change frequencies with the movement of the mobile stations and with the handovers at the neighboring base stations. GSM and also future personal communications systems have dynamic channel alloca-

tion, for example they make use of the pauses in the speech. This all means that the interference sources can be short-lived and the interference pattern changes often - consequently the adaptation process must be quick. Frequency hopping requires that the adaptation should happen well within the time slot of a TDMA system, preferably within the synchronizing header of the burst. Using the adaptive antenna in a mobile unit means that the antenna must compensate the directional changes in the antenna pattern which also requires fast antenna operation.

2.5 Direction of arrival and distance separation

The direction of arrival can be estimated if the antenna array parameters are well known. These parameters should also be regularly checked and the system consequently calibrated.

If two pulses come the same direction, they can be separated by distance. The bandwidth of the signal affects the accuracy. With bandwidth of 5MHz the accuracy of the separation would be around 60m. But the location is very difficult to interpret in the urban area because of the possible lack of the line-of-sight signal, and because of the time and angle dispersion caused by the diffraction and multipath propagation. With continuous signals this effect cannot be used directly, but the space-time processing in multiuser detection, particularly RAKE receiver type systems make use of it [30].

In macrodiversity systems the location of the mobiles can be determined by triangulation.

2.6 Adaptation in transmitting

Normally the adaptive antenna is used in the receivers only, as a postprocessing system. But to make full use of the spatial separation, one should use some sort of adaptability in the transmitting side. The benefit is that the interference to other directions will be much lower and the system capacity will be higher.

The adaptive transmitting antenna can control both the phase and the amplitude of the signal fed to each element, so it is capable to replicate the received signal pattern exactly when transmitting. But in most systems the transmission frequency is different than the received frequency, and consequently the interference situation in transmission is not same as in reception. In addition to that, the uplink and downlink radio paths don't correlate in multipath environment when they have different frequencies, affecting particularly the fading.

The reflections that cause the strong components of the angle spread and negligible delay spread, are near the receiving end. It is not useful to reproduce those near reflection components in the transmission [5].

One approach is to estimate directions from the received signals since uplink weights cannot be directly reused in the downlink because of the frequency dif-

ference in the duplex channels [11], [2]. If the adaptive system can estimate of the direction of arrival of the received signal from the mobile, then it is possible to point a single antenna beam towards the mobile. It is simpler than beam-forming or adaptation, but probably a sufficient method in transmission.

The use of time-division duplex (TDD) has also been suggested for CDMA. TDD means that the same frequency is used in the transmission and the reception, in different time slots. Then only the base station needs to estimate the received channel impulse response and the mobile can have a simpler receiver. When transmitting, the base station multiplies the signal to be sent to a user by the time-inverted complex conjugate of the received channel impulse response. This is a kind of "Pre-RAKE" system. But, if the system bandwidth is asymmetric (using a wider bandwidth in the transmission, like in the Internet applications), then this scheme may not work out. In TDD it is also possible to allocate time slots asymmetrically, provided the channel does not change too rapidly.

One problem in the adaptive antennas is that they **don't attempt to minimize the sidelobes** when adapting in reception. This is one reason why the same weight pattern in transmission should be used only after verifying that there are no high sidelobes.

There has been some research regarding the adaptive transmission with the feedback, using a "probing" mode, during which probing signals received at the mobiles are fed back to the transmitter [8].These probing signals are used to identify an unknown propagation environment, enabling the transmitter to form the necessary transmission beam patterns. It may be too slow for mobile systems. A "radar" type approach has also been published [5], where the signal is not sent towards the nearby reflectors.

2.7 Channel characterization

It is important to develop a good knowledge of the radio channel behavior in order to design an optimal adaptive antenna system. Various statistical rules of thumb are available and computer simulations are being done. The most accurate information comes from the actual measurements. One example of a measuring system is the fast wideband channel sounder which is under development in HUT radio laboratory [1]. For the spread-spectrum channels the measurement system should be able to measure frequency-selective multipath fading. One interesting article about the channel modeling is in [37] .

Outdoors phenomena are: path loss caused by the distance, shadowing for the non-line-of-sight situations, and fading caused by the multipath effects. Doppler effect is caused by the speed of the mobile.

There is not much information available about the mobile channel, but for a system design one could estimate (using [23]) that in a suburban setting the

path channel spread is 5°, and a 10° antenna beam will include most beams in urban areas. Normally there is a main channel direction, but not always in the line-of-sight direction. For the antenna structure, the cross-polarization discrimination requirement is around 6-10 dB. The sidelobe level requirement might be -10 dB.
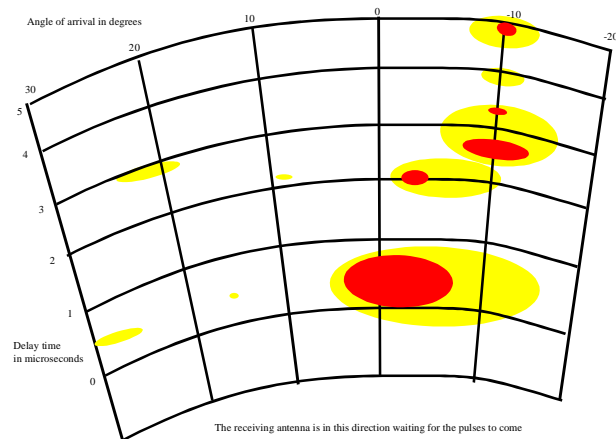
A pulse after multipath propagation channel, angle versus time domain, redrawn using the data in 19

Regarding wireless LAN systems indoors, there are several multipath components in progress and the first reflections are almost equally strong. Fan propellers may cause fast-changing Doppler effects. All that gives additional problems to the system design. A code-division multiple access system with an adaptive antenna might overcome those problems.

Channel simulation is one possible way to find insight to the channel behavior. Ray tracing is being used in mobile systems. In indoors systems, at least in small rooms, the FDTD method has been used successfully***Ray tracing is used in microcell environments [14]. In indoor systems in small rooms the FDTD method has been used [33].

2.8 Cellular network system

The adaptive antenna makes possible to use space division multiple access (SDMA). It means that the same system can allocate the same channel (frequency and time slot) for several users in the same cell. This could change the nature of the network frequency planning. The cell coverage might grow 10%, pages 101-104 in [14]. SDMA may work in larger outdoor cells, but not in indoor cells, when there are several equally strong multipaths. An adaptive antenna may still be useful in indoor cells, helping in CDMA detection.

The multiuser detection, which is an inherent part of the CDMA system, also helps in spatial interference canceling. One can add other intelligence in the network. For example the vehicle locations or movements can be predicted to

some extent, and that information could be added to speed up the adaptation process.

3. Building blocks of the adaptive antenna system

3.1 Antenna structures

Military adaptive antennas used to be bulky, complex and expensive. Nowadays the advances in microelectronics and computing make it possible to manufacture small and reasonably priced commercial applications. The antenna is expected to match these qualities of the microelectronics. Microstrip patch antenna arrays have small size and low profile, and they are suitable for serial production, so they are often suggested for adaptive antennas. On the other hand, the patch antenna arrays have several problems to overcome: narrow bandwidth, low cross-polarization separation, sensitivity to variations in manufacture, surface waves, and sometimes low efficiency.

The base station the antenna can be large, although the tendency is towards small ones. Monopoles and dipoles are widely used, but microstrip patch antennas are becoming more popular. A small base station can be installed on a wall in a briefcase-sized box, and a patch antenna array is an integral part of it, fitted on the largest surface of the box.

The array structure could be linear, planar, cylindrical, or spherical. A spherical array or a cylindrical array with a ground plane may be feasible if the antenna element is directional, like a microstrip patch antenna element [25]. The array can be sparse (having wide element spacing), since the adaptive processing can minimize the effects of the grating lobes.

The antenna array inherently has some space diversity because of the size. The diversity reception in the rural area requires $\lambda \cdot 5 ... \lambda \cdot 40$ spacing, which means up to a 12m antenna dimension for 1GHz. Increasing the size just achieve diversity gain is normally not practical in cellular systems using compact base stations.

The array should have antennas in two orthogonal polarizations with sufficient cross-polarization discrimination in order to make use of the polarization diversity.

The array itself could be linear, planar, cylindrical, or spherical. A spherical array or a cylindrical array with a ground plane may be feasible if the antenna element is directional, like a microstrip patch antenna element [25]. As I see it, a cylindrical array might be feasible when the angular spread is large, especially in micro- and picocells (page 54, table 1 in [30]).

Cylindrical antenna array made of directive elements

The array can be sparse, since the adaptive processing can minimize the effects of the grating lobes, even when the grating lobes are quite high, as long the grating lobes don't point towards interferences. The grating lobes add to the noise level, but in an interference limited communication environment it is less important. Grating nulls may appear towards desired directions. The sparse antenna can have a narrow main beam, and the mutual coupling effects between elements are reduced.

Mobile handheld antennas, like in the personal handheld phones, palmtop or laptop computers cause limitations in adaptive antenna design. The physical size of the handheld units is small, but the antenna array system works better if it is large. In the smallest systems the polarization diversity may be the only effective improvement over the ordinary antenna.

Mobile vehicular antenna setup has various limitations and possibilities: Cars may need to be designed so that the antennas can be hidden in favorable positions from the communications point of view. Trucks are much easier: large surfaces and sufficient height is available.

Airplanes and hot air balloons require a narrow beampointing when flying above the cellular system. Satellite antennas in ships will need adaptive antennas that compensate the movement caused by the sea waves. Trains may require very fast-moving beams. Helmets are being used in many places, like at building work (construction sites), motorcycle or military. A helmet could give a reasonable base for an adaptive array.

3.2 Transceiver technology in adaptive antennas

The phased array antenna can direct the beam electronically. This based on the ability to control the amplitude and phase of the individual antenna elements. The scan angle depends on the phasing and the element spacing compared to the wavelength. Amplitude control is implemented using amplifiers with gain control, or with digital multiplication. The phase control is more complicated.

The phase shifting can be done using analogue phase shifters but it works well for one beam only. Currently the beamforming electronics is moving from RF phase shifting to baseband digital signal processing [27].
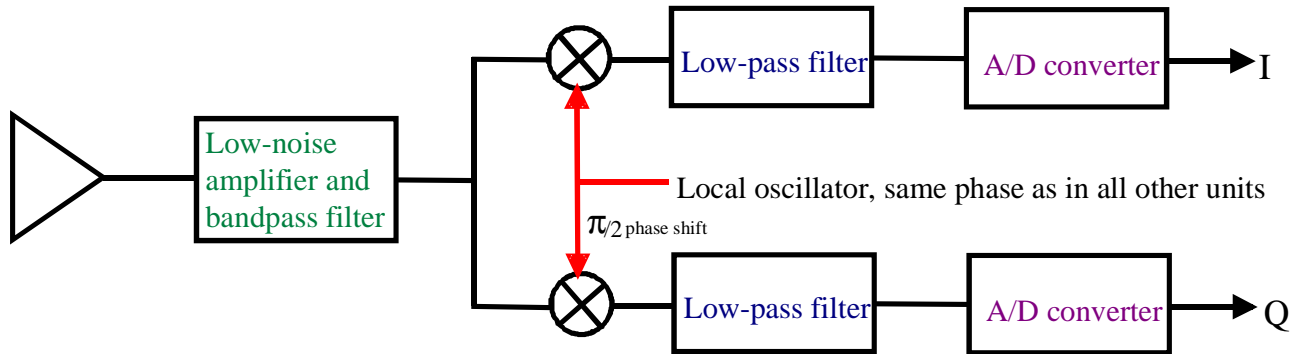
Single-down-conversion elemental receiver for an adaptive antenna
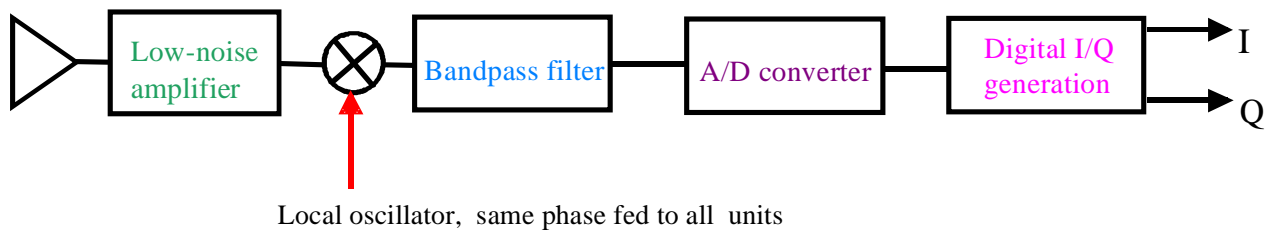
Receiver with digital I/Q generation

The digital processing of the received individual element signals allows full flexibility in the signal processing, so that optimal element patterns can be created for all channels using delay-controlled beamforming and after that the digital I/Q generation and multiuser detection .

The requirements on sensor and receiver calibration, mutual coupling, phase stability, dynamic range etc. become increasingly more rigorous with higher performance specifications [22]. The adaptive system inherently tends to compensate nonidealities in the antenna hardware, like the mutual coupling between antenna array elements [32]. If the beamforming in the transmission is important, the antenna hardware should be well calibrated. An external calibration signal is useful. One open question currently is what is the optimal time interval between calibrations.

Doppler shift is also an area of interest. Would it be possible or necessary that the receiver compensates for the Doppler shift for the rays from different directions? This would require that the adaptive antenna makes different beams for different signal component directions, and that the different signal components would be downconverted separately. Then after downconversion there is an equalizer or a RAKE receiver combining the signal components. If there are separate beams, the Doppler shift information might reveal also tangential

speed and direction, so that the antenna can better predict the movement of the beam?

3.3 Adaptive control

The signals received by the elements are multiplied with complex weights and then added together in order to produce the spatially filtered signal. In other words, the amplification and the phase shift of the signals from the different elements are determined by a signal processor. The control unit assigns the values for the weights for each channel. The controlling unit can be preprogrammed, but normally it uses appropriate search algorithms (like LMS) or neural networks [21], [22].

The control unit uses a multidimensional search algorithm to maximize the signal to interference and noise ratio. In digital systems it means minimizing the bit error ratio (BER). When seen as a beamforming process, the algorithm sets the nulls towards the interferences while the main beam stays towards the signal direction as much as possible.

The adaptive methods are broadly divided into spectral-based (beamforming) and parametric (maximum likelihood) methods. Three types of methods deserve mentioning here: *steering vector based methods*, *reference signal based methods* and *blind algorithms*. The main difference between these algorithms is that the first one exploits the array response information and thus requires precise knowledge of the array properties. The last two ones are insensitive to the imperfections in the array geometry or to the mutual coupling effects between elements.

The *steering vector based methods* require either the employment of a Direction of Arrival (DOA) estimation procedure or some other a priori information about the mobile transmitter locations (useful if line-of-sight channel exists). One example of this kind of method is the Howells-Applebaum beamformer.

The *reference signal based methods* consist of the Least Mean Square (LMS) algorithm and its variants. They are based on minimization of the mean square error between the received signal and the reference signal. Thus a reference signal having a high correlation with the desired signal has to be generated. In digital systems a training sequence can be applied in each transmitting unit for that purpose.

LMS-algorithm, Stepsize = 5.0e-004, Number of Samples = 6000, simulations = 50
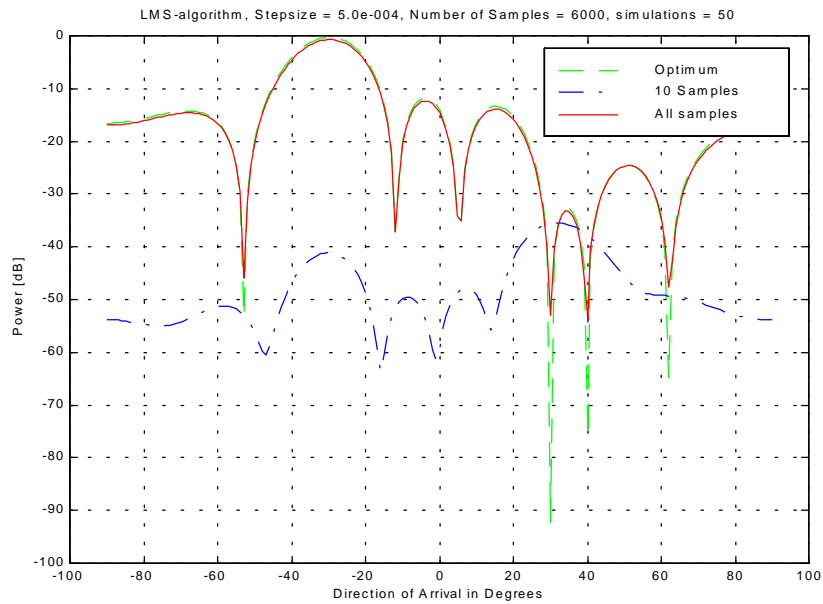
LMS beamforming: The beamform after 10 simulations is shown, and the beamform after all the simulations is shown. The beamform can be seen approaching the optimum beamform. The desired signal is coming from the -30° direction. The interference 1 is coming from the 30° direction and it is 25 dB above the signal level. The interference 2 is coming from the 40° direction and it is 15 dB above the signal level.

LMS-algorithm, Stepsize = 5.0e-004, Number of Samples = 6000, simulations = 50
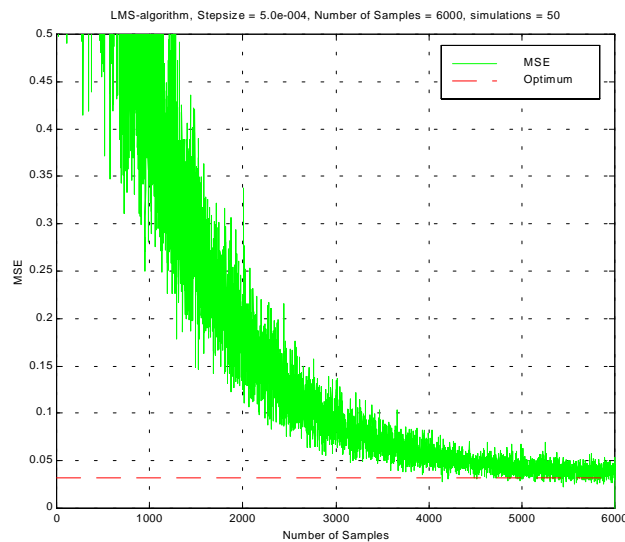
The mean square error of the output signal from the antenna after the adaptive beamformer, compared to the reference signal. The curve is comparable to the S/N or BER ratio, showing the improvement of the reception .The optimum level is at the 15 dB S/(I+N) level. There are two interferers at 25 dB and 15 dB levels.

The 40 dB improvement in the SINR is remarkable in the figure above, but it assumes that the angular spread is very narrow.

The *blind algorithms* generate the reference signal from the array output signal. The initialization of the weights is random, and thus the algorithms may not converge to the desired solution. The system may have several local minimal and it may not find the global minimum in the system. The most important blind algorithms are constant modulus, decision-directed algorithm, and cyclostationary algorithms.

If the interference is stronger than the desired signal, the adaptive process is capable of finding the desired signal. But a conventional adaptive process may suffer by the problems caused by the multipath propagation, so that undesired cancellation may occur [22].

The adaptive process must be fast in order to cope with the mobile situations. There can be quick changes, for example a big truck can block the line of sight between the pedestrian and the base station.

3.4 Detection and multiuser detection

In GSM and similar cellular systems there is only one user using one channel within a cell and neighboring cells. The received signal consists of multipath components of the desired signal. Because it is a narrowband system, equalizers can be used to reduce the intersymbol interference and to combine the energy of the multipath components [30][32].

In CDMA several users are using the same channel in the cell and the neighboring cells. CDMA can separate signals using the code. Because it is normally a wideband system, the delays are larger than the chip duration, so a RAKE receiver can be used to combine the energy of the multipath components [32].

In the multipath situation the adaptive antenna can make one sharp beam, and that will reduce the multipath components and consequently reduce the processing load in the equalizer. Or the adaptive antenna can make a multiple main lobe beam pattern in order to receive the desired components and then the equalizer can do its work like in the case of the single antenna, except facing less interference. If the adaptive antenna makes different beams for different signal component directions, then the equalizer or the RAKE receiver can work in optimal conditions.

The main problem in CDMA reception is caused by the unequal received signal powers. The adaptive antenna can help significantly in this situation. If there is no adaptive antenna, multiuser detection can help [29]. This kind of detection takes advantage of the knowledge of the other users' spreading codes. Explaining the multiuser detection system I could put it out in simple words, according to [2], page 95: "The system detects the strongest signal first, then reconstructs it and subtracts it from the input signal, thus canceling out the strongest user. Then the second strongest signal can be detected, reconstructed, subtracted, and so on, until all signals above the noise level are detected". This is called suc-

cessive processing. In practice, also parallel processing employing matrix operations can be used, or a combination of parallel and successive processing.

As I see it, combining the adaptive antenna, channel estimation and multiuser reception would provide the best functionality. The antenna will make a different beam to different signal components, and the multiuser detection will separate the signals of different users while combining multipath components of the same user.
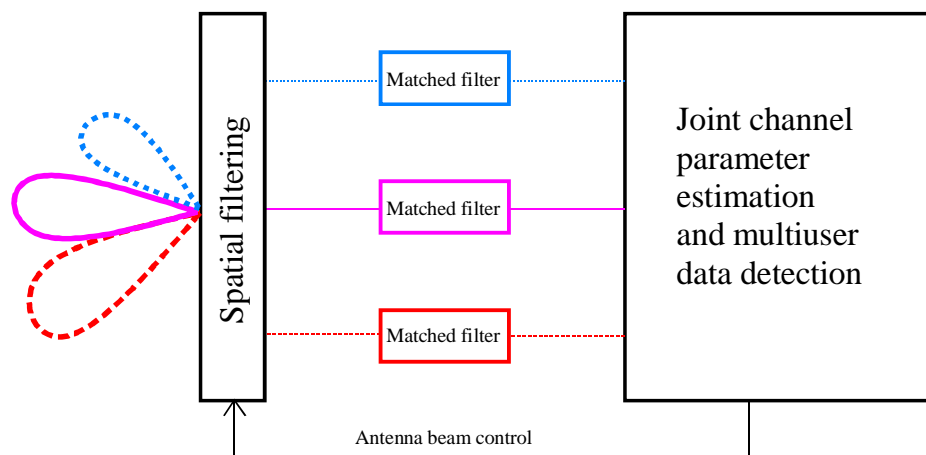
Sketch of a combined adaptive antenna, channel estimation and multiuser detection system. There are different adaptive antenna beams for different users and possibly also for different multipath components.

4. Existing commercial systems and academic research groups

Here is a list of information that I have gathered:

Commercial companies doing research and advertising their products:

- ArrayComm (Intellicell, transparent to digital access methods, PCS 1900 trial in 1996)

- Celwave (12-beam switched beam, adaptive SmartSystem possibly coming in 1997)

- Hagenuk (in Tsunami project) [35]

- Metawave (directional system)

- Mitsubishi (doing research in digital beamforming antennas)

- Northern telecom (SmartBTS)

- Rafael (In USA and Israel)

- Raytheon (DIVERSITY)

- Sinclair

- Thomson (adaptive antenna, AMSAR project).

Academic research groups:

- Aalborg (Tsunami, an EU project)

- MacMaster University, CRL project (Canada, John Litva)

- MPRG (GloMo, Virginia)

- Stanford University (Smart antenna research group, California)

- TU-Wien (Josef Fuhl, adaptive antennas)

- University of Kansas

As far as I know, no one is manufacturing and selling adaptive antennas in the commercial scale yet.

5. Summary

The adaptive antenna concept is very interesting and promising area, and a considerable amount of academic and industrial research is focused on it. The main advantage is the effective use of the radio frequency resources, and the other advantage is the reduction of electromagnetic radiation. The adaptive antenna systems are complex, large, and currently still expensive. The commercial products will probably be available within few years.

References and bibliography

As I could recommend for this audience, the best book I know is [27]. The best articles about the array signal processing are written by Paulraj [30], Krim [22] and Godard [11][12]. [4] and [16] are good general books about adaptive antenna signal processing. [37] gives an introduction to the radio channel aspects.

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