Enhancing cellular network capacity with adaptive antennas

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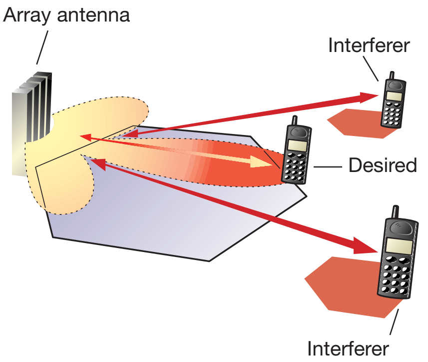
Wireless cellular communication is continuing to grow unabated. In many areas of the world, the demand for cellular communication is so great that operators are tempted to push the capacity of their networks beyond levels that current technology can handle. As wireless data applications over cellular networks become more widespread, the pressure to increase capacity will become even more intense. Capacity in the 800 and 900 MHz bands, where bandwidth is restricted, is already becoming a limiting factor. At 1800 and 1900 MHz, where available bandwidth is greater, the path loss is also greater. Thus, in this frequency band, coverage is one major aspect to consider.

There are a number of ways of enhancing capacity in a cellular network, including frequency hopping, power control, microcells, the introduction of half-rate codecs, and the introduction of adaptive antennas at the base station. Adaptive antennas have been the subject of increasing interest in recent years, and several manufacturers and operators have made them the focus of research and field trials. The main conclusions being drawn from Ericsson's studies indicate that adaptive antennas enable tighter reuse of frequencies within a cellular network—that is, they increase network capacity. Adaptive antennas can also improve speech quality. Moreover, a step-by-step introduction of adaptive antennas into existing networks appears to be practical and economically feasible.

The authors describe the results of Ericsson's research as it relates to adaptive antennas in GSM and TDMA (IS-136) networks, the combined use of adaptive antennas and frequency-hopping techniques (in GSM networks), and the implementation of adaptive antennas in existing networks.

Figure 1
Array antenna arrangement showing the adaptive antenna concept.



Adaptive antennas, what are they?

Unlike conventional cellular antennas, which broadcast energy over the entire cell, adaptive antennas are antenna arrays that confine the broadcast energy to a narrow beam (Figure 1). The advantages of directing the broadcast energy into a narrow beam are increased signal gain, greater range of the signal path, reduced multipath reflection, improved spectral efficiency, and increased network capacity. There are also some disadvantages, the main one being the need to continuously track the angular position of mobile terminals in the cell.

In a conventional cellular network, a single base-station antenna defines the cell parameters and is the focus of all radiated communication. This includes the transmission and reception of revenue-generating data and voice traffic, as well as the broadcasting of system-related information that is necessary for operating the network—information that must be received continuously and simultaneously by every mobile terminal operating within the cell. System-related information includes cell identity, the frequencies in use within the cell, frequency-hopping sequences, maximum power levels, and so on.

An adaptive antenna design that increases system capacity requires that the conventional base-station antenna be replaced by one or more adaptive antenna arrays. Instead of flooding the cell with radiated information from a single source, adaptive antennas fill the cell with several narrow signal beams (typically four or eight). An immediate consequence of this new approach is that a different downlink strategy must be applied; that is, more complex information must be used for transmission from the base station to the mobile terminals in the cell. This is because the system needs to know

- which beam direction reaches which mobile terminals; and
- how it can get system information to every mobile terminal simultaneously.

Two main downlink strategies meet these requirements. The first calls for a beam to be directed toward the mobile terminal; the second requires a beam to be selected from a set of fixed beams (Figure 2). In either case, the downlink beam relies on estimating the direction of arrival (DOA) of the uplink from the mobile terminal. The algorithms that determine the most suitable beam or beam path for downlink are thus vital elements of the adaptive antenna solution.

Several different antenna architectures (with different levels of complexity) can be used for directing radiated energy from an antenna into a narrow beam. For example, the phase front on the antenna elements that correspond to a beam can be generated at baseband using digital beam forming or it can be generated at radio frequency using a passive network or phase shifters. A main advantage of using a beam from a passive network is that it does not require phase coherency between the radio transmitter and the beam former.

While numerous system architectures exist for adaptive antennas—including separate antenna systems for uplink and downlink—Ericsson favors three approaches, each of which appears to offer the appropriate trade-off between system-level performance and the complexity and cost of implementation:

- multibeam or switched-beam architecture with a passive beam-forming network;

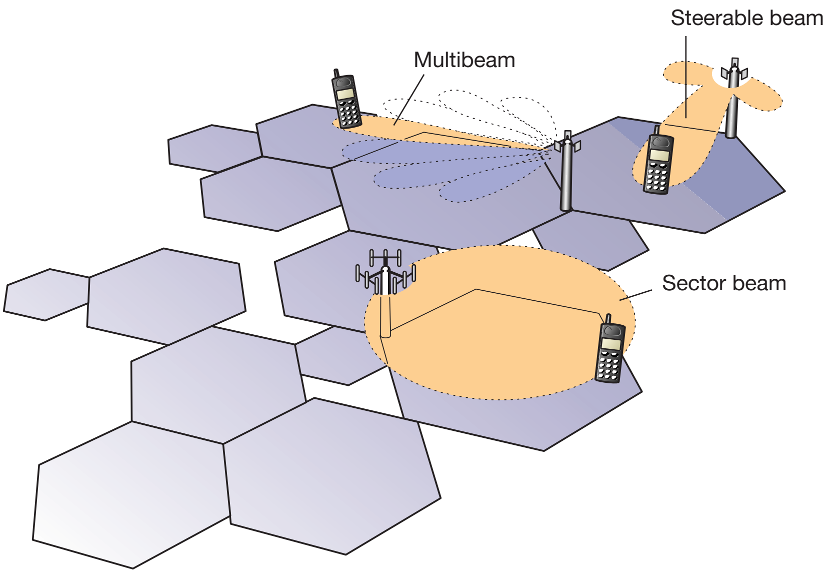


Figure 2
Steerable beam and switched multibeam antennas in network with cells.

- switched interleaved beams in the downlink; and
- fully steerable beams.

The passive beam-forming solution is the least complex one. Because the direction of arrival can identify the best uplink beam, phase coherency is not needed for the uplink or downlink.

The second solution, which requires additional downlink beams, forms beams differently in the uplink and downlink. In the uplink, the number of beams is limited by the number of receiver branches. The direction of arrival is calculated from the uplink information. This information (the DOA) is then used to select a beam from a larger set of downlink beams. In the downlink, several parallel beam-forming networks are present. After the beam has been formed, the signals to the antenna elements are combined. Compared to the steerable-beam approach, this method reduces the phase coherency requirements in the downlink. An accurate direction-of-arrival estimate might require coherent receiver branches and calibration in the uplink.

The fully steerable solution requires an individual transmitter for each antenna element plus phase coherency of the branches on the receiving and transmitting sides. The main advantage of this solution is that beam forming on the downlink is not limited to a fixed set of beams or beam shapes. Moreover, this solution has the potential to reduce interference on the downlink via nulling; that is, by forming the beam with reduced gain toward interfered co-channel mobile terminals.

Ericsson's adaptive antenna program has included extensive field trials for GSM and TDMA (IS-136) in cooperation with two major network operators, Mannesmann Mobilfunk and AT&T Wireless Services. One objective of the trials was to determine how adaptive antennas might be used in different propagation environments—urban, suburban, hilly, and rural areas. An important system-level verification from the trials is that the use of adaptive antennas enhances network quality by decreasing network interference. In particular, the narrow beams reduce received interference in the uplink and the distribution of interference in the downlink (Figures 3 and 4).

GSM and TDMA

As could be expected, differences in the GSM and TDMA standards carry over to the application of adaptive antenna technology. For example, TDMA does not currently support frequency hopping capability. Similarly, the TDMA specification requires that the base station output power on each carrier fre-

BOX A, ABBREVIATIONS

BCCH	Broadcast common control channel
C/I	Signal-to-interference ratio
DOA	Direction of arrival
GSM	Global system for mobile communication
TDMA	Time-division multiple access

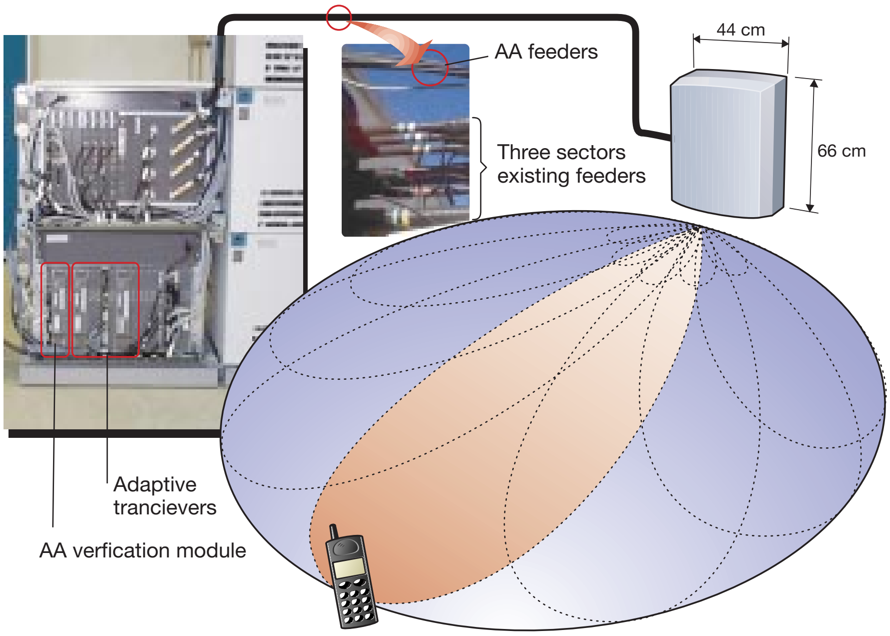


Figure3
Field trial equipment used in live-traffic TDMA network.

quency be held at a constant level for the duration of the frame once one of three available time slots is occupied. However, a proposal has been made to change the specification to allow beam forming and individual power control for each time slot. The current TDMA specification prevents the introduction of downlink beam forming and beam switching individually for each time slot. It is nonetheless possible to form beams on the downlink on a carrier basis. With a carrier-based beam-forming strategy, performance can be improved by introducing beam packing, whereby the system allocates slots on the same carrier frequency to mobile terminals that share a similar line of direction from the base station. Simulations indicate that this technique increases capacity in TDMA networks by approximately 75 to 130%, depending on system parameters.

With cellular networks, adaptive antennas offer two ways of increasing network capacity:

- using carrier signal-to-interference (C/I) gain to implement tighter frequency reuse; and
- using fractional loading.

The most straightforward solution is to use C/I gain to obtain tighter frequency reuse. For GSM networks, this approach can reduce the average reuse from nine to four, and typically improves capacity by100 to 120% for a C/I gain of 5 to 6 dB. What is more, field trials during regular commercial conditions in existing networks have shown that frequency reuse in TDMA networks can potentially be reduced from 21 to 12 or even 9 when adaptive antennas are used together with downlink power control.

Fractional loading regimes have even tighter frequency reuse—as much as one to three. Network quality is maintained when only a fraction of the frequencies are used simultaneously, hence the term fractional loading. This technique is usually applied in combination with radio-network features, such as frequency hopping, power control, and discontinuous transmission. The increase in capacity that results from fractional loading depends on a wide range of variables, such as frequency reuse, C/I gain, discontinuous transmission, and power control. However, field trials and system-level simulations have shown that fractional loading has the potential to increase capacity in GSM networks by as much as 280% under regular conditions.

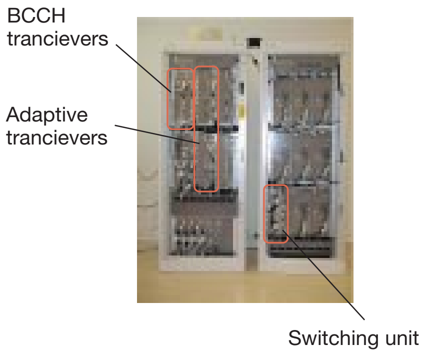
The combination of adaptive antennas and frequency hopping in GSM networks offers the greatest potential for increasing capacity. Moreover, existing cell sites can be used to provide capacity increases over a large area.

C/I gain and fractional loading do not have the same effect on the characteristics of system interference. C/I gain brings interferers closer together, whereas when fractional loading is applied they remain in the same position.

A benefit of frequency hopping is that frequency diversity balances the quality between slow- and fast-moving users. Frequency hopping also introduces interference diversity, which improves performance. Strong interferers are shared by different users; time-varying interference increases interleaving and coding efficiency, which improves receiver performance.

Although complex to implement, fractional loading networks that use frequency-hopping techniques are efficient. This premise is supported by system-level simulations in which each adaptive antenna base station was equipped with eight fixed beams. The results showed that interference diversity is always obtained regardless of

Figure 4
Field trial equipment used in live-traffic GSM network.



traffic load and interference-reducing techniques, such as discontinuous transmission and power control. This is not the case for networks with conventional omnidirectional or sector antennas. The simulations also showed that GSM networks that combine adaptive antenna arrays and frequency hopping are spectrum-efficient, cope with tight frequency reuse, and considerably improve mobile tracking performance.

Implementation in existing networks

The cost of implementing an adaptive antenna solution depends on the complexity of the solution, the desired ease of implementing it, the target level of network quality, and the desired increase in capacity. Simulation trials using actual cell and data traffic supplied by Mannesmann Mobilfunk suggest that a cost-effective, step-by-step migration from a conventional antenna solution to one based on adaptive antennas is feasible. The simulation trials, which were based on existing radio networks, also showed that by installing only a few adaptive antenna base stations, operators could improve the overall quality of the network Figure 5).

Most operators are expected to approach the migration in a step-by-step fashion, since doing so is more manageable and cost-effective. The majority of today's cellular networks are composed of a mixture of large macrocells and smaller microcells. Ericsson's field trials in commercial networks were based on implementing adaptive antennas in a macrocell. Three alternatives have been identified for

- boosting capacity—interference reduction means tighter frequency reuse and an increase in transceivers;
- saving frequency spectrum—instead of increasing the number of transceivers, the current traffic can be served by fewer frequencies; and
- reducing interference—a reduction in macrocell-to-microcell disturbance makes it possible to increase capacity by reusing frequencies in the microcell layer.

The study considered cell relationships, the impact that introducing an adaptive antenna array would have on those relationships, and the addition of frequencies in the target cell and surrounding cells. Uplink performance was also investigated, as were the effects of introducing several adaptive antennas into a network. In each case, the simulations showed that capacity and quality could be enhanced, and that the introduction of only a few adaptive antenna base stations can significantly reduce interference.

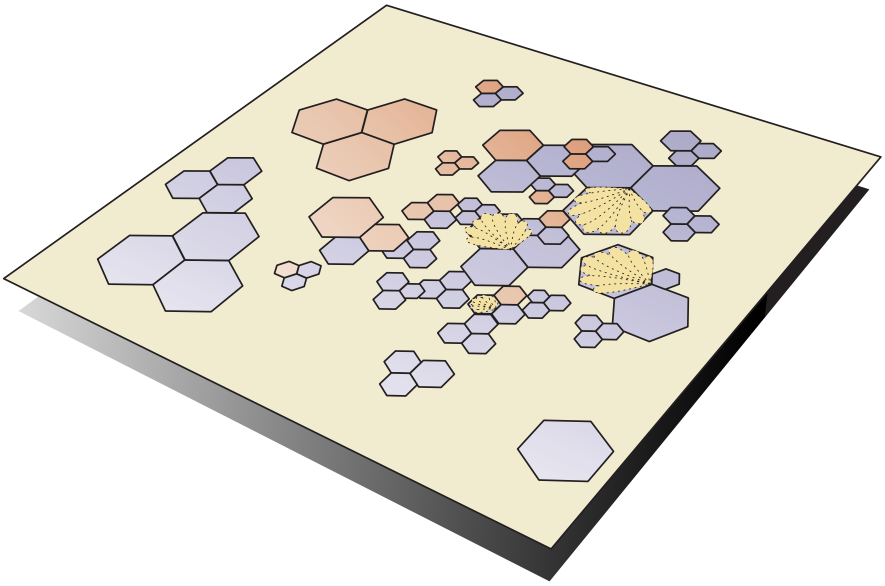


Figure 5
Migration strategy: Adaptive antennas are deployed in a few target cells. This reduces interference in several neighboring cells and substantially increases capacity.

Conclusion

Ericsson has developed a system-level concept that uses adaptive antenna arrays to meet demands for greater capacity in cellular communication networks.

In GSM networks, the combination of adaptive antennas and frequency-hopping techniques is an especially attractive solution that has the potential to increase capacity by nearly 300% at hot spots.

In TDMA networks, the combination of adaptive antennas and downlink power control has the potential to reduce the frequency reuse pattern from 7/21 to 3/9.

The introduction of only a few adaptive antenna base stations can significantly reduce interference.

Adaptive antennas make up an attractive solution that can be implemented in a practical, cost-effective, step-by-step process.