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Advances in new mobile applications coupled with the complexity of radio communication systems have paved the way to new flexible algorithms at the receiver and transmitter in communications systems. One of the most popular spatio-temporal interference cancellation techniques is realized by applying the smart antenna concept. In the prevailing communication landscapes, as shown in Fig. 1, networks are heterogeneous and this imminently dictates the smart antenna to have the capability to operate with not only Universal Mobile Telecommunication Systems (UMTS) standards but also with other multiple radio standards in third-generation mobile networks. The drive for a better grade of service and the need for serving the exponentially growing number of users demand greater synergy between multiple access systems and the spatial filtering technology. Fading resistant beamforming requires better understanding of channel models as well as the development of robust adaptive algorithms. Exploiting the scientific and technology base in space-time receiver modeling is of utmost importance. This will set the scene to better identify the components that will support advanced base stations, eventually resulting in technology-translators via tailor-made solutions for increased capacity.

In the following section, we set the context for space-time interference cancellation for multimedia heterogeneous networks. We then discuss dependencies of space-time interference cancellation on the air interface in terms of duplex mechanisms, multiple access technologies, propagation modeling, and signaling channels. The remainder of the article is organized into three sections. The fourth section primarily describes the interference cancellation studies in three selected representative sets of heterogeneous landscapes. Based on this framework, the fifth section highlights the recent advances in the enabling technology to offer value-added services to end users. The last section includes the concluding remarks.

HETEROGENEOUS NETWORKING WITH SPACE-TIME INTERFERENCE CANCELLERS

In recent years there has been rapid progress in telecommunications, resulting in new application scenarios for mobile networks (Fig. 1). With advances in technology, a variety of communication devices such as Ethernet, WaveLAN, CDPD, Metricom Ricochet, and cellular modems have become available at affordable prices. Today, it is common for a laptop to have access to more than one network. All these technologies offer different network characteristics, leading to heterogeneity in network architectures. To deal with heterogeneous networks, important components of space-time processors need to be identified with a goal to make information services and applications ubiquitous and flexibly available to people on the move. The following three factors need to be considered to adapt the technology in heterogeneous networks:

• Services — real-time interactive services for data, video, and voice, on distributed systems with terminal and server independence.
• Connectivity — efficient implementation of multi-protocol interconnect.
• New application methods — enhancing the service regime using space-time processing.
To conduct a systematic incorporation of space-time processors in heterogeneous networks, surrounding the conceptual studies three critical stages should be carved into the overall techno-commercial plan. This includes testing the mobile applications, pre-tune and ultimately proceed with the validation using testbeds. At the present time, there is world-wide ongoing activity to test space-time technology across several networks. There is immense potential to realize a global picture and identify the architectural commonalities of space-time processing among several prevailing standards. The following three factors are integral to the design strategy and serve as the main guidelines to absorb the technology into the networks:

- Future long-term stability.
- Near-term implementation ability.
- Technical feasibility.

Figure 2 shows the penetration of space-time interference cancellation into heterogeneous wireless networks for provisioning of real-time services. The landscapes are divided into outdoor, outdoor-campus-like, local area networks and fixed wireless access architectures. In each of these technology islands, smart antennas will offer interference rejection capabilities. Researchers will be motivated to apply powerful algorithms in order to gain performance enhancements in all the aforementioned scenarios. Ultimately, the choice of the appropriate technology will depend on the array of the application considerations, including:

- The environment where the smart antenna is deployed.
- The service profile of the user.

In the context of the variety of network topologies and the corresponding end-user requirements, major issues related to the air-interface specifications and their interplay with the spatio-temporal interference cancellation will be reviewed in the following section. This can also help designers shed new light on the signaling requirements of ST processing for future wireless multimedia networks.

### AIR INTERFACE ISSUES FOR SPATIO-TEMPORAL INTERFERENCE CANCELLATION SCHEMES

Smart antennas are a complex technology and their interaction with the air interface design and propagation environment is often complicated. Successful deployment of smart antennas in UMTS will involve many choices that can only be made with a thorough understanding of the technology. The scope of this article does not allow us to address all of these issues, so this section focuses on some of the most important aspects, and the interested reader is referred to the references provided in this article.
GENESIS OF SPATIO-TEMPORAL INTERFERENCE CANCELLATION IN TDMA AND CDMA NETWORKS

There are many ways in which spatio-temporal filtering can be used in a mobile system allowing performance to be traded against the complexity of implementation. Indeed, in some cases simpler techniques give better performance because they are more robust in difficult propagation environments.

Beamsteering refers to the class of algorithms that attempt to direct a beam toward the wanted mobile but make no attempt to null co-channel interference signals. The interference reduction effectiveness of the basic beamsteering may be enhanced by combining it with other techniques such as frequency hopping.

Adaptive nulling can be used to further reduce co-channel interference in the uplink to improve the overall capacity of the system. In TDMA systems there are two principal ways in which adaptive nulling can be used:

• Spatial filtering for interference reduction (SFIR) — In this scheme nulls are formed in the direction of interference sources in uplink and downlink. This improves the carrier to interference (C/I) ratio and allows the frequency reuse pattern to be tightened, thus increasing capacity.

• Spatial division multiple access (SDMA) — This involves the use of adaptive nulling to allow two or more mobiles in the same cell to share the same frequency and time slot. One beam is formed for each mobile with nulls in the direction of the other mobiles.

SDMA requires better nulling performance than SFIR because the high dynamic range of uplink signals within a cell means that the C/I of the wanted signal can be far below 0 dB. In the SFIR case the C/I is usually positive. However, SDMA has the advantage that it can be implemented in isolation in single cells (e.g., traffic hot spots), whereas SFIR must be implemented across whole clusters of cells. Of course, SDMA also requires the establishment of new procedures to manage the air interface resources within each cell. For example, this may involve intra-cell handovers.

In CDMA systems an improvement in C/I leads in principle to a proportional improvement in capacity, and smart antennas may be seen as a direct extension of the sectorization techniques currently used in IS-95 systems. Both beamsteering and SFIR can be used in CDMA. However, SDMA is not appropriate in CDMA systems, since it implies reuse of spreading codes, which is undesirable and unnecessary.

Both beamsteering and SFIR nulling are based on the concept of linear spatial filtering. However, this is by no means the only way to use antenna arrays to enhance performance. Some examples of alternative techniques are given below:

• The Viterbi equalization scheme used in GSM could be directly extended to operate on a vector of signals from an antenna array instead of a single signal from one receiver.

• The joint detection algorithms proposed for TD-CDMA could likewise be extended for vector operation.

• The use of spatial transmit diversity, which involves the transmission of non-identical copies of the downlink signal from two or more transmit antennas in order to exploit the spatial diversity of these antennas. For example, in CDMA the same signal could be transmitted from two antennas with different spreading codes.

SPATIO-TEMPORAL CANCELLER AND THE INFLUENCE OF THE PROPAGATION ENVIRONMENT

A mobile radio channel may be characterized in terms of three basic parameters as follows:

• Delay spread — This describes the time dispersion of the channel, and tells us how fast the channel decorrelates with frequency (correlation bandwidth).

• Doppler spread — This describes the frequency dispersion of the channel and is determined by mobile velocity. It tells us how fast the channel decorrelates with time (correlation time).

• Angular spread — This describes the angular dispersion of the channel and tells us how fast the channel decorrelates with distance.

These parameters vary for picocell, microcell, and macrocell environments. Many of the design parameters of a smart antenna system are effected by these channel parameters. For example, the choice of algorithm, the processing power required and the array geometry are all influenced by these channel parameters. Therefore, there is unlikely to be a single solution that is applicable to all types of cell environment. Instead, it is anticipated that a smart antenna system would be designed based on an assumption of the type of environment in which it is to operate.

RELATIONSHIP WITH THE DUPLEXING SCHEMES

In the traditional cellular systems, only the uplink channel can be estimated by the base station and therefore the downlink beam pattern must somehow be derived from estimates of the uplink channel. The perceived direction of arrival (DOA) of a signal (or, more precisely, its source vector) is a function of both time and frequency in a time varying dispersive channel.

The air interface duplex scheme is therefore significant because it affects the degree of correlation that exists between the uplink and downlink channels.

The performance improvement obtainable from the smart antenna system is not symmetrical between uplink and downlink for this reason. The degree of asymmetry depends on the class of algorithm being employed. The direction of a beam maximum is less sensitive to time and frequency translation than the direction of a null. Therefore, the asymmetry is particularly evident when it is necessary to form deep nulls in the downlink beam pattern, which is a requirement for SDMA.

In TDD schemes the uplink and downlink channels may be considered reciprocal if the source vectors of the signals do not change significantly in the time between the transmit and receive time slots. The rate of change of the source vector is controlled by the mobile velocity and the angular spread of the channel. In a macrocell environment where the angular spreading is low the source vector of the mobile may not change significantly over a distance of many wavelengths. In this situation the source vector is not significantly altered by the fast fading. However, in microcell environments, moving only a small fraction of a wavelength can be enough to significantly change the source vector of the mobile and therefore move out of a null. Forming deep downlink nulls in microcell environments is therefore impractical in almost all cases. An appropriate choice in many systems may be to employ SFIR on the uplink and beamsteering for the downlink.

In FDD schemes the uplink and downlink channels may be considered reciprocal if the source vectors of the signals do not change significantly between the transmit and receive frequencies. Typically the uplink and downlink bands are separated by much more than the coherence bandwidth of the channel, and the source vectors at the two frequencies differ significantly. An exception to this is the open macrocell case with little or no delay spread or angular spread. In this case it is possible to predict the perceived DOA at the downlink frequency using the known geometry of the antenna array.
Broadcast Control and Pilot Channels

In some second-generation cellular systems the implementation of broadcast control and pilot channels causes unnecessary difficulties for smart antenna implementations.

For example, it is difficult to use smart antennas for downlink range extension in GSM. This is because the size of the cell on the downlink is fixed by the broadcast control channel (BCCH) which is measured by the mobiles in neighboring cells. Since the BCCH is a broadcast channel it must be transmitted omnidirectionally. The BCCH must therefore be transmitted at a higher power than the traffic channels to take account of the fact that once a traffic channel is established the beamformer gain will improve the link budget.

In the IS-95 downlink a pilot channel is used which is broadcast to all mobiles for synchronization purposes. This pilot signal must pass through the same channel as the traffic signal in order for the RAKE receiver in the mobile to function correctly. If individual downlink beams are used for each user then this is clearly no longer the case and therefore the current IS-95 air interface is unsuitable for downlink beamforming. UMTS overcomes this problem by providing a dedicated downlink pilot signal for each mobile.

It may be noted that the aforementioned details cover only a selective set of interface or physical layer specifications as representative cases. As new physical layer technologies continue to surface, it will be a prudent investment to look into ST processors that are effectively independent of any air-interface specific. In order to pave the way to design such novel systems, it is mandatory to appreciate the existing ST solutions that are presented in the following section.

Space-Time Interference Cancellation in Heterogeneous Networks

In this section, we view the classification based on the network topology along three directions, including outdoor networks with high user mobility, fixed wireless-based residence users, and indoor as well as low-mobility users in a wide-area campus-like network. Based on this, the performance analysis and underlying parameters that govern the choice of a space-time processing solution in a typical cellular network are described. Because of the recent ongoing activities more emphasis is laid on outdoor network evaluation along with the preliminary details on other landscapes of the prevailing heterogeneous networks.

Interference Cancellation in Outdoor Networks

The design of appropriate spatio-temporal systems for high-mobility systems with possible data rates up to 2 M/s is confronted with a multitude of challenges and it is essential to identify the subsystems encompassing the fundamental blocks in the big picture. The situation therefore calls for the process of incorporating the specialized algorithms in the design. Some aspects of the study and the demonstration for both macro and micro cells was undertaken in a European funded project called TSUNAMI [2]. The following sections outline the tenets of the approach and basic exploration tests conducted to prove the concept of the technology.

Algorithms used for TDMA Systems — The following algorithms were compared in the tests.

- Single element — This is the reference case in which only one element of the array was used for both uplink and downlink. No adaptive processing is performed.
- Maximum ratio combining (MRC) — This algorithm performs maximum ratio combining on the uplink and uses the same weight vector for the downlink. This algorithm was tested using all eight elements (MRC8) and using only the two outer elements of the array (MRC2). The weight vector is updated every four frames (18.46ms).
- Dual element swept phase — In this scheme only the two outer elements of the array are used. Both elements have fixed weights of unit magnitude but the phase of one element is increased in steps of 90 degrees relative to the other element at each iteration. These phase changes occur every four frames (18.46ms).
- Temporal reference beamforming (TRB) grid of beams — This algorithm was developed by the University of Aalborg for use in the field trial system [3]. It operates by using the DCS-1800 training sequence in the uplink received burst to form an estimate of the channel impulse response from the mobile to each array element. These impulse responses are beamformed using a fixed set of beams to obtain an estimate of the received signal energy as a function of both time of arrival (TOA) and direction of arrival (DOA). The impulse response energy in each TOA-DOA bin is averaged over several frames to form an estimate of the average direction of arrival. The beam corresponding to maximum signal energy is selected for downlink transmission. The weight vector is updated every eight frames (36.92ms).

The set of power measurements recorded with each algorithm has been analyzed to derive a cumulative probability density function or outage curve, which is shown in Fig. 3. During each test the mobile records not only the power of the downlink traffic channel but also the power of the base station broadcast channel (BCCH). From Fig. 3 the outage curves of the BCCH power from all tests are shown and it is clear that they match closely, indicating that the results are repeatable over separate test runs.

Since the fast fading is largely obscured by the averaging performed in the power measurement, the outage curves show mainly the statistics of the shadowing process. The use of beamforming on the downlink is not expected to dramatically
alter the shape of the power measurement profile shown in Fig. 4. However, we may expect an increase in the mean received power and a reduction in the number of deep fades. Consequently, the shapes of each of the outage curves in Fig. 3 are largely the same, but shifted to the right by various amounts.

The BCCH signal is transmitted at a higher power than the signals transmitted from each element of the beamformer. A correction factor has been applied in Fig. 3 based on estimates of the transmitted powers made from the base station equipment. The single element curve appears slightly to the right of the BCCH measurements which could be the result of errors in estimation of the transmitted base station powers.

It was found that the TRB grid of beams algorithm provided the best overall performance in terms of received signal power and link quality. However, the maximum ratio combining (MRC) algorithm provided nearly 3 dB more coherent gain than the TRB grid of beams algorithm. The amount of coherent gain obtained with the MRC algorithm is surprising given the large frequency difference and time delay between the uplink and downlink channels. Further investigations are ongoing to obtain more detailed analysis from the field measurements.

Based on this experience, an interference canceller for third-generation outdoor networks can be realized as explained in the following section.

Spatio-Temporal Architecture Realization through Baseband Transmultiplexing and Beamforming — In outdoor networks, each base station may be required to process the signals on more than one carrier simultaneously. Multicarrier reception and transmission require FDMA demultiplexing and multiplexing operations, respectively, and it is important to consider how such operations are to be integrated with the beamforming operation.

The operations of FDMA demodulation and beamforming may be combined in the digital domain by using a digital filter bank, or transmultiplexer (TMUX), to separate all of the car-
rriers at each base station prior to beam-forming and demodulation. At first sight such an approach may seem inefficient, since not all of the channels provided by the demultiplexer will be used. However, this scheme provides a very high degree of flexibility, easily supporting dynamic frequency allocation, for example. By integrating the beamforming and frequency routing functions entirely within the digital domain using efficient digital signal processing methods, an efficient beam-frequency processor architecture may be realized.

A possible receiver architecture based on digital transmultiplexers is shown in Fig. 5. The key features of the architecture of Fig. 5 are as follows:

• A RF stage consisting of \(N_e\) LNAs and \(N_m\) mixers, where \(N_e\) is the number of antenna elements in the array.
• A bank of \(N_c\) quadrature downconverters which translate the whole band of interest to zero IF. \(N_e\) dual A/D converters are used to digitize the wideband element signals.
• A bank of \(N_e\) digital transmultiplexers. Each of these performs a frequency demultiplexing operation, separating the wideband digital input signals into \(N_e\) zero-IF components, each of bandwidth \(B_c\).
• A bank of \(N_e\) digital beamformers and demodulators, each serving a single carrier signal. Note that more than one beam may be formed at each carrier frequency, as implied by Fig. 5. This feature of the architecture would be required for space division multiple access (SDMA) operation. Some form of programmable switch would be used to route the TMUX output channels to the beam-forming modules. The switch could be rapidly reconfigured to support dynamic channel allocation (DCA) functions.

A key advantage of this approach is the transfer of the element-to-beam connection problem from the analog to the digital domain. This increases the inherent flexibility of the architecture, allowing any received carrier to be rapidly re-routed to a beamformer processor under software control. A further advantage of the TMUX scheme is the possibility of implementing mixed levels of frequency demultiplexing in order to offer a variety of different bandwidth channels, corresponding to the different bit rate services envisaged for UMTS.

The equivalent transmitter architecture is shown in Fig. 6. The main attributes of the transmitter architecture are summarized below:

• A bank of digital modulators and beamformers. Each of these produces \(N_e\) complex digital baseband signals.
• A bank of \(N_e\) digital transmultiplexers. Each multiplexer stacks the incoming digital data in frequency, thus translating each baseband signal to the desired carrier position. Note that more than one modulated signal may be transmitted on the same carrier if they are separated spatially by SDMA. This requires summing nodes at the inputs to the multiplexers, as shown in Fig. 6. The outputs of the digital multiplexers are fed to \(N_e\) D/A converters.
• A bank of \(N_e\) quadrature upconverters and power amplifiers.

By combining the transmitted signals digitally at baseband the need for RF power combiners is eliminated. Digital combining is lossless and offers greatly increased linearity and flexibility.

The TMUX approach transfers the operations of quadrature downconversion and upconversion from the analog domain to the digital domain. This reduces the number of analog components required, but the performance requirements of the analog components is increased because they must operate at increased bandwidth and linearity.

In the TMUX receiver automatic gain control cannot be performed in the analog domain on a per-carrier basis. This implies that the A/D resolution be such that the full dynamic range of the carrier signals can be supported. The practical bandwidth of the TMUX architecture is limited by the sample rate at which A/D technology can support the required dynamic range.

Intermodulation distortion between carriers in the analog part of the receiver and transmitter is also a significant problem. The degree of linearity required from these components necessitates the use of advanced adaptive linearization techniques in the receiver and transmitter chains.

Architectures for Spatio-Temporal Processing in CDMA Systems — Spatio-temporal processing in CDMA systems is often modeled as an effective combination of the beamformer and RAKE. This is referred to as a 2D RAKE receiver architecture. Some techniques adopt the approach where there is a pilot or access channel in which just the PN code is transmitted, without any data. Architectures that can also work in the presence of modulating data but without any knowledge of the data that is usually derived from the access channels. However, to incorporate flexibility the approach should also work if a pilot or access channel is employed. The architectures in this case, the searcher function must operate in the presence of modulating data but without any knowledge of the data that is usually derived from the access channels. However, to incorporate flexibility the approach should also work if a pilot or access channel is employed. The searcher architecture operates by correlating the PN code with the received signal to produce an energy-delay profile. This is a measurement of received signal energy as a function of the time delay of the code offset used in the receiver and transmitter chains. The energy-delay profile is then examined to estimate the number of multipath components in the signal and the PN code offset of each multipath component.
This network topology consists of highly bursty packet data assigned one multipath component by the 2D searcher. One possible mechanism to gain insight into the 2-D RAKE architecture is to devise some simulation experiments. The search can be performed independently on every burst in such a simulation exercise. If no multipaths are detected by the 2D searcher all the weights will be set to zero for that burst and the remaining processing is carried out in a straightforward fashion. Several algorithmic solutions are currently being investigated to identify the architectural components of the 2-D RAKE [4, 5] spatio-temporal receiver for 3G wireless outdoor networks.

**Space-Time Interference Cancellation in Outdoor Wide Area Campus and Local Area Networks**

This network topology consists of highly bursty packet data flow with data rates up to 10 Mb/s characterized by low mobility as opposed to typical outdoor networks where users experience high mobility. With ever increasing requirements for broadband capabilities and the recent trend toward data transmission over fixed networks along with the Internet, packet switching platforms are becoming popular. The space-time architecture must be devised to co-exist and deliver acceptable QoS in situations akin to high data-rate packet communications offering a variety of services. More often the terminals may set up and modify sessions for voice, data, image as well as video through wireless connections to the base stations. The following key issues are vital to accommodate space-time processing in these networks.

**Multiple Access System** — CDMA-type multiple access systems are not pursued as feasible options for this network mainly due to the data rates and the corresponding spreading data rates. With rapid proliferation of the Internet combined with the advances in RF and digital technology, new multiple access systems including high-level modulations and OFDM for wireless communications [6] are emerging as potential solutions along with the space-time architectures.

**Additional Requirements Related to the Packet Traffic** — Packet traffic is often characterized as bursty and the traffic profile governs the performance of the architecture. Traversing packets experience latency in the network nodes and in light of the ongoing quality of service activity the role of the space-time architectures is under discussion. Several channel estimation techniques were investigated in the past [7, 8]. The winners are not necessarily the best solutions technically; the solutions that do not increase the computational overhead are crucial.

**Interference Cancellation in Fixed Wireless Access Systems**

This network landscape is also termed wireless local loop (WLL) and in essence looks at more rapid installation by use of radio technology to offer a fixed phone line. The initial WLLs are narrowband offering from 32 kb/s to a maximum of 128 kb/s. New broadband WLL systems are emerging with data rates on the order of 25 M b/s per subscriber by utilizing the mature packet transmission technology and operating at higher frequencies [9]. Unlike the cellular systems, there are no clear standards for WLL. However, the European Telecommunication Standards Institute (ETSI) established a project called Broadband Radio Access Network (BRAN) in April 1997 to realize the multimedia applications and services provided by the combination of broadband radio local-area networks and fixed access radio beyond 2002.

Integration of the space-time processors in this context will mitigate the limitations in relation to capacity and the overall functionality in terms of high-quality, low-delay voice and data. The WLL systems are expected to deliver QoS that is very close to that provided by local exchange carriers. Because of the low mobility combined with relaxed power control and the consequent low carrier-to-interference (C/I) ratio, a high degree of re-use is anticipated when the systems are deployed. The system capacity, therefore, is limited by the co-channel emissions arising from other concurrent transmissions. This should be the overriding concern of the designer to reject the interference from the re-use by forming a narrow beam in the direction of the user. Careful selection of the coefficients of the processor is required to move the beam up and down while maximizing the array gain. This gives rise to the application of well known SDMA for WLL. In order to ensure effective interference cancellation by the space-time processor, the beam pattern generated at the fixed site should also be optimized, and to this end much research is needed to pinpoint suitable optimized algorithms [10].

**Key Areas in Algorithm Research for Space-Time Processing in Heterogeneous Networks**

Based on the analysis of each service scenario presented in the preceding section, it will be a natural extension to closely examine current research trends to extract the relevant factors associated with the design and development of effective ST processors. Since the advent of adaptive beamforming techniques, numerous algorithms and stand-alone testbeds have been developed for interference cancellation in wireless networks. Such solutions form the bedrock of the current adoption of ST processing in second-generation networks. In the following sections, we first examine the algorithms designed under various banners. We then offer brief comments on the baseband solutions and RF technology for the sake of completeness of the presentation.
EXISTING TECHNOLOGY SOLUTIONS AND CURRENT TRENDS

The key requirement for advanced flexible space-time architectures is to employ robust adaptive algorithms to ensure reliable operation of the smart antenna. The explosive growth of interference communications systems has given rise to a variety of algorithms in different frameworks. The crux of the problem is to devise flexible algorithms suitable for implementation when the user moves between various network topologies. This motivates the intervention of the network management system to sense the migration of the user from one landscape to the other. The user's movement will trigger a downloading mechanism in the network to supply a suitable algorithm to the radio access network that is going to serve the user. It may be noted that soft handover is excluded in this case. Under the circumstances, it is imperative that the network should be aware of the user's location with sufficient accuracy. This will also reduce the signaling overhead in the network. There is intensive ongoing work related to the location management of the user in heterogeneous networks. The European Commission organized a workshop recently [11] at which several location estimation techniques were discussed, including the Global Positioning System (GPS)-based solution. One possible step further is to think of an implementation to incorporate some kind of handshaking between the space-time architecture and the resource management entities in the network nodes to utilize the location information determined by the ST processor.

In the algorithmic arena, employing advanced blind-weight updating principles is the norm. Temporal structure methods span from constant modulus (CM) [12–14] and higher-order-statistics (HOS) methods [15]. The CM algorithm tries to alleviate the structural damage of the signal introduced by the channel and the interference. This is accomplished by maintaining the constant output at the array while preserving the phase of the array. Special properties of the received signal, including the cyclostationarity and the modulation format, are exploited in these formulations. CM algorithms can in principle employ the steepest-descent approach or the least-squares-based approach to minimize the CM cost function. Recently, the HOS-based framework [16] has received increased interest. One of the popular solutions is to construct a cumulant matrix and then perform the singular value decomposition (SVD) of the corresponding matrix to recover the source signals for beamforming. The advantage of these techniques is that they can be applied to any arbitrary array configuration and does not require any knowledge of the array response. Most importantly, this framework overcomes the sensitivity problems associated with the mismatch in the assumed steering vectors in the design of beamformers.

In a different class of algorithms, when an adaptive solution is sought, techniques to improve the convergence speed without falling into the local minima and the tracking ability are of paramount importance. Provision of a reference signal is crucial for such training algorithms. In the case of decision-directed algorithms, after the demodulation of the array output a binary decision is made that is fed back to provide a reference signal. A temporal reference signal is also needed on the uplink to enable efficient estimation of spatio-temporal channel estimation or 2-D impulse response in TDMA systems. However, suitable long training sequences with desirable correlation properties are needed to help the adaptive antenna to distinguish the mobiles within the vicinity of the base station. The length depends on the number of antenna elements employed within the adaptive antenna and the type of spatio-temporal processing applied. On the other hand, in CDMA systems user-specific spreading codes satisfy this requirement. The length of the codes is also significant in relation to identifying different paths and for more complex interference cancellation systems.

Another closely related topic is the channel estimation technique based on the space-alternating generalized expectation-maximization (SAGE) algorithm [17]. Performance studies for the real channels were also reported in the literature [18]. In CDMA systems, the adaptive antenna architectures operate by estimating the direction of wanted signals from the received data enabling the space division multiple access (SDMA), implying that users are separated within one cell by predominantly spatial processing sharing the common frequency [19]. A detailed simulation study in this report highlighted the uplink and downlink CIR processing gains compared to a single element to be 15dB and 6dB, respectively. In the case of CDMA, the number of user loads on the adaptive antenna place constraints, and it is recommended to carry out the direction estimation after despreading [20]. A different class of algorithms based on hidden Markov models were considered in the blind-array processing [21, 22]. This algorithm basically operates on a trellis-like structure and has a dual functionality through initialization and then blind mode using re-estimation procedures. From these existing solutions, effective space-time architectures for both uplink and downlink should be prudently selected to eventually map these into reconfigurable space-time architectures for heterogeneous networks.

Specifically, for third-generation outdoor networks where W-CDMA was selected as the air interface, joint mitigation of the inter symbol interference (ISI) and multiple access interference (MAI) is a requirement to attain a maximal spectral efficiency. Research is in place at various institutes to optimize flexible algorithms based on this air interface [23, 24] where the interrelationship between the beam pattern distortion effects and the high bit rate services were elucidated. Research is also underway to evaluate capacity enhancement through applying multiple antenna elements at the mobile terminal. A recently published paper [25] reported a case in which three elements were considered at the receiving antenna of the mobile. The proposed technique was the joint approximate diagonalization of eigenmatrices (JADE) to extract the multiple cochannel signals arriving at the antenna array to demonstrate the capacity enhancement through simulations. A recent study on the relative performance of adaptive and non-adaptive smart antenna solutions at the terminal was also reported in [26] for a varying number of antenna elements, target bit error rates, cochannel interference levels, array sizes, and real-life vehicular antenna element patterns.

Another interesting branch of high-capacity space-time architectures has emerged to cater to the needs of delay-sensitive multimedia traffic networks [27–29]. For narrow-band systems space-time coding techniques offer significant performance improvements over the standard approach of separately de-spreading and demodulating each user signal. Benefits arise from combining transmit diversity and receive diversity to create a multi-input multi-output (MIMO) [30–32] or matrix channel. Space-time algorithms for broadband high bit rate communications are a natural extension of these techniques that make optimum use of the diversity provided by the antenna array. Also, techniques for combining space-time coding and array signal processing are now beginning to be explored. Most of the published techniques have only addressed the performance in idealized conditions or without consideration of system aspects and complexity. With the added reliability offered by MIMO techniques, new algorithms are required to diminish the sensitivity to channel estimation errors.

One of the main objectives of future research should be to explore the current trends in space-time coding and matrix channel techniques and devise novel solutions to incorporate multi-level space-time coding into flexible transceiver technologies [33]. Different levels of coding provide protection...
against different types of channel impairments. This umbrella activity should bring together the advances in the space-time coding area and new investigations. This will give rise to the creation of a unique framework of smart antenna interference cancellation algorithms at both the transmitter and the receiver, the multi-dimensional space-time codes for slow and rapidly varying channels. The main driver for this research is to make the best use of the diversity gain offered by the MIMO channels and devise smart space-time codes.

The complexity of the array processing algorithms, along with the non-ideal system conditions and different array topologies, is a key issue in their feasibility for use in future base stations. Therefore simpler and more conventional space-time coding-based array processing approaches should not be neglected by designers and effort should focus on complexity versus performance trade-offs.

Another important issue is to address the performance loss due to the failure of the receiver and transmitter chains. High-performance algorithms and their implications on the air interface standardization, as well as implications of handover strategies and power control loop dynamics, should also be investigated.

**Choice of Baseband Technology**

In heterogeneous networks, recent worldwide research has shown that software radio [34] is computationally powerful, given sufficiently high speed digital signal processors (DSPs). It offers a high MIPs performance and easy direct memory access (DMA), suitable for parallel processing at the expense of high power consumption. Present technology requires hardware accelerators alongside the DSP processors. The integration density is potentially far greater than that offered by conventional dual-mode (stacked radio) design, and the derivation of the software from the network offers a degree of reconfigurability for software bug-fixing and, to a certain degree, future-proofing. Its weakness is that its computational efficiency is low, implying high power consumption, but this is not a very important factor in the algorithm design. It requires an array of DSPs, ideally in an IC for commercial implementation. However, the size of the IC or DSP card is again unimportant for space-time processor applications and could be extended to a small-package, low-voltage version for mobile use. The freedom to use large, high power consumption devices makes software radio-based space-time architectures possible using today’s technology, but flexibility clearly exacts a price due to technical complexity.

This software radio approach is markedly different from hardware-configurable designs employing field programmable gate arrays (FPGAs). FPGAs offer lower power consumption and present an easy route to ASICs, but designs are physically large due to the requirement for multiple FPGAs. They have a longer reconfiguration time and reduced MIPs than the DSP approach with present technology, and DMA is more difficult.

**Noteworthy Developments Related to RF Technology**

In a typical outdoor network air-interface using W-CDMA technology, one of the key RF requirements is the linearity of the input-output transfer function. This is crucial to ensure that adjacent channel interference is kept within the strict specifications required from most systems and precise formation of the beams. This is a stringent requirement for the power amplifier, as it must exhibit a high output power while retaining a very low level of distortion. Furthermore, for large-bandwidth systems, gain and phase flatness across the whole bandwidth and uniform matching between the amplifier used to drive each array element are also important. TSU NAM I studies indicated gain and phase matching levels of 0.3dB and three degrees, respectively, to achieve a null depth of approximately 30dB. Interesting studies related to these aspects were reported in great detail [35, 36].

Wireless Systems International (WSI) in the UK developed an ultra-high linearity RF power amplifier for the DCS1800 frequency range under the ACTS TSU NAM I project. This amplifier was capable of meeting the exacting DCS1800 adjacent channel interference specification and had an appropriate gain and phase flatness for adaptive antenna applications. In addition, it was based on feedforward techniques which are fundamentally capable of achieving gain and phase matching levels of 0.3dB and three degrees between different units in a common rack and, perhaps more importantly, will automatically compensate for any changes within the RF amplifier units to ensure that this matching is maintained with varying output power levels and temperature changes, etc. In the case of a smart antenna system, power level variations through each amplifier are much greater than what might be anticipated, since such variations are intrinsic to the beam steering operation. An ability to maintain gain and phase matching with a wide input dynamic range is therefore essential to correct operation of the system.

The availability of a suitable precision power amplifier is therefore a crucial enabling technology for the successful implementation of almost any adaptive antenna system (even those not employing baseband beamforming) and based on the results from the TSU NAM I project WSI has indicated that this is now achievable.

A follow-up project, called SUNBEAM [37] in Europe, is examining the use of this (and other) techniques over a wider frequency range for increased flexibility (e.g., to allow migration between or simultaneous operation of DCS1800 and UTRA). It is also examining the use of these systems in software radio adaptive antenna base stations, bringing in issues of receiver RF processing, transmit upconversion, etc., again bearing in mind the very precise gain and phase matching requirements in addition to the stringent linearity requirements.

**Conclusion**

In conclusion, advanced research is required in the area of interference cancellation for heterogeneous networks, which may ultimately be superseded by reconfigurable space-time processing techniques. However, these techniques would require additional processing overheads at the physical layer. Further upgrades are required at the network level to download the suitable algorithms as soon as the user equipment migrates from one landscape to the other. Significant research is also needed in smart antenna deployment tools and the changes to the upper layers (MAC) in various networks. In the immediate future, advanced techniques such as flexible space-time architectures with adaptive antennas are likely to offer the following advantages: a higher level of integration, a degree of future proofing due to upgradeable software, extension of coverage, increased capacity due to frequency re-use, increased interference tolerance, and lower receiver noise floor. Many of these techniques depend on high-speed DSP processing, the improvement of which is clearly a key enabling mechanism.

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BIography

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