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Linearity Considerations in Adaptive Antenna Array Applications

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Abstract - The use of adaptive antenna in mobile communications base stations is self-explanatory. It offers the potential of increased spectrum efficiency, extended range of coverage and reduced delay spread. However, one major concern for adaptive antenna system is the non-linearity effects of the RF/IF chain upon digital baseband beam forming network. This contribution investigates these effects on the performance of adaptive antennas and suggests the use of linearised transceiver system to tackle the non-linearity problem.

INTRODUCTION:

With the fast growth of mobile communication and high demand for better services, the drive for new systems is ever more strong. The evolving standards, such as Future Public Land Mobile Radio Telecommunications System (FPLMRS) in north America and Universal Mobile Telecommunications Systems (UMTS) in Europe [1], for third generation wireless system are placing very demanding requirements upon the air interface specifications of such systems. In order to meet the twin goals of high capacity alongside the support of the full range of tele-services specified for these networks, the integration of adaptive antenna techniques is seen as an attractive solution for the air interface design.

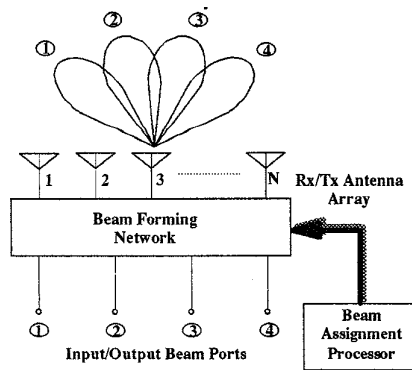


Figure 1 Schematic of an adaptive antenna system

A generic adaptive antenna array is shown in Figure 1; which consists of N antenna elements connected together via beam forming networks (BFNs). The BFNs can control both amplitudes and phases (weights) of the excitation to the antenna array such that single or multiple outputs can be created. The BFNs are under the control of a real-time adaptive signal processor, thus the antenna array beam pattern, frequency response and various other parameters can be automatically adjusted in order to enhance the performance of the embedded system. By adjusting the beam former weights, $N-1$ radiation pattern nulls can be formed towards interfering signal sources. Alternatively, the main beam of the antenna can be electronically steered towards a desired signal source in order to enhance the antenna's gain in a particular look direction. In addition, the array can be configured to form multiple radiation pattern maxima, or optimise the main beam to sidelobe response. One of the key applications of adaptive antenna arrays considered here is that of spatial filtering in order to separate multiple signal sources, which is sometimes referred to as Spatial Division Multiple Access (SDMA). Figure 2 illustrates adaptive SDMA in a cellular system.

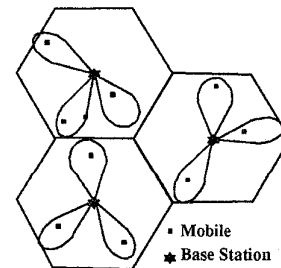


Figure 2: Adaptive SDMA in a cellular system

By exploiting the spatial filtering properties of adaptive antenna arrays in mobile cellular environments it is possible to confine the radio energy associated with a given mobile to a small

addressed volume, thus reducing the amount of co-channel interference experienced from and by co-channel users. This ultimately leads to a capacity enhancement for interference limited systems [2]. In terms of UMTS this can be exploited as a capacity enhancement technique, thereby reducing the need for very small cell sizes in traffic hot spot areas, and thus considerably reducing the infrastructure costs and visual impact of the network. In addition, the adaptive antenna basestation could be used to focus energy towards street canyons where 'black-spots' in system coverage currently exist. This approach relies upon the exploitation of roof-top diffraction in order to provide the necessary 'in-fill', as shown in Figure 3. In the long term, this approach may eliminate the need for 'Repeaters' in many systems.

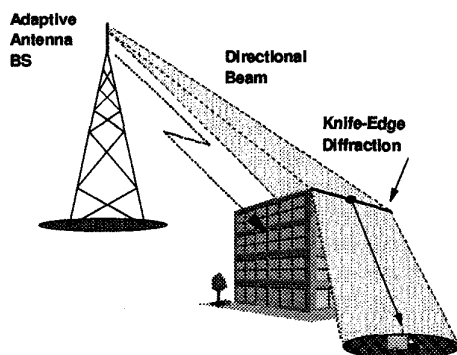


Figure 3: Diffraction 'In-fill'

The raw throughput of many air interface techniques is limited by the delay spread of the channel. Adaptive antenna techniques can be applied to help combat multipath activity, and thus support higher bit rate services within a given operational environment [3]. This is extremely important in terms of the range of services foreseen for UMTS with data rates of upto 2Mbit/s.

Mobility between different cell types is a necessary prerequisite in UMTS, and thus the umbrella cell has been proposed to support fast moving vehicles within a microcellular service areas, and also support gaps between the service areas offered by the different cell types. However, in order to provide an elegant implementation of seamless handover within

a mixed cell environment, all cells types must operate on identical carrier frequencies.

The only foreseeable means of achieving the necessary RF power balancing within each service area, and thus avoiding the near-far effect, is to exploit the spatial filtering properties offered by adaptive antenna systems.

Despite all these advantages adaptive array antennas offer, their applications in commercial mobile communications systems are not common. This is partly due to system implementation[4]. Works on feasibility and system issues are interesting research areas, (see for example [5]). This paper addresses the linearity problem in adaptive array antenna system implementations.

LINERITY REQUIREMENT IN ADAPTIVE ANTENNA ARRAY SYSTEMS

The beam forming network of an adaptive antenna array can be implemented using either analogue technology at Radio Frequency (RF) or Intermediate Frequency (IF) or Digital circuit technology at Base-band (DB). As discussed in [4,5], RF and IF techniques, although once popular, are relatively inflexible when considering the various adaptive antenna architectures suitable for UMTS. The advent of high speed VLSI (Very Large Scale Integrated Circuit) CMOS (Complementary Metal Oxide Semiconductor) digital processing makes this technology suitable for beam forming hardware at DB. However, the use of DB beam forming technique poses high linearity demands on both the RF/IF up- and down-conversion chain. This is because that the weights of the beam former are carefully constructed at digital base-band, any distortion in the up- and down-conversion chain would alter the antenna beam pattern. Some of the fixed mismatches between channels can normally be calibrated out using on-line calibration techniques. The non-linearity effects in the transceiver chain, however, will cause intermodulation distortion which can not be calibrated out in a practical way. These intermodulation products (IMPs) will

ultimately render the adaptive antenna useless. This is illustrated in Figure 4.

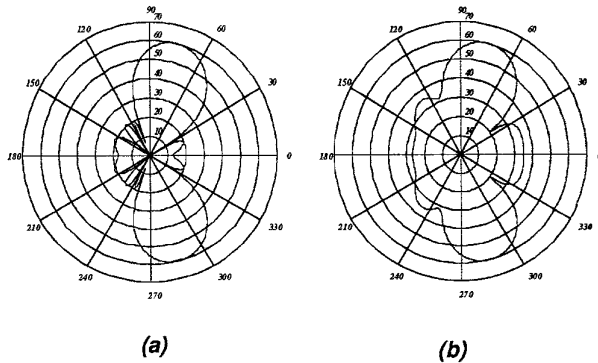


Figure 4: (a) Dolph-Chebyshev weighted linear array (b) the same array with non-linearity presents

Here a linear eight element Dolph-Chebyshev weighted antenna array beam pattern is generated with sidelobe level suppressed to be 40dB below the main lobe. In an ideal system, this would mean that in the un-wanted look directions, there are little radiations. However, when some non-linearity is introduced to the system, the antenna beam pattern is severely distorted. Sidelobe levels come back to be just over 20dB below the main lobe. Null depth is reduced with null directions changed. This not only limits the resolution of SDMA but also increases the amount of interferences emissions. It limits the amount of interference cancellation achievable by an adaptive antenna array system as well. This effect is clearly not wanted in a adaptive array antenna system.

Antenna beam pattern and the IMPs:

The relation of IMPs and the antenna amplitude and phase weighting (see Figure 5) can be shown to be :

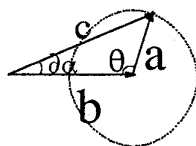


Figure 5: Effect of IMPs

$$AMP = \sqrt{1 + \exp(IMP/10) - 2 \times \exp(IMP/20) \cos \theta}$$

$$\partial \alpha = \cos^{-1} \frac{1 - \exp(IMP/20) \times \cos \theta}{\sqrt{1 + \exp(IMP/10) - 2 \times \exp(IMP/20) \times \cos \theta}}$$

Here, $IMP = 20 \log(a/b)$, where a is the IMP amplitude level; b is the original amplitude weighting; θ is the IMP angle relative to the original weighting vector; AMP is the resultant amplitude weighting; and $\partial \alpha$ is the additional phase weight due to IMPs.

By incorporating the above equations into a simulation program using a third-order non-linear model similar to that of [13], the effect of non-linearity on antenna array parameters, such as side lobe levels (SLLs), null depth (ND), main beam width (BW) and change in null direction (CND), can be derived.

IMP (dB)	BW (°)	SLL (dB)	ND (dB)	CND (°)
-10	11.7	8.7	35.7	9.9
-17	13.3	12.6	29.0	7.4
-20	14.1	15.0	26.2	6.2
-27	15.6	21.4	24.6	2.6
-30	15.9	23.1	25.8	1.7
-75	16.4	29.6	42.5	0

TABLE 1 IMP LEVEL EFFECT

Table 1 lists these parameters against different level of IMPs in a transceiver system for an 8 element linear array with Dolph-Chebyshev weighting for a sidelobe level of 30dB below main lobe. It can be seen clearly that with a non-linear system the side lobe level comes up, the null position shifts as well. The latter has much more serious system implication. This is because that when one tries to suppress an interference at a given look direction, the non-linearity in the system will move the null away from the desired direction.

It is also worth noting that the null depth deepens when the IMP level gets high. This is due to the 30dB Dolph-Chebyshev weighting get distorted. The SLL is clearly proportional to the amount of IMP level in the system. For comparison an IMP level of -75dB is included in the table as well. It is

worth noting that although the BW, SLL and CND do not change much for a system with 30dB IMP level, the ND is reduced from 42.5 to 25.8. The interference cancellation capability is reduced by approximately 50 times (17dB). This will seriously impair the system performance.

Near-far effects and the IMPs

The other linearity requirement in a mobile communications system comes from the near-far resistance, or co-adjacent-channel interference requirement. The IMPs generated by the up- and down- conversion chain tends to drown out the signal from a distant user. This is illustrated in Figure 6.

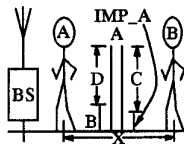


Figure 6: Near-far effects

Here two users, A and B are spatially separated by a distance $X(m)$ which gives a signal pathloss difference of $D(dB)$ between A and B. The level of IMPs of the near user, A in this case, IMP_A is $C(dB)$ below the signal level (A) in the system. However, IMP_A must be sufficiently lower than that of the far user signal (B) such that user B may establish a successful link. However, if $D > C$, the signal from user B will not be demodulated successfully, since IMP_A is larger than signal from user B.

The requirement of co-adjacent-channel protection ratio (CPR/APR) is system dependent[6-10]. It is therefore difficult to generalise this parameter. However, if a typical CPR/APR of 70dB is used, most un-linearised amplifiers will not meet this specification without large back-off.

In order to fully utilise the potential benefits offered by adaptive antenna array system, the non-linearity effects in the transceiver system will have to be suppressed to a degree (say about -70dB) such that they will become acceptable.

Sources of non-linearity

There are many sources of non-linearity in a transceiver system. Assuming the DB part works in a reliable way, the ADC and DAC non-linearities can be circumvented by using large dynamic range chips, namely, more bits. This option although more expensive is seen as more and more viable with the fast development of IC technology. Devices, such as the up- and down- converters, working by non-linearity can be made to behave more linearly by setting the drive levels of these devices properly. Given that these devices working at lower frequencies, these constraints are met fairly easily. The most problematic parts of a transceiver lie in the front-end, namely, the low noise amplifiers (LNAs) for receivers and the power amplifiers (PAs) for transmitters.

The linear dynamic range problem for the LNA is a tricky one: on the one hand, it will have to be able to cope with multiple signals with different amplitude levels without drowning the weak signals from a distant user by a near user's IMPs; on the other hand, it must meet the receiver sensitivity requirement specified to a given system. Efforts have been made in the Centre for Communications Research (CCR) to look into this problem.

The scattering environment will also have impact on the performance of an adaptive array antenna system. However, due to the limited space, this problem will be discussed in a future paper [14].

The PA linearisation problem is a classic problem. Various techniques exist to achieve linearity in different system. Techniques in achieving high linearity over a broad operational bandwidth have been presented recently [11]. It will not be repeated here other than stating that the feed forward linearisation technique is the most suitable approach for base station applications.

IMPACT OF LINEARISED TRANSCIVER SYSTEM

The effect of a large linear dynamic range transceiver system have a number of significant implication on mobile communications systems. First of all, it will allow an adaptive antenna system

working to its best possible performance. This will not only extend the range of coverage of a mobile base station; it will also improve the overall system performance. Recent simulation work [12] has shown that with the use of an adaptive array antenna system, the RMS delay spread can be reduced by a factor of 3. This in most practical systems will eliminate the need of a channel equaliser. Secondly, it will make dynamic frequency allocation possible, which will enhance network performance tremendously. It will also permit the use of linear modulation format which will improve system capacity even further.

CONCLUSIONS AND DISCUSSIONS

The effects of non-linearity on the performance of adaptive array antennas has been presented. The feed forward linearisation technique is identified as the most suitable for mobile communication base station applications. This is because that the large bandwidth requirement and multiple carrier operations at base stations. The effect of using linearised amplifiers in communications system has also been discussed.

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