Adaptive Modulation and Adaptive Antenna Array Assisted Network Performance of Multi-User Detection Aided UTRA-like FDD/CDMA Systems

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Abstract— **The adaptive antenna array and adaptive modulation aided network performance of a Frequency Division Duplex (FDD) Code Division Multiple Access (CDMA) based system is investigated using system parameters similar to those of the Universal Mobile Telecommunication System (UMTS). A number of performance metrics, such as the call dropping probability, the average throughput as well as the required average transmit power are quantified. It is demonstrated that the employment of adaptive modulation techniques in conjunction with adaptive antenna arrays resulted in significant network capacity gains in the scenarios investigated.**

I. INTRODUCTION

Although the various third-generation (3G) system parameters [1] undergo perpetual evolution, it is beneficial to study the network performance of a typical advanced UTRA-like FDD CDMA system. Albeit the initial 3G systems are expected to refrain from employing the most powerful performance enhancement techniques available at the current state-of-the-art, in this contribution we embark on quantifying their potential joint performance benefits. Specifically, in contrast to the previous literature [2]- [4], the novelty of this paper is that it jointly optimises the performance benefits of adaptive antennas [1], adaptive modulation [5] and multi-user detection [6], bridging the physical and network layer.

The outline of this contribution is as follows. Section II introduces the system parameters, leading to a discussion of the performance metrics in Section III. The performance benefits of using adaptive modulation [5] in a pedestrian scenario are quantified in Section IV and we conclude our discussions in Section V.

II. SYSTEM PARAMETERS

The soft handover, the power control and spreading code allocation principles of the system studied were outlined in [1], hence here we refrain from detailing these issues. New call channel allocation requests were placed in a resource allocation queue for up to 5s. If during this period a call was not serviced, it was classed as blocked. The mobiles moved freely, in random directions, at a speed of 3 miles/hour (mph) within the simulation area, which consisted of 49 cells of an infinite wrapped-around cellular system [1]. The employment of this wrapped-around mesh allowed us to avoid the 'desert-island-like' edge effects associated with a reduced co-channel interference near the boundaries of a finite area. The cell-radius was 150 m. The inter-call periods were Poisson distributed, while the call duration was negative exponentially distributed, both obeying the mean values shown in Table I. For our initial investigations we have assumed that the basestations and mobiles form a synchronous network, both in the up- and the down-link.

Furthermore, the basestations are assumed to be equipped with the Minimum Mean Squared Error Block Decision Feedback Equaliser (MMSE-BDFE) based Multi-User Detector (MUD) [6]. The post-despreading SINRs required by this MUD for obtaining the target BERs were determined with the aid of physical-layer simulations using an adaptive modulation assisted CDMA scheme [5], in conjunction with $1/2$ rate turbo coding [9] and MUD, when communicating over a COST 207 seven-path Bad Urban channel [5, 12]. Using this turbo-coded MUD-assisted transceiver and a spreading factor of 16, the post-despreading SINR required for maintaining the target BER of 1×10^{-3} was 8.0 dB. The BER corresponding to low-quality access was stipulated to be 5×10^{-3}. This BER was exceeded for SINRs below 7.0dB. Furthermore, a low-quality outage was declared, when the BER of 1×10^{-2} was exceeded, namely for SINRs below 6.6 dB. These values can be seen along with the other system parameters in Table I.

III. PERFORMANCE METRICS

There are several performance metrics that can be used for quantifying the performance or quality of service provided by a mobile cellular network. The following performance metrics have been widely used in the literature and were also advocated by Chuang [11]:

- New call blocking probability, P_B.
- Call dropping or forced termination probability, P_{FT}. A call is dropped when the lower of the uplink and downlink SINRs dips consecutively below the outage SINR, where the BER exceeds 1% a given number of times.
- Probability of a low quality access, P_{low}, quantifies the chances of either the uplink or downlink signal quality being sufficiently poor, resulting in a low quality access, where the BER exceeds 0.5%.
- Probability of outage, P_{out}, is defined as the probability that the SINR is below the value at which the call is deemed to be in outage.
- Grade-Of-Service (GOS) was defined by Cheng and Chuang [11] as :

$$\begin{aligned} GOS &= P\{\text{unsuccessful or low-quality call accesses}\} \\ &= P\{\text{call is blocked}\} + P\{\text{call is admitted}\} \times \\ &\quad P\{\text{low signal quality and call is admitted}\} \\ &= P_B + (1 - P_B)P_{low}. \end{aligned} \tag{1}$$

In order to determine the number of users that may be supported with adequate call quality by the network, we have defined a conservative and a lenient scenario which are formed from a combination of the performance metrics, as follows [13]:

- *Conservative scenario* :
$P_B \leq 3\%$, $P_{FT} \leq 1\%$, $P_{low} \leq 1\%$ and $GOS \leq 4\%$.
- *Lenient scenario* :
$P_B \leq 5\%$, $P_{FT} \leq 1\%$, $P_{low} \leq 2\%$ and $GOS \leq 6\%$.

Since in [1,10] we identified an attractive handover algorithm, in this contribution **we focus our attention on the joint benefits of adaptive modulation [5] and Adaptive Antenna Arrays [1] (AAAs)** on a UTRA-like network's performance in a pedestrian scenario. Specifically, our investigations were conducted using the relative E_c/I_o based soft handover algorithm of [1] in conjunction with the new call acceptance threshold of T_{acc}=-10 dB and call dropping threshold of T_{drop}=-18 dB, using a spreading factor of 16. Given that the chip rate of

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Parameter	Value	Parameter	Value
Noisefloor	-100 dBm	Pilot power	-5 dBm
Frame length	10 ms	Cell radius	150 m
Multiple access	FDD/CDMA	Number of basestations	49
Adaptive modulation scheme [5]	QAM	Spreading factor	16
Minimum BS transmit power	-44 dBm	Minimum MS transmit power	-44 dBm
Maximum BS transmit power	21 dBm	Maximum MS transmit power	21 dBm
Power control stepsize	1 dB	Power control hysteresis	1 dB
Low quality access (BER $\geq$ 0.5 %) SINR	7.0 dB	Outage (BER $\geq$ 1%) SINR	6.6 dB
Pathloss exponent	-3.5	Size of Active Basestation Set (ABS)	2
Average inter-call-time	300 sec	Max. new-call queue-time	5 sec
Average call length	60 sec	MS speed	3 mph
Maximum consecutive outages	5	Signal bandwidth	5 MHz
Target SINR (at BER=0.1%)	8.0 dB		

TABLE I

SIMULATION PARAMETERS.

UTRA is 3.84 Mchips/sec, this spreading factor corresponds to a channel data rate of $3.84\times10^6/16 = 240$ kbps. Applying $1/2$ rate error correction coding would result in an effective data throughput of 120 kbps, whereas utilising a $2/3$ rate error correction code would provide a useful throughput of 160 kbps. Again, a cell radius of 150 m was assumed and a pedestrian walking velocity of 3 miles/hour was used, while the remaining system characteristics - including the power control scheme, the OVSF code allocation algorithm [1, 8] and the multi-user detector [6] - were identical to those used in [10], which are also summarised in Table I.

IV. PERFORMANCE OF ADAPTIVE ARRAYS AND ADAPTIVE MODULATION IN A HIGH DATA RATE PEDESTRIAN ENVIRONMENT

A. *The Antenna Arrays*

In our previous investigations employing AAAs at the base station [13] we observed quite significant performance gains as a direct result of the interference rejection capabilities of the AAAs invoked. Since the CDMA based network considered here has a frequency reuse of 1, the levels of co-channel interference are significantly higher than in [13], and hence the adaptive antennas may be able to null the interference more effectively. On the other hand, the high number of interference sources may limit the achievable interference rejection.

In order to render the simulations realistic, we used two multipath rays, in addition to the line-of-sight ray, each having a third of the direct-path's power. The angle-of-arrival of each multipath ray was determined using the so-called Geometrically Based Single-Bounce Elliptical Model (GBSBEM) of [14, 15] with parameters chosen such that the multipath rays had one-third of the received power of the direct ray. The Probability Density Function (PDF) of the angle-of-arrival distribution used in the simulations generated using the GBSBEM is shown in Figure 1. It was assumed that the multipath rays arrived with no time delay relative to the LOS path. However, in a practical system a space-time equalizer [16, 17] would be required to prevent the nulling of the delayed paths.

Network performance results were obtained using two and four element adaptive antenna arrays, both in the absence of shadow fading, and in the presence of 0.5 Hz and 1.0 Hz frequency shadow fading exhibiting a standard deviation of 3 dB. **The adaptive beamforming algorithm used was the Sample Matrix Inversion (SMI) algorithm [1]. Below the specific adaptive beamforming implementation used for calculating the AAA weights in the CDMA based network studied here is briefly highlighted as follows [13].**

Specifically, one of the eight possible 8-bit BPSK reference signals was used for identifying the desired user, and the remaining interfering users were assigned the other seven 8-bit reference signals. The received signal's autocorrelation matrix was then calculated, and from the knowledge of the desired user's reference signal, the receiver's optimal antenna array weights were determined with the aid of the SMI algorithm [1]. Since this implementation of the algorithm only calculated the basestation receiver's antenna array weights, i.e. the antenna arrays weights used by the base station in the uplink, these weights may not be suitable for use in the downlink, when independent up/downlink shadow fading is experienced. Hence, investigations were conducted in two specific scenarios, namely where the uplink and downlink AAA weights were identical, as well as when they were separately determined for the uplink and downlink. The corresponding uplink beamforming scenario is portrayed for the sake of illustration in Figure 2, while an appropriately modified, but similar scenario is valid for the downlink, which is not shown here for reasons of space economy.

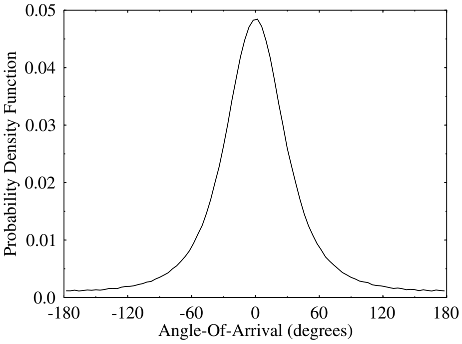

Fig. 1. Probability density function of angle-of-arrival of the multipath rays, centred about the angle-of-arrival of the line-of-sight path.

The two separate uplink and downlink AAA weight calculation scenarios allowed us to determine the potential extra performance gain that may be achieved by separately calculating the AAA weights to be used in the downlink. The AAA weights were re-calculated for every power control step, i.e. 15 times per UTRA data frame, due to the potential significant changes in terms of the desired signal and interference powers that may occur during one UTRA frame as a result of the maximum possible 15 dB change in power transmitted by each user. The performance of both of these

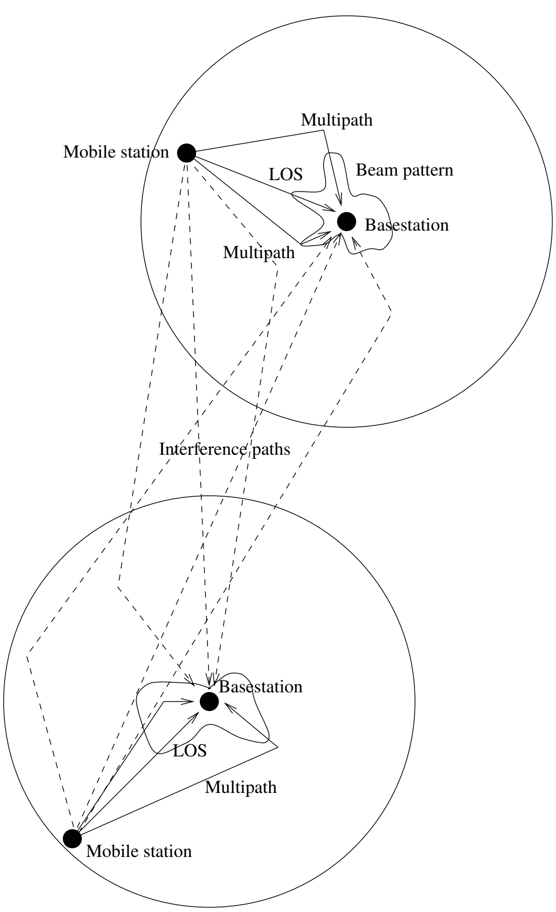

Fig. 2. The multipath environments of the uplink showing the multipath components of the desired signals, the line-of-sight interference and the associated base station antenna array beam patterns.

scenarios was summarised in Table II [1]. In the next section we will show the benefits of employing adaptive modulation [5].

B. *Employing Adaptive Modulation*

In this section we apply Adaptive Quadrature Amplitude Modulation (AQAM) techniques [5]. **There are two main objectives, when employing AQAM, namely counteracting the effects of time-variant channel quality fluctuations as well as the effects of the time-variant interference load imposed by the time-variant number of variable-rate users supported.** [1] The various experimental conditions investigated were identical to those used for generating the results of Table II, except for the application of AQAM [5]. Since in Table II an increased network capacity was achieved due to using independent up- and down-link beamforming, this procedure was invoked in these simulations. AQAM involves the selection of the appropriate modulation mode in order to maximise the achievable data throughput over a channel, whilst minimising the Bit Error Ratio (BER). More explicitly, the philosophy behind AQAM is the most appropriate selection of a modulation mode according to the instantaneous radio channel quality experienced [5, 19]. Therefore, if the SINR of the channel is high, then a high-order modulation mode may be employed, thus exploiting the temporal fluctuation of the radio channel's quality. Similarly, if the channel is of low quality, exhibiting a low SINR, a high-order modulation mode would result in an unacceptably high BER or FER, and hence a more robust, but lower throughput modulation mode would be employed. Therefore, AQAM combats the effects of time-variant channel quality, while also attempting to maximise the achieved data throughput, and maintaining a given BER or FER. In the investigations conducted, the modulation modes of the up and downlink were determined independently, thus taking advantage of the lower levels of co-channel interference on the uplink, or of the potentially higher transmit power of the base stations.

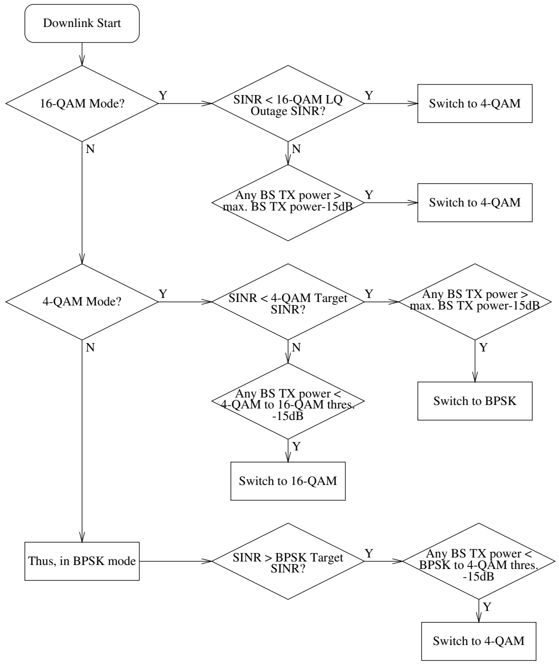

Fig. 3. The AQAM mode switching algorithm used in the downlink of the CDMA based cellular network.

The particular implementation of the AQAM mode switching procedure used in these investigations is illustrated in Figure 3 [1]. This figure describes the algorithm in the context of the downlink, but the same implementation was used also in the uplink. For a detailed discussion of the inner working of the algorithm the interested reader is referred to [1]. Table III shows the BPSK, 4-QAM and 16-QAM reconfiguration SINR thresholds used in the simulations. The BPSK SINR thresholds were 4 dB lower, than those necessary when using 4-QAM, while the 16-QAM SINR thresholds were 5.5 dB higher [12]. In other words, in moving from the BPSK modulation mode to the 4-QAM modulation mode, the target SINR, low quality outage SINR and outage SINR all increased by 4 dB. When switching to the 16-QAM mode from the 4-QAM mode, the SINR thresholds were increased by 5.5 dB. However, it was necessary to set the BPSK to 4-QAM and the 4-QAM to 16-QAM mode switching thresholds to a value 7 dB higher than the SINR required for maintaining the target BER/FER, in order to prevent excessive outages due to sudden dramatic channel-induced variations in the SINR levels.

Performance results were obtained both with and without beamforming in a log-normal shadow fading environment, at maximum fading frequencies of 0.5 Hz and 1.0 Hz, and a standard deviation of 3 dB. Again, a pedestrian velocity of 3 mph, a cell radius of 150 m and a spreading factor of 16 were used, as in our previous investigations.

Figure 4 shows the significant reduction in the probability of a dropped call, achieved by employing AAAs in conjunction with AQAM in a log-normal shadow faded environment. The mean transmission power versus teletraffic performance is depicted in Figure 5, suggesting that the required mean uplink transmission power was always significantly below the mean downlink transmission power, which

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[1] Unless otherwise stated, for the sake of simplicity we will refer to time-variant channel quality fluctuations, regardless, whether these were imposed by fading effects or by co-channel interference fluctuations.

Shadowing	Beamforming:	independent up/down-link	Conservative scenario, P_{FT}=1%, P_{low}=1% Users	Traffic (Erlangs /km^2/MHz)	Power (dBm) MS	BS
No	No	-	256	1.42	3.1	2.7
No	2 elements	-	325	1.87	3.75	0.55
No	4 elements	-	480	2.75	4.55	1.85
0.5 Hz, 3 dB	No	-	$\approx$150	0.87	-1.2	-1.7
0.5 Hz, 3 dB	2 elements	No	203	1.16	0.1	-1.1
0.5 Hz, 3 dB	4 elements	No	349	2.0	2.0	0.65
0.5 Hz, 3 dB	2 elements	Yes	233	1.35	0.2	-0.8
0.5 Hz, 3 dB	4 elements	Yes	$\approx$375	2.2	2.15	0.85
1.0 Hz, 3 dB	No	-	144	0.82	-1.1	-1.6
1.0 Hz, 3 dB	2 elements	No	201	1.12	-0.3	-1.1
1.0 Hz, 3 dB	4 elements	No	333	1.88	1.6	0.5
1.0 Hz, 3 dB	2 elements	Yes	225	1.31	0.1	-0.9
1.0 Hz, 3 dB	4 elements	Yes	365	2.05	1.65	0.6

TABLE II

Maximum mean carried traffic and maximum number of mobile users that can be supported by the network, whilst meeting the conservative quality constraints. The carried traffic is expressed in terms of normalised Erlangs (Erlang/km^2/MHz) for the network described in Table I both **with and without beamforming (as well as with and without independent up/down-link beamforming), and also with and without shadow fading having a standard deviation of 3 dB** for SF=16.

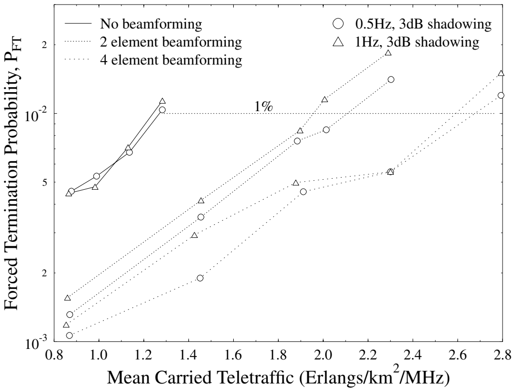

Fig. 4. Call dropping probability versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds both **with and without beamforming in conjunction with AQAM as well as with shadowing having a standard deviation of 3 dB** for SF=16.

can be attributed to the pilot power interference encountered by the mobiles in the downlink. This explanation can be confirmed by examining Figure 6, which demonstrates that the mean modem throughput in the downlink, without AAAs, was lower than that in the uplink even in conjunction with an increased downlink transmission power. However, the increase in the mean downlink transmission power resulted in a more substantial increase in the mean downlink modem throughput, especially with the advent of the four element antenna arrays, which exhibited an approximately 0.5 BPS throughput gain over the two element arrays for similarly high traffic loads which can be seen in Figure 6.

A summary of the maximum user capacities of the networks considered in this section in conjunction with log-normal shadowing having a standard deviation of 3 dB, both with and without employing beamforming using two and four element arrays is given in Table IV. The teletraffic carried, the mean mobile and base station transmission powers required, and the mean up- and down-link modem data throughputs achieved are also shown in Table IV. For more performance results on the topic the interested reader might like to consult reference [1].

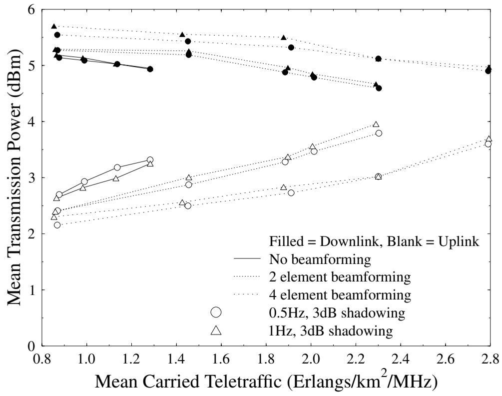

Fig. 5. Mean transmission power versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds both **with and without beamforming in conjunction with AQAM as well as with shadowing having a standard deviation of 3 dB** for SF=16.

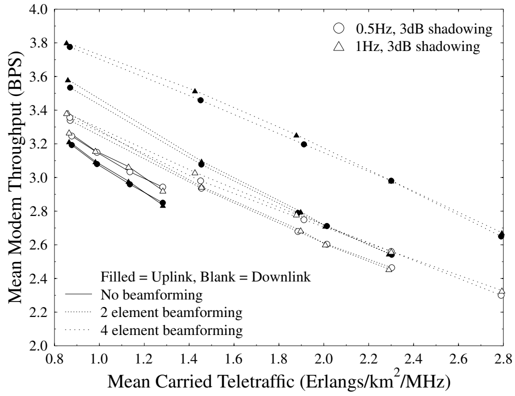

Fig. 6. Mean modem throughput versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds both **with and without beamforming in conjunction with AQAM as well as with shadowing having a standard deviation of 3 dB** for SF=16.

		Conservative scenario					
			Traffic (Erlangs	Power (dBm)		Throughput (BPS)	
Shadowing	Beamforming	Users	/km^2/MHz)	MS	BS	Uplink	Downlink
0.5 Hz, 3 dB	No	223	1.27	3.25	4.95	2.86	2.95
0.5 Hz, 3 dB	2 elements	366	2.11	3.55	4.7	2.56	2.66
0.5 Hz, 3 dB	4 elements	476	2.68	3.4	5.0	2.35	2.72
1.0 Hz, 3 dB	No	218	1.24	3.3	4.95	2.87	2.96
1.0 Hz, 3 dB	2 elements	341	1.98	3.5	4.9	2.62	2.73
1.0 Hz, 3 dB	4 elements	460	2.59	3.5	4.95	2.4	2.8

TABLE IV

Maximum mean carried traffic and maximum number of mobile users that can be supported by the network, whilst meeting the conservative quality constraints. The carried traffic is expressed in terms of normalised Erlangs (Erlang/km^2/MHz), for the network described in Table I both **with and without beamforming (using independent up/down-link beamforming), in conjunction with shadow fading having a standard deviation of 3 dB, whilst employing adaptive modulation techniques** for SF=16.

SINR Threshold	BPSK	4-QAM	16-QAM
Outage SINR	2.6 dB	6.6 dB	12.1 dB
Low Quality Outage SINR	3.0 dB	7.0 dB	12.5 dB
Target SINR	4.0 dB	8.0 dB	13.5 dB

TABLE III

The target SINR, low quality outage SINR and outage SINR thresholds used for the BPSK, 4-QAM and 16-QAM modulation modes of the adaptive modem.

V. Summary and Conclusions

The impact of AAAs upon the IMT2000 / UTRA network capacity was considered in both non-shadowed and log-normal shadow faded propagation environments, which was further improved with the aid of AQAM techniques. **In conclusion, the employment of AQAM increased both the average throughput and the robustness of the network, since a sudden channel quality reduction did not result in dropping the call supported, it rather activated a lower-throughput, but more robust modulation mode.**

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