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An Assessment of Interference Cancellation Applied to BWA

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Abstract— **It is a general principle that a communication system should be designed to avoid interference in the first place, either through network planning or with effective radio resource management and medium access control. However to meet the increasing demands placed upon the radio spectrum, more efficient use is required and stringent requirements on interference levels can lead to large co-channel re-use distances in some radio systems. This paper assesses the effectiveness of interference cancellatio0n techniques applied in an urban Broadband Wireless Access (BWA) scenario. This demonstrates that greater coverage and throughput can be achieved in interference limited scenarios. Large gains were achieved with omnidirectional antennas, which is pertinent for mobile systems**

Index Terms—**OFDM, BWA, interference cancellation**

I. INTRODUCTION

In systems where geographical co-channel frequency re-use is employed, Interference Cancellation (IC) techniques have the potential to allow spectrum efficiency improvements by allowing the distance between co-channel transmitters to be reduced. This potentially includes a wide range of wireless systems including Cellular, Fixed Links, Broadcast and Satellite. However, technical and commercial constraints can mean that in some systems introducing interference cancellation techniques may not be viable. It was the aim of this study to quantify what spectral efficiency benefits would be possible within deployments of a broadband wireless access (BWA) system by the use of interference cancellation techniques. In the context of this study, interference cancellation techniques are any technique or combination of techniques that allow an existing receiver to operate with higher levels of co-channel interference.

It is a general principle that a communication system should be designed to avoid interference in the first place, either through network planning or with effective radio resource management and medium access control. However to meet the increasing demands placed upon the radio spectrum more efficient use is required and stringent requirements on interference levels can lead to large co-channel re-use distances in some radio systems. If Interference Cancellation can allow a receiver to operate with higher levels of interference, then there is potential for a spectrum efficiency improvement. Furthermore, the increasing use of license exempt spectrum means that interference is unavoidable and so the radio system must not only avoid interference but also mitigate against its presence. A key point is that the strategies employed to mitigate interference are very dependent on the source of the interference and its relationship to the wanted signal.

This paper presents analysis of IC schemes applied to the WiMax BWA system. Section II presents the physical layer performance. Sections IV & V then present the system level analysis for the downlink (DL) and uplink (UL) respectively.

II. PHYSICAL LAYER PERFORMANCE

The OFDM variant of IEEE802.16 for operation below 11GHz [1] has been examined for the BWA scenario. The version considered is a 256 sub-carrier OFDM system. A number of modes have been defined, that vary the data rate and robustness according to the modulation and coding used. The mode parameters studied here are given in Table 1.

Mode	Overall Code rate	Modulation	Throughput (Mbps)
0	½	BPSK	1.73
1	½	QPSK	3.46
2	¾	QPSK	5.19
3	½	16QAM	6.92
4	¾	16QAM	10.3
5	2/3	64QAM	13.84
6	¾	64QAM	15.57

Table 1

To give an idea of the level of interference that can be tolerated, for the 802.16 system, the required SNR ranges from 9.4dB for QPSK to 24.4dB for 64QAM (AWGN channel, 10^{-6} bit error rate) [1]. With interference added, and assuming the effect is the same as adding the same amount of noise (reasonable in unsynchronised OFDM systems), then the required signal to interference ratios (C/I) that do not degrade noise performance by more than 0.5dB for these modes are 17dB and 33dB respectively. Without interference cancelling techniques, the required C/I is maintained by combinations of:

- Frequency re-use (cell separation)
- Transmit power setting during network planning – but low power setting will reduce the cell coverage area.
- Antenna directionality, typically sectorisation at the basestation (BS) and/or highly directional (few 10's of degrees) antennas at the customer equipment (CPE). Sidelobe levels of -10 to -20 dB are reasonable [2].

Such protection factors lead to larger separation distances between co-channel transmitters.

After consideration of the different IC techniques [3], a

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multiple antenna approach has been chosen based on the MMSE algorithm that uses the preamble symbols to determine the combining coefficients. One, two and four receiver elements have been considered. When there are multiple users, and the channels for each are known, for an M element array, L users, $L<M$, then a channel matrix $\boldsymbol{H}$ (LxM) can be defined [5], and the multiuser MMSE solution is (MU algorithm):

$$\boldsymbol{w}_{MU\text{-}MMSE}=(\boldsymbol{HH}^H+\sigma^2\boldsymbol{I})^{-1}\boldsymbol{H} \quad (1)$$

The diagonal loading term sets σ^2 to be the noise power. Where only a single user's signal is required, as in the BWA scenario, the final term can be replaced by $\boldsymbol{H}(0)$ (the channel response for the first user). The calculation of the correlation matrix and the users' channels in (1), imposes a high computational complexity, and so a complexity reduced version only uses the estimated channel of the wanted user, giving (SU algorithm):

$$\boldsymbol{w}_{SU\text{-}MMSE}=(\boldsymbol{H}^{(0)}\,\boldsymbol{H}^{(0)\,H}+\sigma^2\boldsymbol{I})^{-1}\boldsymbol{H}^{(0)} \quad (2)$$

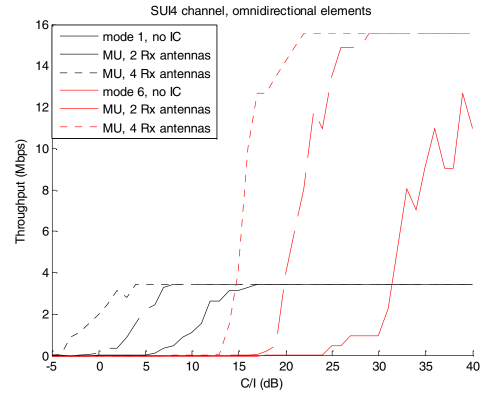
Which is essentially MRC with diagonal loading. The preamble information will be used to derive the channel estimate of the wanted signal to each antenna for the SU algorithm. In this study, for the MU algorithm the channels are assumed to be known (perfect estimation). The weight vectors for each sub-carrier will hence be calculated from (1) and (2).

In order to develop the IC scheme, the Stanford SUI channel models have been used [4], as these were developed for BWA applications. The multipath profile is modeled as the usual tapped delay line filter with exponentially decaying multipath components – only 3 components are used in the models. A number of channels for different environments have been defined in [4] for omnidirectional and directional (30º) antennas at the CPE. For simulations we assume a quasi-static channel (i.e. constant over one packet).

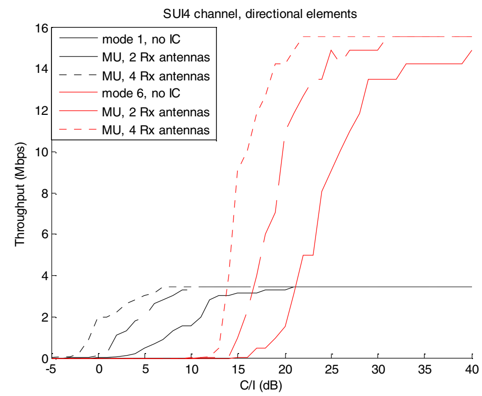
The model does not include medium access control functionality, such as ARQ. The results presented here use 8 data symbols per packet, plus 2 preamble symbols. From the PER the throughput of the raw data is then derived. The throughput figure includes system overheads and signaling data, not just user data, and does take into account ARQ retransmissions.

The simulation results shown below in Figure 1 plot throughput against Signal to Interference Ratio (C/I) for different channel coding and modulation modes and compare sectored and omnidirectional antennas for the multi-user algorithm. The example shows results for the SUI-4 channel, with dispersion in both time and azimuth.

Simulations show that IC achieves the largest performance improvement with omni-directional antennas and high degrees of scattering in the channels, whereas at the with directional antennas and low degrees of scattering in the channel performance improvements are much less. Directional elements reduce the interference power, but they also reduce the channel diversity with a respective impact on IC performance.



SUI-4 Channel Omnidirectional Elements



SUI-4 Channel Directional Elements

Figure 1 PHY performance

III. System Level Simulation

The network level simulation for the BWA scenario considered the city centre of Bristol, with an area of 3km by 1.8km. Five base stations are deployed, one in the centre of the area for the cell of interest (BS1), and four surrounding base stations (BS2-5) providing the interference environment to the central BS. The BS locations were chosen to occupy tall buildings (approximately 30m in height). CPEs are mounted at rooftop level on buildings (e.g. approx. 6m), and are distributed over the geographic area. The CPEs were assigned to the BS/sector with the strongest path. Of the 100 CPEs, 48 are assigned to the central BS (BS1), with the other BSs being assigned the remaining 52 CPEs. With 120 degree sectors, there are 16 CPEs in each of BS1's sectors.The location of CPEs and affiliation to BSs is shown in Figure 2. In the figure locations of CPEs and BSs are overlaid on a terrain map of Bristol city.

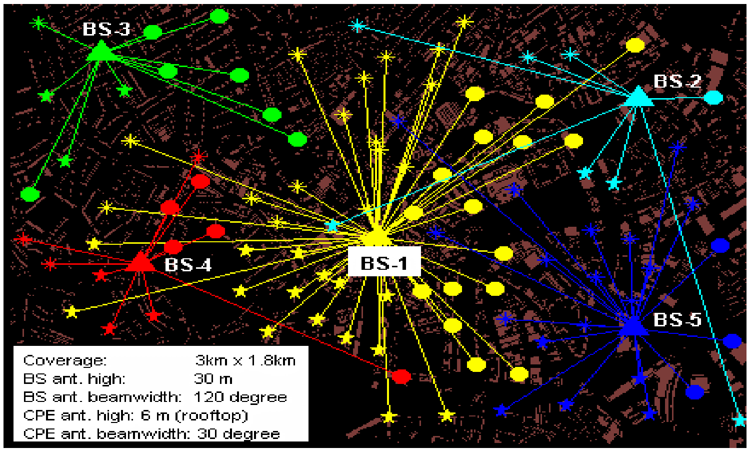


Figure 2 Locations of basestations and CPEs

An FDD mode of operation is used, and the 3.5GHz band has been modeled. The UK allocation in the 3.5GHz band is for paired spectrum 3480-3500MHz and 3580-3600MHz. The 20MHz spectrum blocks will initially be sub-divided into 4 individual 5MHz bands. The IEEE 802.16 air interface considered here is FDD/TDMA and there will be so no intra-cell interference for data packets.

When cancellation is based on the channel spatial properties it is important to correctly model the channels, including their correlations. For this reason, the simulation uses a ray-tracing model to generate channel impulse responses for each of the paths between the BS transmit antenna(s) and the CPE receive antenna(s). With the set of channel impulse responses from the ray-tracing model, a link level simulation was executed to determine the throughput for that particular set of channel impulse responses. The whole process was repeated a sufficient number of times to allow averages of the throughput seen by each CPE to be obtained. Although computationally intensive, this approach avoided the difficulties in attempting to abstract the physical layer model when, as in this situation, the throughput is very dependent on the spatial and temporal variation of the wanted and interfering signals. More accurate results are obtained using this method than when physical layer modeling is performed independently from the system level modeling using abstractions of the physical layer in the system level model.

Other key points of the scenario are:

- Antenna spacing – 1 wavelength at CPE, 5 wavelengths at BS. Multiple transmit antennas are used for basic transmit diversity, but no space-time coding.
- CPE antenna arrays are always linear (ULA), broadside oriented towards the assigned BS (along the line of the strongest path).
- BS arrays are uniform circular array (UCA) for omnidirectional patterns, and uniform linear array (ULA) for sectored system (in standard triangular configuration). The broadside orientations for the 3 sectors at all BSs are 90º (east), 210º and 330º. This 3 sector system is consistent with the SUI model assumptions, and so provides consistency between the physical layer results and this section.
- 2 array configurations are considered: 1. CPE & BS are both omnidirectional; 2. Three 120º BS sectors and directional 30º CPE elements.
- For directional elements types SS1 (beam width 120º) for the BS and DN2 (beam width 30º) for the CPE were used from [2].
- Transmit power is 30dBm for UL and DL, with the sectored system this total power is shared between the sectors. 10º of down tilt is applied to the BS antennas only. A boresight antenna gain of 6dB was applied to all antennas. This configuration was chosen to ensure the comparison was based on equivalent EIRP between scenarios, and in most locations performance was interference limited.
- 100 packets are transmitted for each link, with 8 OFDM data symbols plus preamble symbols in each packet.

On the DL, interference comes from the other BSs, whereas on the UL interference comes from CPEs in other cells. Only one CPE will be active in each cell/sector, but which one will change over time and therefore each UL simulation was repeated 10 times with a different selection of active interfering CPEs.

The packet error rate (PER) for each of the 6 modes over each link is determined. Based on an ARQ mechanism and taking account of throughput losses due to retransmissions, a throughput for each mode can be found. The mode with the highest throughput is chosen subject to the actual throughput achieving at least 75% of the maximum throughput for that mode, otherwise the number of retransmissions would be too high. The process is repeated for every link, and then the mean of the achieved throughputs is calculated to give a figure of merit. Coverage figures relate to the proportion of CPEs assigned to BS1 that have a viable link in any mode.

Antennas	Downlink, omnidirectional, SU algorithm					Downlink, omnidirectional, MU algorithm				
	Throughput		Coverage		Spect. Effy	Throughput		Coverage		Spect. Effy
	Bps	Relative	%	Relative	bps/Hz	bps	Relative	%	Relative	bps/Hz
No IC	1.22	1.00	25%	1.00	0.24					
1x2	3.11	2.55	48%	1.92	0.62	5.50	4.51	73%	2.92	1.10
4x4	4.08	3.34	52%	2.08	0.82	10.5	8.57	96%	3.84	2.09

Table 2 Downlink with omnidirectional antennas

Antennas	Downlink, directional, SU algorithm					Downlink, directional, MU algorithm				
	Throughput		Coverage		Spect. Effy	Throughput		Coverage		Spect. Effy
	Bps	Relative	%	Relative	bps/Hz	bps	Relative	%	Relative	bps/Hz
No IC	7.68	1.00	83%	1.00	1.53					
1x2	9.85	1.28	94%	1.13	1.98	12.31	1.60	100%	1.20	2.46
4x4	10.96	1.46	100%	1.18	2.19	14.93	1.94	100%	1.20	3.00

Table 3 Downlink with directional antennas

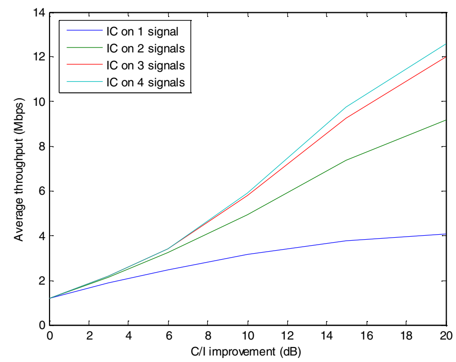
IV. Downlink Results

Figure 3 considers the performance with fixed IC (i.e. the received power of N interferers is reduced by XdB), and compares throughput as different numbers of interferers have this applied. When not all interferers are reduced, the reduction is applied to the strongest received signals. These simulations were carried out using a 1x1 physical layer simulation with the channels from the ray-tracing model.

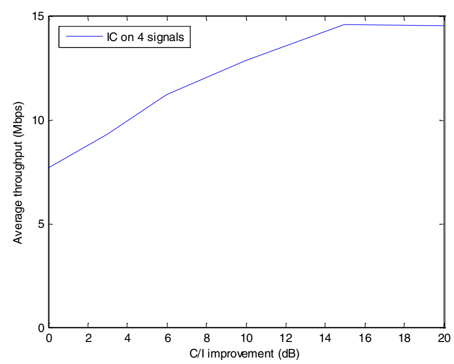
In this interference limited scenario with omnidirectional antennas the average throughput without IC is less than 8% of the maximum achievable throughput (the maximum possible throughput is 15.57Mbps). These show that with moderate levels of cancellation applying IC to only a few interferers is still effective, and thus few antenna elements are required. But to achieve more cancellation, the number of elements needs to be close to the number of transmissions (or more). In the simulations below up to 4 antenna elements are considered, which would allow cancellation of 3 interferers.

Tables 2 & 3 demonstrate the benefits if IC with the different algorithms and antenna configuration on the DL. The key points to note from the omnidirectional DL analysis are:

- The SU algorithm is showing approximately the equivalent of 5 and 7dB of perfect IC with 2 and 4 antennas respectively.
- Equivalent figures for the MU algorithm are 9 and 15dB.
- There is little to be gained for transmit diversity in this scenario, this is not surprising given the limited scattering near the BS antennas. There is no improvement with 2 antenna transmit diversity, and a modest improvement with 4 antenna transmit diversity. This is due to the larger spatial separation between the extreme elements.
- The SU algorithm can only achieve 50% coverage, with an average throughput less than 26% of the maximum.
- The MU method provides close to 100% coverage with 4 receive antennas, and 2/3 of maximum throughput.



(a)Omnidirectional antennas



(b) Directional antennas

Figure 3 Performance with fixed IC

Introducing directional antennas provides a significant step forward in the coverage and achieved throughput. The key conclusions for this scenario are:

- The SU algorithm is showing approximately the equivalent of 4 and 6dB of perfect IC with 2 and 4 antennas respectively. These are only 1dB less than achieved with the omnidirectional case.

Antennas	Uplink, omnidirectional, SU algorithm					Uplink, omnidirectional, MU algorithm				
	Throughput		Coverage		Spect. Effy	Throughput		Coverage		Spect. Effy
	bps	Relative	%	Relative	bps/Hz	bps	Relative	%	Relative	bps/Hz
No IC	1.02	1.00	35%	1.00	0.20					
1x2	1.70	1.67	50%	1.41	0.34	3.60	3.53	67%	1.88	0.72
4x4	2.05	2.01	48%	1.35	0.41	11.3	11.08	96%	2.71	2.26

Table 4 Uplink with omnidirectional antennas

Antennas	Uplink, directional, SU algorithm					Uplink, directional, MU algorithm				
	Throughput		Coverage		Spect. Effy	Throughput		Coverage		Spect. Effy
	bps	Relative	%	Relative	bps/Hz	bps	Relative	%	Relative	bps/Hz
No IC	4.31	1.00	79%	1.00	0.86					
1x2	5.74	1.33	85%	1.08	1.12	11.6	2.70	100%	1.27	2.32
4x4	7.79	1.81	83%	1.05	1.56	15.1	3.50	100%	1.27	3.01

Table 5 Uplink with directional antennas

- Equivalent figures for the MU algorithm are 8 and over 15dB, which again are similar to the omnidirectional case.
- As before there is little to be gained for transmit diversity, and even 4 element transmit diversity provides no additional benefit.
- Without IC, sectorisation and directional elements at the CPE provide clear benefits, with high coverage figures, though less than 50% of maximum throughput.
- The SU algorithm can achieve high levels of coverage, but not 100%, with average throughput approximately 2/3 of the maximum. Additional benefits with 4 antennas are limited, and so the extra costs may not be justified.
- The MU algorithm provides 100% percent coverage in all cases, and 80% and 96% of maximum throughput with 2 and 4 antennas respectively.

V. Uplink Results

The analysis for the UL is presented in Tables 4 & 5. The conclusions for the UL are:

- Again, there are clear benefits of deploying a sectored system, with typically a spectrum efficiency improvement by over a factor of 3. This gain is reduced with more effective IC in operation.
- The UL is more susceptible to interference than the DL and therefore in most scenarios there will be an asymmetry between UL and DL throughputs. This is less significant for the MU algorithm, and does not exist for the 4x4 MU configuration.
- Transmit diversity is more effective on the UL, since scattering local to the CPE can be exploited.
- The MU algorithm again offers the best performance, with 100% coverage and 96% of maximum throughput being possible in the directional scenario.

VI. Discussion

This paper has described an investigation into the performance of a realistic BWA scenario, and has presented a performance analysis with alternative IC algorithms and antenna configurations.

The performance with omnidirectional and directional elements has been investigated. Directional elements provide a mechanism for interference avoidance, which is always to be preferred to allowing interference and then trying to remove it. This demonstrated the clear benefits of using directional elements, but on their own cannot provide 100% coverage of a high throughput across the whole cell. Therefore IC in conjunction with direction elements has shown the high coverage levels can be achieved even in the highest throughput modes. However, the relative gains of IC is greater with omnidirectional elements, and this is most pertinent for mobile terminals as in the IEEE802.16e broadband wireless access standard (mobile WiMax).

The SU algorithm is effective as low cost option, with 2 antenna receive diversity always providing benefits. As expected the MU algorithm is more effective, but did assume perfect channel knowledge. In both cases, transmit diversity offers little if any additional benefit on the downlink. On the uplink, transmit diversity is more effective (especially with the MU algorithm), since the scattering local to the CPE can be exploited more effectively.

The UL degrades most with interference and so an asymmetry in throughputs between UL and DL is evident with no IC or the SU method. In most cases the MU method reduces or removes the asymmetry.

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