Cutting Edge at the Cell Edge: Co-Channel Interference Mitigation in Emerging Broadband Wireless Systems

Bhaskar Ramamurthi
Hon. Director, Centre of Excellence in Wireless Technology, Chennai
Professor, Dept. of Electrical Engineering, IIT Madras
bhaskar@tenet.res.in

***Abstract*—Emerging Broadband Wireless systems, such as those based on IEEE 802.16m or 3GPP LTE-A, will re-use spectrum in every sector ($1:1$ reuse) and maximize system spectrum efficiency. In so doing, the spectrum efficiency for cell-edge users is very poor in comparison with the system-wide average, and nomadic users located near the cell edge experience very low throughput. This is an important concern for India, where nomadic users constitute 85% of mobile phone users, urban cells are relatively small, and the fraction of cell-edge users is as high as 40%. The basic approach to improving cell-edge performance is the so-called fractional frequency reuse (FFR), where spectrum reuse is less than $1:1$ for cell-edge users. However, techniques that mitigate/cancel interference can improve the spectrum efficiency of FFR. This paper reviews an integrated package of three techniques, proposed by CEWiT for inclusion in the international standards, which mitigate the impact of cell-edge co-channel interference in the downlink: two-dimensional phase offset diversity, inter-cell interference cancellation, and conjugate data repetition. The first two techniques employ multiple transmit antennas. The first and third are open-loop techniques, which will work for nomadic as well as high-speed users, while the second is closed-loop and involves base-station co-operation, and is suitable for nomadic users. All three techniques share the important feature that the transmit signal from each basestation appears to be emanating from a single transmit antenna, enabling the use of low-complexity multi-antenna interference suppression algorithms at the receiver. The paper will discuss the performance of each technique, and also show that they can be employed together in a complementary manner to improve cell-edge performance.**

I. Introduction

Next-Generation (4G) Wireless Networks meant for broadband services will be based on Orthogonal Frequency Division Multiplexing (OFDM). Major emerging standards, such as 3GPP LTE [1] and IEEE $802.16e/m$ [2], [3], and 3GPP2 UMB [4], are similar in this respect. Further, the new technologies will employ multiple antennas at the base station and subscriber terminal $-$ typically four at the former (per sector) and two at the latter. The spectral bandwidth will be typically 20 MHz, and may go up to 100 MHz in case of multi-band operation. The throughput of bi-directional data through each cell-site will be of the order of 200 Mbps, assuming 20 MHz spectrum is employed in $1:1$ reuse mode in all sectors. Many of these specifications are incorporated in the IMT-A [5] requirements issued by ITU.

One of the features of this class of systems is that the terminals near the cell boundary (or edge) experience significantly poorer performance than the terminals in the cell interior when spectrum is reused in all cells ($1:1$ reuse mode). In acknowedgement of this reality, the specification for spectum efficiency only requires that at least 95% of the terminals should be served at better than approximately 0.1 bps/Hz [4]. The system average, on the other hand, is expected to be $2.5-3$ bps / Hz per user. Thus, nomadic users who are near the cell edge could experience poor throughput for a sustained period (unless a disproportionate amount of the bandwidth is allocated to the user). Fig. 1 shows the cdf of SINR experienced by users across the cell in a $1:1$ reuse system, as obtained by simulations. The figure indicates that around 40% of users are 'near' the cell-edge in the sense that they all have a low SINR (Signal-to-Interference-and-Noise-Ratio) below 2 dB. While the throughput experienced by the remaining 60% of the users essentially determines the cell average, improving the throughput of this 40% is very important for the cell-edge users themselves. A system with 40% of nomadic users experiencing unsatisfactory performance is unacceptable.

A technique proposed in the emerging standards to improve cell-edge performance on the downlink is to back off from reuse-one, by employing the so-called Fractional Frequency Reuse (FFR) technique. In this technique, neighbouring base stations transmit with full power in non-overlapping parts of the spectral band allotted to the system. In the part of the spectrum (with bandwidth w_1 in fig.2 in which one base station transmits with maximum power density (α), the other neighbouring base stations transmit with lower power (β). Cell-edge users are served in the sub-band with maximum power. While the technique is illustrated in Fig. 2 for three base stations, it can be extended to any number. As a special case, if $w_1 = w_2$ and $\beta = 0$, we get the conventional $1:3$ reuse case. The FFR technique improves cell-edge SINR. An operator can distribute transmit power across frequency so as to achieve the desired SINR cdf, and maximize system capacity while meeting service requirements. It is possible to adapt the FFR curve dynamically by changing the sub-band widths as well as their power density levels, with co-ordination across base stations.

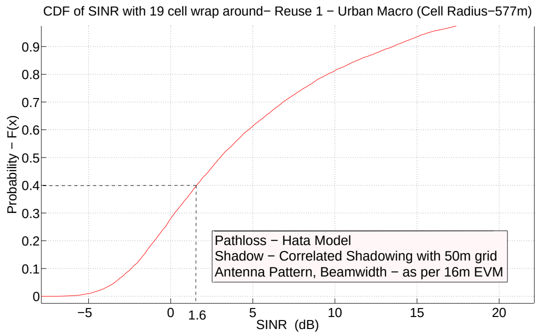

Fig. 1. SINR CDF for Reuse $1:1$ showing the 40% point

In deployments with a large fraction of cell-edge users, the use of FFR is critical to meeting service quality requirements for these users. Physical Layer (PL) techniques, in particular MIMO and interference cancellation methods, that improve the SINR of cell-edge users will improve the efficiency of FFR. In this paper, we consider three such PL techniques for improving downlink SINR. Two-dimensional Phase Offset Diversity (2DPOD) [6] and Conjugate Data Repetition [7] are 'open-loop' techniques that require no feedback from the terminals, while Inter-Cell Interference Cancellation (ICIC) [8] is a 'closed-loop' technique. Either 2DPOD or ICIC can be combined with CDR to give cumulative gains, while 2DPOD and CDR can be employed singly or together on the uplink as well.

We discuss these techniques for the case of 2×2 MIMO, i.e., two transmit and two receive antennas. They can be extended to the case with more antennas as well, as discussed, for example, in [6] for the case of 2DPOD. We show that all three techniques share an important feature that the transmit signal appears to be emanating 'from a virtual single transmit antenna'. This makes the use of multi-antenna interference cancellation (IC) techniques at the receiver practically feasible. While 2DPOD provides the expected diversity from two antennas, IC at the receiver improves SINR. CDR achieves further improvements in SINR, when needed, by doubling the resources (equivalently bandwidth) employed. The closed-loop ICIC technique improves the SINR by modifying the transmit signals at several base stations (that cause the interference) *jointly*. Thus, ICIC involves base station co-operation, an area of great interest in the current standardization efforts. While the open-loop techniques will work for terminals moving at any speed, the closed-loop ICIC technique is suited only to slow-moving terminals. Our interest, in any case, is in the performance for the nomadic user at the cell edge. This paper shows that it pays to take cognizance of interference and tackle it head-on. All the techniques discussed here are being actively considered for inclusion in the emerging broadband wireless standards. We now discuss each technique separately, before considering simulation cases where the techniques are employed singly or jointly.

II. System model

We first introduce the system model and define the variables and parameters of interest. We consider the downlink of an OFDMA-based broadband wireless communication system with two transmit and two receive antennas at each Base Station (BS) and each subscriber terminal (ST) respectively. The channel seen by each subcarrier is assumed to be a flat fading Rayleigh channel and the path gain from the u^{th} transmit antenna of BS_i to the v^{th} receive antenna of ST_j served by BS_j, on the k^{th} subcarrier and l^{th} OFDM symbol, is denoted by $h_{ij}^{uv}(k,l)$. The path gains are modeled as independent samples of zero-mean, complex, Gaussian random variable with variance $\frac{1}{2}$ per real dimension. Fig 3 shows, for illustration, two base stations having two antennas each, and two terminals at the cell boundary, one in each cell. These terminals are assumed to be operating on the same frequency resources simultaneously, i.e., they are co-channel interferers of each other. The notation that follows is more general in that the number of base stations, N, and corresponding co-channel terminals, could be more than two.

In the emerging OFDMA-based IEEE 802.16m [3] and 3GPP LTE [1] standards, data is allocated in groups of resource blocks (RBs). Each (RB) is composed of P sub carriers and Q OFDM symbols, and it is called a localized RB when the P subcarrires are contigouus, and distributed RB when the P subcarriers are dispersed across the entire frequency band. (P and Q are 18 and 6, respectively for IEEE 802.16m, and 12 and 7, respectively for LTE). In the localized mode, the RBs allocated to a user can be either contiguous or distributed over the entire band. For most services, the number of RBs allocated at a time to a single terminal is more than one. These RBs are encoded and decoded as one coding block. Both for distributed RBs and multiple localized RBs distributed sufficiently separated in frequency, frequency diversity will accrue; else we have to rely on space diversity from the antennas to combat fading. It is this latter case, when there are two or more contiguous localized RBs in a coding block, that is of particular interest to us in the next section.

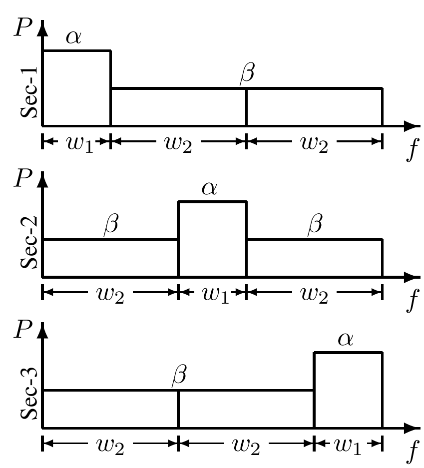

Fig. 2. Fractional Frequency Re-Use

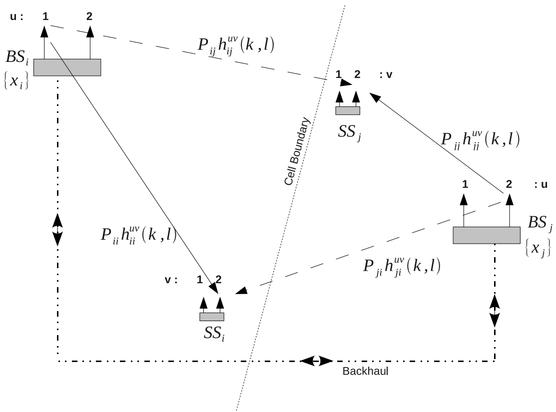

Fig. 3. Illustration of the system model

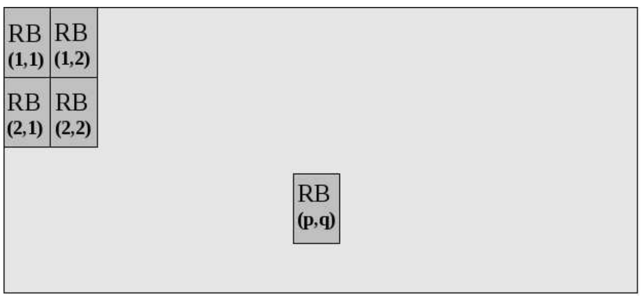

Fig. 4. Resource blocks in a frame

III. 2D Phase Offset Diversity (2D-POD)

It is assumed that there are at least two RBs in a coding block, and more likely, four or more. These RBs could be extending in one dimension only (say, across frequency or time), or in both dimensions. The latter case is shown in Fig. 4.

The same data/pilot tones are transmitted through both the antennas, with a RB-dependent phase rotation applied to one of the antennas:

$$\begin{bmatrix} x_j(k,l) \\ x_j(k,l)e^{j\Phi(p,q)} \end{bmatrix} \tag{1}$$

Here, $x_j(k,l)$ is the transmitted data from BS_j on the $(k,l)^{th}$ tone, and (p,q) denote the two-dimensional RB indices along frequency and time directions respectively. The phase $\Phi(p,q)$ determines the rotation applied to the transmit signal in one of the antennas, and this is kept constant for the $(p,q)^{th}$ RB.

The signal received by ST_j from BS_j on the k^{th} subcarrier in time l at the v^{th} receive antenna can be written as,

$$y_j^v(k,l) = h_{jj}^{1v}(k,l)x_j(k,l) + h_{jj}^{2v}(k,l)x_j(k,l)e^{j\Phi(p,q)} + n_j^v(k,l) \tag{2}$$

After simplification, it can be rewritten as

$$y_j^v(k,l) = [h_{jj}^{1v}(k,l) + h_{jj}^{2v}(k,l)e^{j\Phi(p,q)}]x_j(k,l). \tag{3}$$

POD effectively makes the signal transmitted from the two antennas *look like a signal transmitted from a single virtual antenna with an effective channel* $h_{jj}^v(k,l) = h_{jj}^{1v}(k,l) + h_{jj}^{2v}(k,l)e^{j\Phi(p,q)}$. We will see in the next section that this facilitates the use of the MMSE receiver to suppress interference from co-channel users. Since the pilots are also phase-rotated with the same phase used for data in that RB, it is enough to estimate one effective channel. Therefore, channel estimation becomes simpler in the sense that we need not estimate two channels. This results in either a reduction in pilot overhead to half when compared to STBC without compromising on channel estimation quality, or better channel estimation with the same pilot overhead.

TABLE I
2D-POD Phase Patterns

Phase in RB	2D-POD code-1	2D-POD code-2	1D-POD
$\Phi(1,1)$	0	0	0
$\Phi(1,2)$	π	π	0
$\Phi(2,1)$	$\pi/2$	π	π
$\Phi(2,2)$	$3\pi/2$	0	π

The RB-dependent phase offsets can be chosen such that the total diversity benefit is maximized. 2D-POD induces variation in the channel, both in time and frequency directions simultaneously, as shown in Table 1. In order to maximize the spatial diversity, it is preferable to choose a phase pattern such that the RBs having contiguous allocations are assigned with uniformly separated phase values between 0 and 2π.

It should be pointed out that 2DPOD gives the expected diversity when the RBs are contiguous only when the FEC coding rate is around 0.5. As the coding rate increases, the diversity gain drops. However, this is not an issue for cell-edge terminals, since the SINR is low at cell-edge and these terminals typically operate in Rate-1/2 QPSK mode

IV. MMSE Interference Suppression

We will now show that a standard MMSE interference suppression algorithm can be used in a multi-antenna receiver along with POD at the transmitter. With two antennas, the receiver can suppress one dominant interferer. It is shown in [6] that if a whitened MLD detector is employed instead, two interferers can be suppressed. However, this latter detector requires that the modulation alphabet of the dominant interferer be known at the receiver. We will not consider this type of receiver here. When there is a single (either real or virtual) transmit antenna, and N_r receive antennas, each symbol in an RB is received by the N_r antennas as,

$$\mathbf{y}_j = \mathbf{h}_j x_j + \sum_{i=1, i\neq j}^{N} \mathbf{h}_i x_i + \mathbf{n}_j. \tag{4}$$

where $\mathbf{y}_j = [y_j^1(k,l)y_j^2(k,l)...y_j^{N_r}(k,l)]^T$ is the received signal vector with the baseband complex-valued entries of the signals received by the N_r receive antennas, $\mathbf{h}_j = [h_{jj}^1(k,l)h_{jj}^2(k,l).h_{jj}^{N_r}(k,l)]^T$ is the channel vector consisting of the effective channel from BS_j, and $\mathbf{h}_i = [h_{ij}^1(k,l)h_{ij}^2(k,l)h_{ij}^{N_r}(k,l)]^T$ is the effective channel from the interfering BS_i, and $\mathbf{n}_j$ is the thermal noise vector of variance

$\frac{N_0}{2}$ per real dimension. The size of all vectors in (4) is equal to N_r. In (4), the frequency and time dependencies of the received samples are dropped, because the receiver algorithm runs independently for each resource element.

The scalar decision metric $\hat{x}$ obtained from $\mathbf{y}$, in (4) using a MMSE filter $\mathbf{w}$ is given by, $\hat{\mathbf{x}} = \mathbf{w}\mathbf{y}_j$. From MMSE filter theory [9], it is well known that $\mathbf{w} = \mathbf{r_{xy}}\mathbf{R_{yy}^{-1}}$, where, $\mathbf{r_{xy}} = \mathbb{E}[x_j\mathbf{y}_j^H] = \mathbb{E}[x_j^2]\mathbf{h}_j^H = \mathbf{h}_j^H$, (because $\mathbb{E}[x_j^2] = 1$), $(.)^H$ denotes the matrix Hermitian operation, and $\mathbf{R_{yy}} = \mathbb{E}[\mathbf{y}_j\mathbf{y}_j^H] = \mathbf{h}_j\mathbf{h}_j^H + \mathbf{R_{(i+n)}}$, with $\mathbf{R_{(i+n)}} = \sum_{i=1, i\neq j}^{N} \mathbb{E}[x_i^2]\mathbf{h}_i\mathbf{h}_i^H + N_0\mathbf{I}$. Using the matrix inversion lemma [10], we get

$$\mathbf{w} = (1 + \mathbf{h}_j^H\mathbf{R_{(i+n)}^{-1}}\mathbf{h}_j)^{-1}\mathbf{h}_j^H\mathbf{R_{(i+n)}^{-1}} \quad (5)$$

The MSE at the output of the filter is $r_{ee} = (1 + \mathbf{h}_j^H\mathbf{R_{(i+n)}^{-1}}\mathbf{h}_j)^{-1}$. The scalar value $\alpha = 1 - r_{ee}$ (bias), when eliminated gives the estimate $\hat{\mathbf{x}}_{MMSE} = (\alpha)^{-1}\mathbf{w}\mathbf{y}_j$. These decision variables are given to a conventional symbol demodulator, which in turn calculates the log-likelihood ratios (LLR) for each bit. Note that the SINR at the output of the MMSE filter, after bais removal, is given by

$$SINR_{U,MMSE} = \mathbf{h}_j^H\mathbf{R_{(i+n)}^{-1}}\mathbf{h}_j$$

It is well known that this type of MMSE receiver with N_r receive antennas can fully suppress $N_r - 1$ interferers [11]. If the system contains more than $N_r - 1$ interferers, the MMSE receiver provides a partial interference cancellation (IC) gain.

V. Inter Cell Interference Cancellation (ICIC)

We first consider a single cell served by BS_i with two transmit antennas as before and a terminal ST_i, also with two antennas, which treats interference akin to thermal noise. In the well known technique of phase-beamforming [12], [13], [14], the same symbol is transmitted from both the antennas but with a relative phase shift. The signal received by the v^{th} antenna at the receiver of ST_i can be written as,

$$y_i^v = \left(h_{ii}^{1v} + e^{\jmath\vartheta_i}h_{ii}^{2v}\right) x_i^1 + \sum_{\substack{j=1\\ j\neq i}}^{2}\left(h_{ji}^{1v} + e^{\jmath\vartheta_j}h_{ji}^{2v}\right) x_j^1 + n_i^v \quad (6)$$

BS_i chooses a precoding angle ϑ_i, $i \in \{1,2\}$ which maximizes $S_i = \sum_{v=1}^{2}|h_{ii}^{1v} + e^{\jmath\vartheta_i}h_{ii}^{2v}|^2$, the received signal strength of ST_i after Maximum Ratio Combining of the signals received by its two antennas. This is a convex optimization problem with $\vartheta_i \in [-\pi, \pi)$. If $\theta_{ii} = \arg(\sum_{v=1}^{2} h_{ii}^{1v*}h_{ii}^{2v})$, then the solution for S_i to be maximum is the beamforming angle $\vartheta_i = -\theta_{ii}$.

When SINR is maximized in this manner, each base station ignores the impact of its beamforming on its co-channel user. This particular problem was studied in [8]. In this paper we consider BS cooperation within the FFR framework discussed earlier. With FFR, we have ST_i at the cell-edge being served by BS_i with PSD α, while BS_j and BS_k serve ST_j and ST_k respectively, on the same RBs (ie. they are co-channel) with PSD β, which are in-cell.

The discussions that follow needs some understanding of the manner in which ϑ_i affects the array gain. The precoding angle ϑ_i in eqn (6) is written in terms of $\tilde{\vartheta}_i$, termed the *offset angle*, which refers to the angular difference of the ideal beamforming angle ($-\theta_{ii}$) from the precoding angle (ϑ_i). The precoding angle is thus given by $\vartheta_i = \tilde{\vartheta}_i - \theta_{ii}$. In fig 5, simulation results characterizing the array gain for varying offset angles is given. The averaging is done over a large number of realizations of $\boldsymbol{h}_{ji}$, $\left(= h_{ji}^{uv}, \forall u, v\right)$. It can be seen that the gain varies only by about 2 dB in the in-phase region ($|\tilde{\vartheta}| < 90^o$), while in the out-of-phase region ($|\tilde{\vartheta}| > 90^o$) it varies by a much larger 3.9 dB. Fig. 5 is valid even when considering the interfering link from BS_j to ST_i (or BS_k to ST_i). However, for interference mitigation, $\tilde{\vartheta}_i$ is chosen so as to minimize the interference. It is desirable that BS_j and BS_k choose $\tilde{\vartheta}_i$ such that they minimize the interference while still constraining $|\tilde{\vartheta}_{j(k)}| < 90^o$.

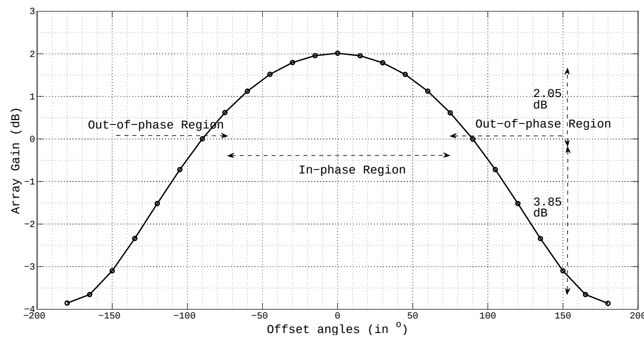

Fig. 5. The array gain seen in a 2 Tx ×2 Rx antenna configuration for varying offset angle

Restricting the beamforming angle at each BS to be in the range $[-\pi/2,\ \pi/2]$, ensures that the diversity order is always four (for a 2×2 system). Note that this optimization requires the angles θ_{ji} and θ_{ki} to be known at BS_j and BS_k respectively. This requires a modest amount of backhaul capacity between basestations as well as feedback on the air from the terminals to their respective basestations. Similar cooperation exercises also takes place, independently on orthogonal RBs for cell edge users served by BS_j and BS_k. In these cases, the other BSs cooperate to minimize interference while BS_j (or BS_k) does beamforming.

VI. Conjugate Data Repetition (CDR)

When the SINR at a terminal is negative, and the number of significant interferers is more than one, 2DPOD or ICIC with MMSE-based IC alone does not give a sufficiently low block error rate to support applications, even when the FEC coding rate is at its lowest possible. In such cases, the transmit symbols are usually repeated [2] in order to gain SINR by combining. This is a naive approach and performs poorly in an interference-limited situation. Indeed, if the same signal and interference both collide repeatedly, combining gives negligible SINR improvement (only whatever accrues due to noise averaging). We will show that repeating *with conjugation* can lead to significant SINR gain when the receiver implements MMSE IC. However, in order to realize this gain, all the

	Base station i		Base station j	
	Sym. n	Sym. n+1	Sym. n	Sym. n+1
f1	x1	...	y1	...
f2	x1*	...	y1*	...
f3	x2	...	y2	...
f4	x2*	...	y2*	...
f5	x3	...	y3	...
f6	x3*	...	y3*	...
f7	x4	...	y4	...
f8	x4*	...	y4*	...
f9	x5	...	y5	...
f10	x5*	...	y5*	...
f11	x6	...	y6	...
f12	x6*	...	y6*	...

Fig. 6. [Illustration of CDR by Two Basestations.

interfering base stations must implement CDR on the co-channel symbols. This is illustrated in Fig. 6, where co-channel RBs of two base stations are shown. It is apparent that when two symbols interfere, so do their complex-conjugated copies. In order to ensure this, a certain portion of each frame must be reserved by all base stations for cell-edge terminals that need CDR. The channel coefficient for the conjugate pairs are assumed to be the same since the resource elements on which they are transmitted are chosen to be close in frequency.

Let us now consider what happens when an MMSE IC receiver is used with N_r antennas, and the conjugated symbol pairs received by all the antennas are processed together. Every conjugated symbol is re-conjugated before being assembled in a vector with the remaining symbols. Thus, the received vector can be represented again by eqn. (4), where $h_l = [h_l^1, h_l^1*, \cdots, h_l^N, h_l^N*]^T$ denote the equivalent channel vectors of desired and l^{th} interfering signals, respectively. The MMSE detector is as in section IV. Since the channel parameters h_{ij}^v and h_{ij}^v* are equivalent to independent antennas, we equivalently have a receiver with $2N_r$ antennas. Thus, the MMSE IC receiver can suppress $2 \times N_r - 1$ interferers. With two antennas, we can suppress 3 interferers. Since the interferers are never equal in strength, it turns out that the receiver can handle more than three interferers as well.

CDR can be combined with 2DPOD or ICIC. Since there are rarely more than three dominant interferers, this combination can take care of most of the situations that arise at the cell edge.

VII. Results and Conclusions

We now focus attention on how the interference mitigation techniques discussed in Sections III-VI can benefit a cell-edge user. We will study the benefits by studying the block error rate (BLER) performance on the downlink for a nomadic cell-edge user in the presence of interference generated by neighbouring base stations. While a multi-cell system simulator that simulates real traffic flows to hundreds of users can give a more complete picture of system performance, the study of a cell-edge link can give us insight into the potential benefits of the proposed techniques. We assume a Ped-A channel model with a Doppler of 5 Hz. The channel is assumed to be independent from block ton block, giving us the performance of the link averaged over a long time duration. Since the cell-edge user usually experiences a low Signal-to-Interference-plus-Noise Ratio (SINR), we assume that the adaptive modulation and coding mode will settle at Rate-$1/2$ QPSK, which is the most robust mode typically available for low SINR operation. The simulations have been done for a frame, RB, and pilot (reference signal) structure as in the draft $802.16m$ standard. The performance results shown were obtained using estimated parameters for channels and interference statistics (using conventional 2D-MMSE estimators). No ideal or genie-assisted receivers were employed.

In this work, we make a distinction between dominant interferers and background interference. The former are comparable in strength to the signal, ranging from levels $0-6$ dB lower than the signal, and is typically caused by base stations that are adjacent to the base station serving the cell-edge user. The dominant interferer is modeled similar to the signal, and not as noise. On the other hand, the background interference is caused by a relatively larger number of more distant base stations, and it is clubbed with the noise and modeled as AWGN. We specify the level of background-interference-plus-noise relative to the signal level and call it ”SNR”.

We now define the Regime of Interest (RoI), in which the operation of the link is beneficial to the cell-edge user. The RoI refers to the combination of downlink BLER $< 10\%$ at an SNR that is around $3 - 6$ dB below the weakest dominant interferer. The SINR, in computing which the dominant interferers, background interference and noise are all included, may be much lower than the SNR. The rationale for defining the RoI in this fashion is that a BLER $< 10\%$ will permit efficient working of HARQ [1] and the user will experience good link efficiency. However, this must occur without requiring the SNR to be too low relative to the dominant interferers, since such a scenario will hardly play out in practice. The improvement offered by a novel interference mitigation technique is not of much use unless it pushes the link into the RoI.

Consider the link results shown in Fig.7. We will be mostly considering dominant interferers in the range $0-3$ dB below signal level. The RoI is shown in the region where SNR is $6-9$ dB. Curve II shows the performance of 2DPOD with a MMSE IC receiver, in the presence of one dominant interferer at -3 dB relative to the signal. We see that the link does operate within the RoI, and that the SINR in the RoI is around 2 dB. Thus, the IC receiver mitigates the impact of the dominant interferer, and enables the link to operate in the RoI. Curve I shows the link performance when there are two dominant interferers at -6 dB each relative to the signal. The curve floors above 10% BLER, and misses the RoI. Notice that the SINR is unchanged but the link does not work satisfactorily, because there are two dominant interferers instead of one, and the IC receiver with two antennas can only mitigate one interferer.

Next, we consider the nomadic users who are able to

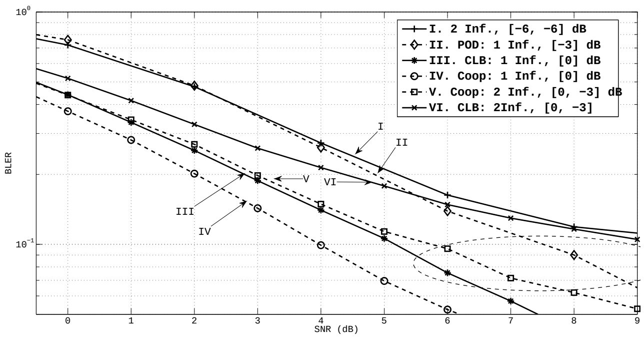

Fig. 7. Link Performance for 2DPOD and ICIC

employ closed-loop beamforming (CLB) on the downlink by feeding back channel state information. Curve III shows the performance when a cell-edge user employs CLB in the presence of one dominant interferer at a level equal to that of the signal (i.e., 0 dB relative to signal). Since the IC receiver can mitigate one dominant interferer, the curve does not floor (till a very low BLER is reached), and one can operate in the RoI (which is shifted to the left to some extent). However, when we consider two dominant interferers, relative to signal, we get Curve VI which floors at a high BLER and we cannot operate in the RoI. This is similar to the case of Curve II. If, however, the two base stations causing the dominant interference co-operate, as discussed in Section V, we get Curve V. Now, despite there being two dominant interferers, we can operate in the RoI, because the interference levels are reduced by the co-operating base stations and this reduces the BLER floor. It is important to point out that in this simulation, the transmit power levels of the interfering base stations to their in-cell users has been increased adaptively to compensate for the loss in array gain for their (in-cell) users arising out of co-operation. Thus, in this simulation, the in-cell users pay no price due to the co-operation. Despite the increase in transmit power, we see that there is a significant net reduction in interference due to the co-operation, which shifts the curve well into the RoI. Notice that the link performance is within the RoI in spite of the SINR being around -2.5 dB. Also shown in fig. 7 is the performance of ICIC in the presence of one dominant interferer at 0 dB (curve VI). It is well within the RoI (which will be shifted to the left).

Finally, we consider the case when there are more than two dominant interferers and the SINR is in the range below -3 dB. We see from Fig. 2 that the fraction of users (at the cell-edge) who fall in this category is not insignificant. Neither 2DPOD nor closed-loop ICIC will work by itself now. We need to combine with CDR in either case, so that we can mitigate three dominant interferers. We show in Fig. 8 the performanicce of 2DPOD+CDR in the presence of three dominant interferers at relative levels of $0, -3$ and -6 dB respectively. We see that the curve falls well within the RoI (9 dB ¡ SNR ¡ 12 dB). In comparison, we see that simple repetition of the signal, which does not provide the interference mitigation capability that CDR does, floors at a high BLER and the curve is outside the RoI.

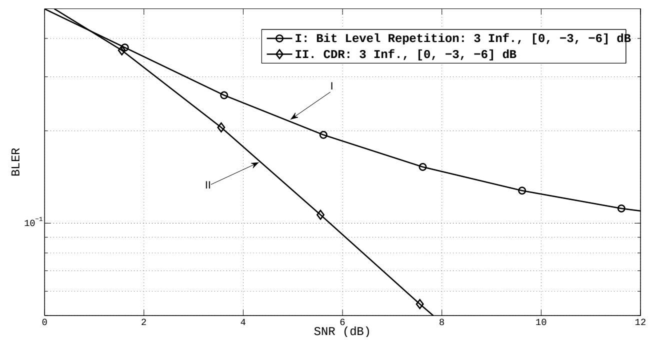

Fig. 8. Link Performance for 2DPOD combined with CDR

In summary, we see that using open-loop 2DPOD, closed-loop ICIC, and either of these in combination with CDR, one can establish links to cell-edge users that operate in the RoI even when the SINR is in the range -3 dB to 2 dB. When the SINR goes significantly negative, CDR is needed to set up a robust link. When the SINR is around 0 dB, and close-loop beamforming is feasible, base station co-operation for ICIC delivers, while 2DPOD works well when the SINR is around 2 dB. In all cases, an MMSE IC receiver employing two antennas is crucial. System simulations will enable us to quantify the throughput improvements for cell-edge users and for the entire system as a whole when these techniques are employed.

Acknowledgment

The author acknowledges the significant contributions made by the staff of CEWiT, in particular Kiran Kuchi, J Klutto Milleth, J Vinosh Babu James, R Vinod, M S Padmanabhan, V Ganesh, M K Dileep, and B Dhivagar, as well as his colleague K Giridhar of IIT Madras, in developing this package of techniques that presents a complete solution to the problem posed by cell-edge users in an interference-limited scenario.

References

[1] Third Generation Partnership Project (3GPP), *Evolved UTRA aspects: Physical Layer Procedures (36.2xy series documents)*, ETSI, 2008.

[2] IEEE Standard for Local and metropolitan area networks, *Part 16: Air interface for fixed and mobile broadband wireless access systems*, 2005.

[3] IEEE 802.16m 08/003r1, *The Draft IEEE 802.16m System Description Document*, IEEE 802.16 Task Group m, 2008.

[4] Qualcomm Incorporated, *Ultra Mobile Broadband Technology Overview and Competitive Advantages*, 2008.

[5] ITU-R SG05, *Invitation for submission of proposals for candidate radio interface technologies for the terrestrial components of the radio interface(s) for IMT-Advanced and invitation to participate in their subsequent evaluation*, Circular Letter 5/LCCE/2, 2008.

[6] R Vinod, M S Padmanabhan, V Ganesh, M K Dileep, B Dhivagar, Kiran Kuchi, J Klutto Milleth, “Performance comparison of phase offset diversity and stbc in interference limited ofdma systems,” .

[7] Kiran Kuchi, R Vinod, M K Dileep, M S Padmanabhan, Dhivagar, J Klutto Milleth, “Interference mitigation using conjugate data repetition,” .

[8] J. Vinosh Babu James and Bhaskar Ramamurthi, “Interference Mitigation using Distributed Co-operation among Cellular Basestations,” .

[9] J. Cioffi, *EE:379 Stanford Class Notes*.

[10] R.A.Horn and C.R.Johnson, *Matrix Analysis*, Cambridge University Press, 1990.

[11] J. H. Winters and J. Salz, "Upper bounds on bit error rate of optimum combining in wireless systems," *IEEE Trans. on Commn.*, pp. 1619–1624, Dec. 1998.
[12] R. W. Heath Jr., and A. Paulraj, "A simple scheme for transmit diversity using partial channel feedback," in *Proc. of the 32'nd Asilomar Conf. on Signals, Systems and Computers*, Nov. 1998, pp. 1073–1078.
[13] K. K. Mukkavilli, A. Sabharwal and B. Aazhang, "Design of multiple antenna coding schemes with channel feedback," in *Proc. of the 35'th Asilomar Conf. on Signals, Systems and Computers*, Pacific Grove, USA, Nov. 2001.
[14] K. K. Mukkavilli, A. Sabharwal, M. Orchard and B. Aazhang, "Transmit diversity with channel feedback," in *Proc. of the International Symposium on Telecommunications*, Tehran, Iran, Sep. 2001.