Fractional Frequency Reuse with Enhanced Scheduling Strategies

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Abstract

Heterogeneous networks are used to meet both capacity and coverage demands in a cellular network. As the frequencies are reused due to the limited spectrum availability, there exists co-channel interference (CCI) between the high power and low power nodes in such networks apart from the CCI between high power nodes. Inter cell interference coordination (ICIC) is a big challenge towards heterogeneous network deployments since users located at the cell range expansion (CRE) area are more vulnerable to stronger interference caused by the signals from the high power nodes. To enhance capacity, achieve good user experience and improve spectral efficiency interference management techniques like fractional frequency reuse (FFR) with enhanced scheduling strategies and ICIC using expectation maximization algorithm are proposed to mitigate the effects of the CCI. The resource allocation in FFR is done for the users in the cell center (full reuse) and CRE (partial reuse) regions based on the optimum post processing signal to interference plus noise ratio threshold with different schedulers in the two regions. It is shown that a particular combination shows the best throughput performance for the proposed enhanced FFR scheme.

Keywords Cellular network · Co-channel interference · Fractional frequency reuse · Heterogeneous network · Scheduling

1 Introduction

Spectrum is a scarce natural resource, and it needs to be used in an efficient manner. It is a tremendous job to increase the system capacity in such bandwidth limited wireless environment. The initial phase of the development of the wireless technology was aimed at utilizing the spectrum more efficiently by adopting various techniques like frequency reuse, using multiple antennas at both transmitter and receiver ends (a.k.a.multiple input multiple output (MIMO) system), and also using technologies like orthogonal frequency division multiplexing (OFDM) that allows overlapping of subcarriers. The cellular network apply frequency reuse by reusing the same frequency in every cell leading to

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co-channel interference (CCI) from nearby cells. Traditionally, the CCI was avoided by reusing the same frequencies only in far off cells [1]. The network is evolved over time due to the increased data rate requirements by shrinking the cell size further to increase such capacity demands. Moreover, the network became reuse one or full reuse with the same frequency reused in every cell making the CCI more severe in such scenarios [2]. When multiple antennas are used at the transmitter and receiver to increase the spectral efficiency, the interference problem from adjacent cells became much worse [3]. Furthermore, as more and more data hungry applications became popular, the exponential growth in mobile broadband traffic paved way for moving from the traditional homogeneous deployment of cells to the heterogeneous network (HetNet) deployment as shown in Fig. 1 by overlaying low power nodes (a.k.a as pico eNodeB (eNB)) with less transmit power within the high power nodes (a.k.a macro eNB) coverage area [4], which results in further increase in the CCI to the cell edge users attached to the picocell [5].Due to the fact that the transmit power of the pico cell is low, more users will tend to be associated to the macro eNB. Therefore, to extend the coverage area of the pico cell, cell range expansion (CRE) techniques like biased association are used to associate more users to the pico eNB. It is shown in Fig. 2 where an offset is applied to the transmit power of the pico cell while computing the signal to interference plus noise ratio (SINR) for associating a user equipment (UE) to a cell. Therefore, there is a need to split the pico cell into cell center (CC) and CRE region [6]. Techniques like fractional frequency reuse (FFR) are adopted where a frequency reuse one is used in the CC and a frequency reuse greater than one in CRE regions, and several such FFR schemes like strict FFR, soft FFR and FFR-3 are proposed in [7]. These schemes can be statically or semi statically configured in the network based on the traffic and interference conditions. Coordinated multipoint transmission (CoMP) is another interference mitigation technique that helps to reduce the interference for cell edge users in Hetnets [8]. Massive MIMO system with large number of antennas at the transmitter and receiver tend to reduce the inter cell and intra cell interference and improve the system throughput using signal processing techniques at the receiver [9]. Joint transmission and receiver processing are performed in CoMP

**Fig. 1** Heterogeneous network with macro and pico eNB
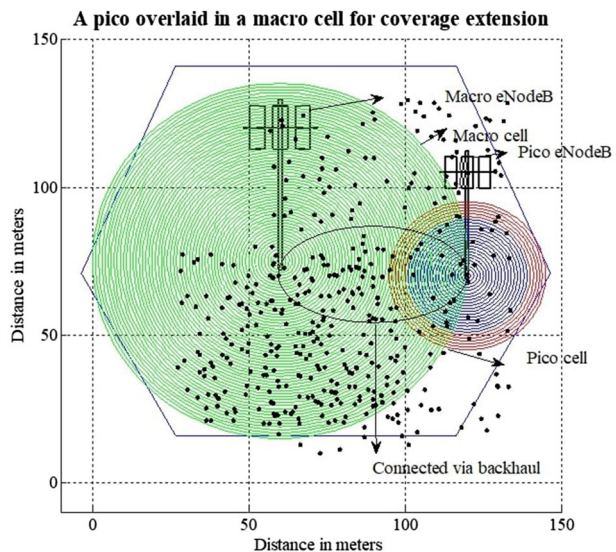
Fig. 2 Cell range expansion and cell center from pico and macro to UE desired and interference signal
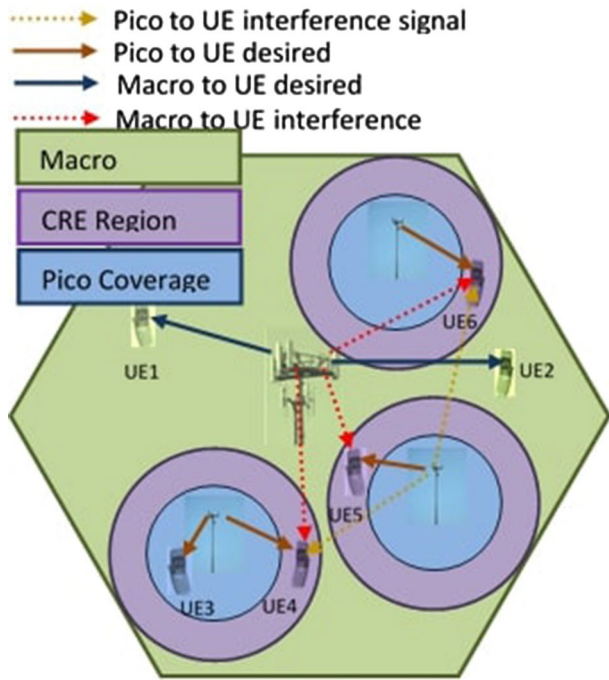
transmission in a MIMO network using inter cell interference coordination (ICIC) to mitigate interference [10]. Enhanced ICIC (eICIC) described in [11] enhances coverage and improves spatial spectrum efficiency of the network. Additionally, reducing the interference in wireless communication system tend to increase the spectral efficiency to achieve high performance in the network [12]. Moreover, efficient resource allocation schemes using appropriate scheduling strategies should be deployed to mitigate the interference [13]. Resource scheduling techniques have been used in both homogeneous networks and HetNets [14]. A single scheduler like round robin and proportional fair is applied for the entire cell assuming the throughput requirements of every user in the system is same [15]. All the above methods to improve the spectral efficiency, limit the gains that can be achieved by these methods in HetNets due to interference resulting in reducing the throughput and reliability of the wireless communication system. High capacity gains can be achieved when all potential technologies are combined together [16]. Therefore, there is a need for using multiple interference mitigation techniques to mitigate CCI. One such technique by applying receiver processing and resource allocation using a fixed scheduler in both CC and CRE in HetNets is described in [17]. However, the propagation, channel and interference conditions at the users close to the eNB and far off from the eNB are different, particularly near the cell boundary interference is very severe [18]. Therefore, using a same scheduler in both regions may not be the best approach. In this paper, an enhancement to the strict FFR scheme is proposed by using different combinations of schedulers applied to the CC and CRE regions. The proposed enhanced FFR (eFFR) scheme configures the frequency sub bands used in the CC and CRE regions in a cell are orthogonal and also frequency used in the CRE regions across cells orthogonal with a frequency reuse of three as like strict FFR scheme shown in Fig. 3.

Fig. 3 Resource allocation in strict FFR and eFFR scheme
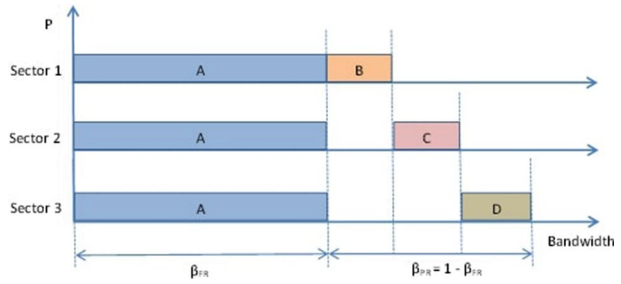
2 System Model

The total available bandwidth is divided into multiple parallel narrow band subcarriers. The resource block (RB) allocated for data transmission consists of 12 such subcarriers over seven OFDM symbols. Link adaptation using quadrature phase shift keying (QPSK), 16 quadrature amplitude modulation (QAM) and 64 QAM modulation is applied depending on the radio channel conditions of the allocated time frequency resources. This translates to 2 bits, 4 bits, and 6 bits, respectively per subcarrier in an OFDM symbol duration, and hence, the total number of bits in an OFDM symbol is obtained by multiplying the number of bits per subcarrier with the number of used subcarriers for data transmission. For the bandwidth of 10 and 20 MHz, the numbers of RBs are 50 and 100 respectively. The UE will be allocated with a RB or a group of RBs depending on the data rate requirement. The system consists of L eNBs with N_t antennas and Q UEs with N_r antennas. The interfering L-1 eNBs can be macro or pico or combination of both. A strict FFR scheme with the CC region using a frequency reuse one and the CRE region using a frequency reuse three as shown in Fig. 3 is considered for performance evaluation of the proposed scheme. Every cell has an inter site distance of 500 m consisting of three sectors having one eNB in each sector. The transmission mode 4 (TM4) of the long term evolution (LTE) technology, which is a feedback based closed loop spatial multiplexing (CLSM) scheme is used in the simulations. It requires computation of channel quality indicator (CQI) based on the channel conditions, rank indicator (RI), and precoding matrix indicator (PMI) at the UE, and reported to the eNB using a feedback channel. The eNB chooses the number of stream to be transmitted based on the RI, and the signal to be transmitted on different transmit antennas are precoded based on a PMI that maximizes the post processing SINR. The CQI computed based on the post processing SINR of the minimum mean square error (MMSE) receiver at the UE is used to choose the appropriate modulation and coding scheme (MCS). The scheduler uses the CQI information of users to decide on the allocation of the resources by the eNB for its downlink transmission. The different channel dependent and independent schedulers are considered for performing system level simulations in both the CC and CRE regions.

2.1 Bandwidth Split

The frequency reuse technique of reuse one and reuse three are widely used in cellular networks over different frequency partitions in certain time intervals in downlink and uplink transmissions to mitigate the interference experienced by the users. The

efficiency is improved by reusing a large portion of the available bandwidth for the CC users while assigning the rest to the CRE users. The number of resource block allocated corresponds to $\beta_{CC} = 0.64$ and $\beta_{CRE} = 0.36$ is considered for simulations. Hence out of the total 100 RBs available, 64 RBs are allocated to CC UEs and the remaining 36 RBs are allocated to the CRE UEs. In FFR total BW is partitioned into CC and CRE as in (1).

$$B_T = B_{CC} + B_{CRE} \tag{1}$$

The normalised CC and CRE bandwidths are denoted as β_{CC} and β_{CRE} and represented by (2) and (3).

$$\beta_{CC} = \frac{B_{CC}}{B_T} \tag{2}$$

$$\beta_{CRE} = \frac{B_{CRE}}{B_T}. \tag{3}$$

2.2 Optimum FFR SINR Threshold

The simulations are performed for various threshold that specifies pre-processing SINR point at which the switching is performed between CC and CRE regions. The proposed scheduling method allocates resources to the users experiencing high post processing SINR of the MMSE receiver except in the case of round robin scheduler. The performance is evaluated for the scenario as shown in Fig. 2 considering macro and pico to UE interference and macro to pico UE desired signal for eFFR schemes with various split between the CC and CRE region as shown in (4) and an optimum value of threshold Γ_o is obtained for the separation.

$$\Gamma_o = \frac{G_d L_d (P_{txmd} + P_{txpd})}{\sigma_n^2 + \sum_{i=1}^{M} G_i L_i (P_{txmi} + P_{txpi})} \tag{4}$$

G_d and G_i are the antenna gains of the desired and the ith interfering eNB, respectively. L_d and L_i path loss from the desired and the ith interfering eNB to the UE, respectively. P_{txmd} and P_{txmi} are the transmit powers of the desired and the ith interfering macro eNB, respectively. P_{txpd} and P_{txpi} are the transmit powers of the desired and the ith interfering pico eNB, respectively.

The various simulation parameters are shown in Table 1.

2.3 Scheduling in CC and CRE Zone

The various scheduler combinations using (1) round robin (RR) (2) proportional fair (PF) (3) best CQI (BCQI) (4) resource fair (RF) and (5) max min (MM) are applied to both the CC and CRE regions. The eNB allocates resources to the UE as per the bandwidth split in Sect. 2.1 and the post processing SINR seen by the UE, and also decides its MCS based on their CQI values.

Table 1 FFR simulation parameters

Parameters	Values
Inter eNB distance	500 m
Number of UEs	10
Path loss model	Urban area
Minimum coupling loss	70 dB
Shadow fading	10 dB
Number of antennas	$N_t = 2, N_r = 2$
Antenna radiation pattern	KATHREIN 742212
Total bandwidth	10 and 20 MHz
Transmit power at eNB	46 and 49 dBm
Number resource blocks	50 and 100
Transmission mode	*TM*4 CLSM
Feedback	CQI, RI and PMI
Channel model	Winner +
UE speed	5 km/h
Receiver	MMSE
Thermal noise	− 174 dBm/Hz
Noise figure	9 dB
CC region	Reuse 1
CRE region	Reuse 3
Bandwidth split	β_{CC} and $\beta_{CRE} = 1 - \beta_{CC}$
Simulation duration	10,000 TTIs
Scheduler FR	RR, RF, MM, PF, and Best CQI
Scheduler PR	RR, RF, MM, PF, and Best CQI

2.4 Capacity for CC and CRE Zones

The Shannon capacity at a location (u,v) is represented by (5) and (6) for the CC and CRE regions for a given CC−CRE boundary ρ FFR bandwidth partitioning β_{CC} and $\beta_{CRE} = 1-\beta_{CC}$ is done at a position (u,v) using (2) and (3).

$$C_{\beta_{cc}}(u, v) = \frac{\beta_{CC}}{G_{CC}(\rho)} \log_2(1 + \Gamma_{CC}(u, v)) \tag{5}$$

$$C_{\beta_{CRE}}(u, v) = \frac{\beta_{CRE}}{3G_{CRE}(\rho)} \log_2(1 + \Gamma_{CRE}(u, v)) \tag{6}$$

$\Gamma_{CC}(u, v)$, $\Gamma_{CRE}(u, v)$, and G_{CC}, G_{CRE} are the SINRs and gains of the CC and CRE region respectively.

2.5 ICIC and CoMP

The CCI can be reduced by using CoMP and ICIC techniques. CoMP is a technique where joint transmission of data from multiple eNBs to a UE and/or joint reception of

the signal from a UE at multiple eNBs. The joint transmission and joint processing of the received signals from multiple eNBs are performed in a coordinated manner across eNBs. The coordination between eNBs for joint transmission and reception can be done at a centralized location or at individual eNBs by exchanging relevant information across eNBs using a backhaul link. The ICIC scheme mitigates the interference by appropriate choice of the transmit power and the frequency reuse factor. The proposed eFFR scheme is very flexible to adjust the transmit power and the frequency reuse factor depending on the pico cell location. The biasing based UE association is used to attach more UE to a pico eNB for load balancing as follows. The UEs will apply a power offset of O to the received power P_R in dB at the reference signal (RS) from a pico eNB and $O = 0$ for macro eNB, and is given by (7).

$$P_R = 10 \log(O * A * P) \tag{7}$$

where A is the path loss between the eNB and the UE with a power P applied to the RS. The serving cell S is identified for a UE by associating it to an eNB with maximum P_R using (8).

$$\begin{aligned} S &= \arg \max[10 \log(O * A * P)] \\ &= \arg \max(O * A * P) \end{aligned} \tag{8}$$

The split between the CC and CRE regions is obtained using the expectation maximization algorithm as follows. After associating all the UEs in the HetNet using the above procedure, the expected value of the received power P_e of all the the UEs associated to a pico eNB is obtained using (9).

$$P_e = E[O_s * A_s * P_s] \tag{9}$$

Where O_s and P_s are the bias and power applied to the RS, respectively in a serving cell S_s with a path loss of A_s between the serving cell and the UE s. This expected value has to be obtained for all the pico eNBs in the HetNet. The boundary B between the CC and CRE region for a pico eNB is obtained by maximizing the expected value as in (10).

$$B = \max E[O_s * A_s * P_s] \tag{10}$$

After obtaining the split using the expectation maximization algorithm explained above, the eFFR scheme using different combinations of scheduler is applied in the proposed method to perform the evaluation.

3 Results and Discussion

Two bandwidth configurations of 100 and 50 RBs corresponding to a bandwidth of 20 and 10 MHz, respectively are considered to evaluate the performance when different schedulers are used for the FR and PR zones. The spectral efficiency and throughput of the strict FFR is evaluated for the above two configurations using different scheduler pairs using RR, RF, MM, PF and Best CQI scheduling schemes for both CC and CRE zones.

3.1 Measurement of Threshold

The proposed method to obtain the optimal SINR threshold allocate resources to the users experiencing high post processing SINR of the MMSE receiver except in the case of RR and MM scheduler. The throughput is evaluated for the strict FFR schemes with various SINR to split between the CC zone using RR scheduler and CRE zone using RR, PF, MM, RF and BCQI schedulers. The throughput results are plotted as a function of SINR for various scheduler combinations as shown in Fig. 4.

Since RR scheduler is used for CC zone in all the simulations, and the number of RBs are same in all the cases, the difference in throughput performance will be only due to the schedulers used in the CRE zone. It is seen from the figure that the RR scheduler followed by the RF scheduler gives the worst performance. This is due to the fact that the channel condition is not considered while allocating the resources in both schedulers. Therefore, resource may be allocated to an UE even when its channel condition is not good, which will bring down the throughput. However, in RF scheduler, ensures that bandwidth is not wasted even while same number of resource is allocated.The MM scheduler performance is better than both the channel independent schedulers, while it suffers throughput loss while trying to maximize the minimum throughput. It may allocate more resources even when the channel conditions are not good to maximize the minimum. The PF scheduler performs better as expected as it allocates resources only when the channel is good even while maintaining the fairness. The best performance is obtained for the Best CQI scheduler, which is along the expected lines as it schedules users with the best CQI all the time. However, it is evident that the split using an SINR of 14 dB is found to be the optimum threshold irrespective of the schedulers used in the CRE zone for RR scheduler used in the CC zone.

3.2 Measurement of Throughput

The simulations are performed keeping one of RR, RF, MM, PF, and BCQI schedulers for CC users and various combination RR, RF, MM, PF, and BCQI schedulers for CRE users. For total bandwidth of 100 RBs and 50 RBs, the throughput per cell site is calculated as the product of spectral efficiency and bandwidth allocated. The Figs. 5, 6, 7, 8 and 9 shows the throughput performances of various combinations of RR, RF, MM,
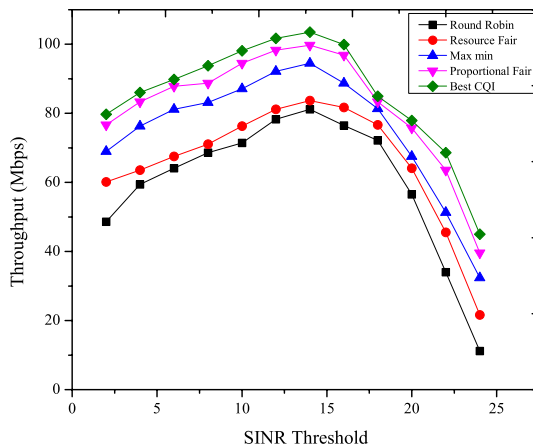

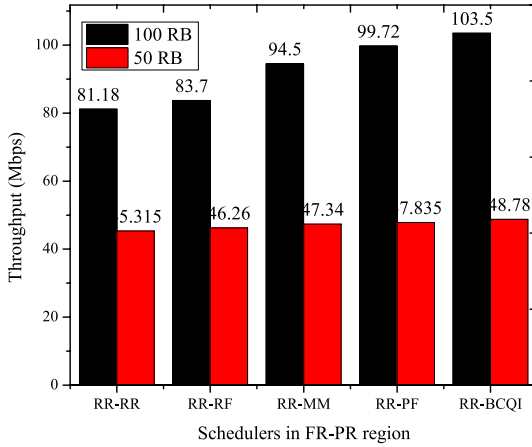**Fig. 4** SINR threshold obtained using RR, RF, MM, PF, and Best CQI schedulers

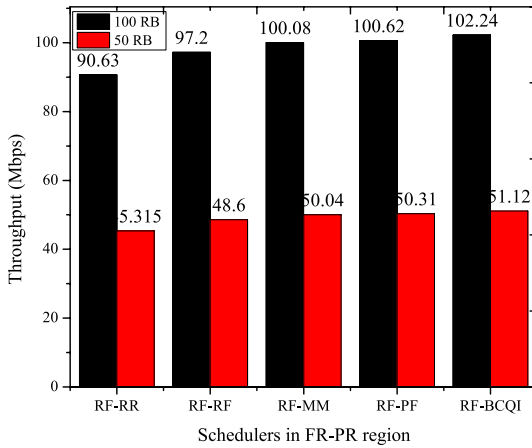**Fig. 5** Performance using RR scheduler with a threshold of 14 dB SINR

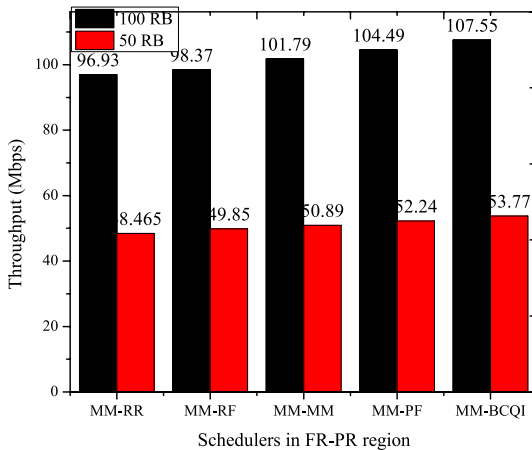**Fig. 6** Performance using RF scheduler with a threshold of 14 dB SINR

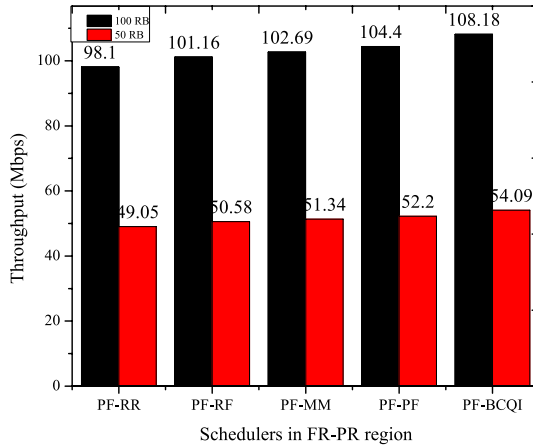**Fig. 7** Performance using MM scheduler with a threshold of 14 dB SINR

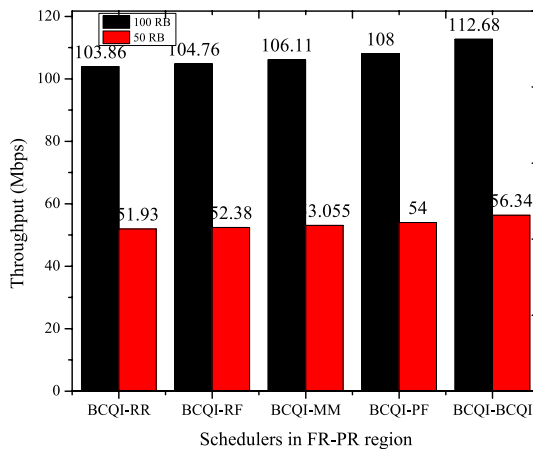**Fig. 8** Performance using PF scheduler with a threshold of 14 dB SINR

Fig. 9 Performance using BCQI scheduler with a threshold of 14 dB SINR

PF, and BCQI schedulers in CC and CRE zones for different bandwidth of 20 MHz and 10 MHz. Moreover it is observed from the figure that there is a negligible mismatch in the spectral efficiency number between results of 100 RBs and 50 RBs in all the figures. It is due to the fact that it is obtained using a statistical simulation, and this is expected due to the averaging. Resources are allocated cyclically to users and ignores the channel state information, and thus does not make use of the available diversity. The RR-RR scheduler combination provides the best fairness to all the users in both CC and CRE zones, but with a loss in spectral efficiency.If RR is available in the CC zone 2.52%, 13.32%, 18.54%, 22.32% improvement is seen when RF, MM, PF and BCQI schedulers are used in CRE zone considering 100 RB s and 0.94%, 2.03%, 2.52%, 3.46% improvement with 50 RB s as inferred from Fig. 5.

When RF is available in the CC zone 6.57%, 9.45%, 9.99%, 11.61% improvement is seen when RF, MM, PF and BCQI schedulers are used in CRE zone considering 100 RB s and 3.28%, 4.73%, 5%, 5.81% improvement with 50 RB s as inferred from Fig. 6.

When MM is available in the CC zone 1.44%, 4.86%, 7.56%, 10.62% improvement is seen when RF, MM, PF and BCQI schedulers are used in CRE zone considering 100 RB s and 1.21%, 2.43%, 1.35%, 5.31% improvement with 50 RB s as inferred from Fig. 7.

PF aims at increasing the throughput by scheduling users whenever their channel conditions are good in the CC zone with respect to their own average channel quality even while scheduling users with poor channel conditions to maintain fairness. When PF is available in the CC zone 3.06%, 4.59%, 6.3%, 10.08% improvement is seen when RF, MM, PF and BCQI schedulers are used in CRE zone considering 100 RB s and 1.53%, 2.29%, 3.15%, 5.04% improvement with 50 RB s as inferred from Fig. 8.

The best CQI scheduler assigns resources to the users with best channel conditions. Therefore, the throughput is significantly higher than all the schedulers; however, there will be scenarios where several users do not get resources for data communication. The BCQI-BCQI scheduler combination provides the best spectral efficiency, but will not allocate resources to all the users in a fair manner. At times it may not even allocate resources to users in the cell edge users because of their low SINR. When BCQI is available in the CC zone 0.9%, 2.25%, 4.14%, 8.82% improvement is seen when RF, MM, PF and BCQI schedulers are used in CRE zone considering 100 RB s and 0.45%, 1.12%, 2.07%, 4.41% improvement with 50 RB s as inferred from Fig. 9.

3.3 Measurement of Spectral efficiency

In this section, spectral efficiency with no interference mitigation and with existing interference mitigation schemes are compared with the proposed method. The HetNet shown in Fig. 2 is considered with three such macro eNBs and varying number of pico eNBs from 2 to 16 with a radius of 10 m in each macro eNB coverage area.

Lower blue line indicates no interference mitigation on signaling transmission with low spectral efficiency, line with red indicates the eICIC on signalling transmission with better spectral efficiency, line with green indicates the CoMP scheme using linear MMSE (LMMSE) equalizer with better spectral efficiency and our analyzed interference
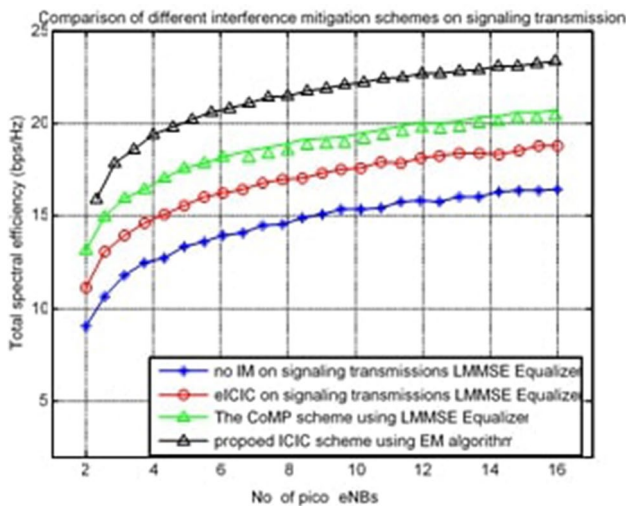

Fig. 10 Spectral efficiency improvement using eICIC schemes

coordination scheme gives higher spectral efficiency than the other schemes as shown in Fig. 10.

4 Conclusion

The performance of the proposed FFR scheme with different scheduling algorithms based on the post processing SINR is evaluated and compared. Scenarios combining FFR with five different scheduling algorithms (round robin, resource fair, max min, proportional fair and best CQI) have been considered by employing it in a hexagonal cell layout overlaid with circular pico cells. It is found that for a given fixed scheduler for the CC zone, the BCQI scheduler achieves the best performance, and RR scheduler achieves the worst performance in terms of throughput. However, when fairness is used as the metric, RR is best and BCQI is worst. The other schedulers performance are in between the above best and worst case for both the metrics. In terms of throughput performance, the RF scheduler follows RR, followed by MM, followed by PF in the increasing order. The spectral efficiency is significantly improved using the proposed eICIC schemes eliminating CCI. The eFFR scheme has the potential to play a role in future 5G systems as internet of things (IoT) devices require different QoS.

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