Massive MIMO and Femto Cells for Energy Efficient Cognitive Radio Networks

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Abstract. In this paper, energy efficiency (EE) was investigated for a cognitive radio network (CRN) where massive multiple-input multiple-output (MIMO) was combined with femto cells. A heterogeneous network was considered to maximise EE, while massive MIMO was implemented to increase spatial reuse and focus energy into smaller spatial regions. Cooperation between femto cell based relay stations (RS) and a micro cell based secondary base station (SBS) allowed for secondary user (SU) quality-of-service (QoS) requirements to be met and also for control over primary user (PU) interference. Two key issues were addressed by the proposed model, namely improved CRN EE and reduced PU interference. The formulated EE optimisation problem was non-convex and thus converted into a semi-definite problem. Simulation results show that combining massive MIMO at the micro cell level with femto cells, lead to a CRN EE improvement. The addition of femto cells also lead to a reduction in PU interference.

Keywords: Cognitive radio network · Energy efficiency · Femto cells · Massive MIMO

1 Introduction

In recent years wireless communication networks have experienced tremendous growth due to an increase in the demand for services such as mobile data communications, high speed internet and live video conferencing. At first glance, it would appear that the spectrum available to operators is limited and would thus not be able to cope with this ever increasing demand for high speed data communication and the associated bandwidth. However, a closer look suggests that spectrum utilisation is more of a problem, rather than the actual availability thereof. Large portions of the usable spectrum are either largely underutilised or partially occupied [1]. Furthermore, the practice of anywhere-anytime access to the network has triggered a dramatic expansion of network infrastructure. It has become essential for mobile network operators to maintain sustainable capacity growth.

M. Weichold et al. (Eds.): CROWNCOM 2015, LNICST 156, pp. 511–522, 2015.
DOI: 10.1007/978-3-319-24540-9_42

This subsequently leads to a drastic increase in the energy consumption of the network. Given that energy costs (diesel, electricity) are constantly increasing and since this energy expenditure constitutes a major portion (20% - 30%) of the operators's total energy expenditure [2], it is necessary to consider schemes that can increase the energy efficiency (EE) of the network, while maintaining required quality of service (QoS) levels for secondary users (SUs).

Cognitive radio (CR) [11] has been identified as an efficient technology, that allows secondary users (SUs) to make use of underutilised or partially used spectrum that is in fact licensed for use by primary users (PUs). Using licensed channels means that SUs must always consider the interference that they may inflict on PUs. Therefore, it is very important to keep the SU interference level below the level that is acceptable to the PU. Since there is a relationship between the EE of the network and the amount of power required to guarantee the level of QoS experienced by SUs, techniques should be investigated that minimise base station (BS) power consumption while maintaining the level of QoS required by SUs. As suggested in [6], there are many techniques through which the power consumption of the base station can be minimised. Of these techniques, energy aware cooperation between BSs, the integration of femto cells within micro cells and the use of multiple-input multiple-output (MIMO) are considered to be most beneficial. These techniques have already been incorporated into existing wireless communication networks.

"Massive MIMO"[7] is currently seen as a promising cellular network architecture offering several attractive features over regular MIMO. It has been shown that even simple linear pre-coders and detectors are optimal when the ratio of antennas per BS to the number of user terminals per cell is very large [10]. In [9], cooperation between the primary BS (PBS) and the SBS was compared with the case when there is no cooperation between them. It was shown that the signal-to-interference-plus-noise-ratio (SINR) requirements of all SUs can be met when there is cooperation between the secondary base station (SBS) and the PBS. In [12], an EE improvement was demonstrated for a heterogeneous network (HetNet) deployment when compared to a single cell scenario. While HetNets have been considered for cognitive radio networks (CRNs), traditional wireless networks and massive MIMO for traditional wireless networks, the unique contribution in this research work is the combination of both massive MIMO and HetNets in a CRN.

In this paper, femto cells are deployed within the micro cell and a massive MIMO system is used at the secondary BS (SBS). Coordination between an amplify-and-forward relay station (RS), in a femto cell, and the SBS, in the micro cell, is considered. It is assumed that both the RS and the SBS can serve the SUs within their coverage area, depending on the efficiency of the network. These secondary micro cells are assumed to lie within the primary cell. Since the RS has a smaller coverage area, the total transmission power as well as the static power of the RS is less than that of the micro SBS. An optimization problem is formulated where the objective is to maximize the energy efficiency (EE) of the overall CRN while satisfying the QoS requirement at each SU as well as adhering

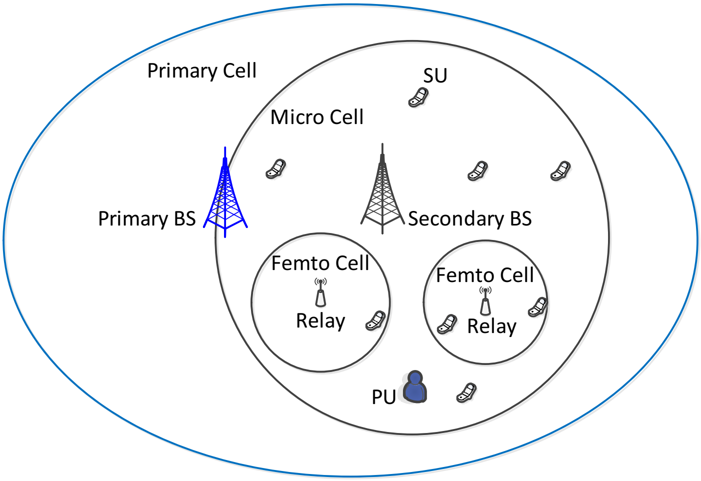

Fig. 1. System model for an underlay CRN with a primary cell covering multiple secondary cells.

to the interference constraints for each PU (with a per antenna power constraint at both the SBS and the RS). Since this optimization problem is non-convex, it is converted into a convex problem. Maximisation of EE for the overall network is then solved. From the results it is shown that the introduction of massive MIMO at the micro cell level together with the addition of femto cells, improves the EE of the network. The addition of femto cells within the micro cells is shown to reduce the interference experienced by the PUs.

Notation: The subscript zero is used to denote micro cell SBSs and PBSs. Any other subscript values denote RSs.

2 System Model

An underlay CRN, as illustrated in Fig. 1, is considered where the SBS is equipped with K_{BS} antennas that are serving N number of SUs ($K_{BS} >> N$). Each of these SUs have a single antenna. Two femto cells are considered within the coverage area of the SBS. Each of these femto cells are equipped with a single RS which has K_R number of antennas, where $K_R \in \{1, 2, 3\}$. The primary cell surrounds the secondary cells. A single PU can be located anywhere within the primary cell. If the PU lies outside the coverage zone of the SBS then the model reduces to the one shown in [5], which is similar to the case of traditional communication network. The PBS is assumed to have a single antenna. A single antenna PU is assumed to be located randomly within the coverage area of the SBS.

It is assumed that the SBS and RSs at each of the femto cells are coordinated in such a way that either a RS or a BS or both of them, can provide service to the SUs. Since the transmission power of the RS is much less than that of the

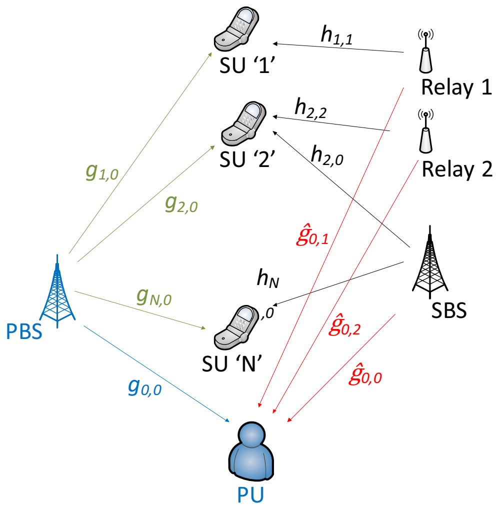

Fig. 2. Conceptual diagram for the proposed model.

BS, it would be preferable to serve the SUs using the RS. However due to the small coverage area of the RS, it may not be able to serve all of the SUs that lie within the secondary micro cell. Hence, if it is energy efficient, those SUs that are not being served by the RS would be served by a combination of the RS and the SBS. Otherwise they would be served by the SBS alone. This decision is taken based on the solution to the optimisation problem for the maximisation of the EE of the overall CRN.

As shown in Fig. 2, $\mathbf{h}_{t,0} \in C^{1\times K_{BS}}$ and $\mathbf{h}_{t,j} \in C^{1\times K_R}$ represent the channel gains from the SBS to the t^{th} SU and from the j^{th} RS to the t^{th} SU respectively. The terms $g_{t,0}$ and $g_{0,0}$ represent the channel gains from the PBS to the t^{th} SU and from the PBS to the PU respectively. The terms $\hat{g}_{0,0}$ and $\hat{g}_{0,j}$ represent the channel gains from the SBS to the PU and from the j^{th} RS to the PU respectively. A flat fading sub-carrier is considered, as in [5], and the base band channels are assumed to be perfectly know at both sides of each channel [4]. The received signal power at the t^{th} SU is given by,

$$y_t = \mathbf{h}_{t,0}^H \mathbf{x}_0 + \sum_{j=1}^{R} \mathbf{h}_{t,j}^H \mathbf{x}_j + g_{t,0}^H x_p + n_t, \tag{1}$$

where n_t is the circularly symmetric complex Gaussian noise with zero mean and variance σ_k^2, R is the number of femto cells (i.e. number of RSs), $\mathbf{x}_0 \in C^{K_{BS}\times 1}$, $\mathbf{x}_j \in C^{K_R\times 1}$ and x_p are the transmitted signals from the SBS, the RS and the PBS respectively. The transmitted signal can be written as,

$$\mathbf{x}_j = \sum_{t=1}^{N} \mathbf{w}_{t,j} x_{t,j}, \quad j = 0, 1, ...R \tag{2}$$

$$SINR_t = \frac{| \mathbf{h}_{t,0}^H \mathbf{w}_{t,0} |^2 + \sum_{j=1}^{R} | \mathbf{h}_{t,j}^H \mathbf{w}_{t,j} |^2}{\sum_{i=1,i\neq t}^{N}(| \mathbf{h}_{t,0}^H \mathbf{w}_{i,0} |^2 + \sum_{j=1}^{R} | \mathbf{h}_{t,j}^H \mathbf{w}_{i,j} |^2) + | g_{t,0}^H |^2 + \sigma_t^2} \geq \hat{\gamma}_t \quad (3)$$

where $x_{t,j}$ is the information transmitted from the SBS or the RS to the t^{th} SU, $\mathbf{w}_{t,j}$ is a beam forming vector where j is the transmitter serving user t with $\mathbf{w}_{t,0} \in C^{K_{BS}\times 1}$ and $\mathbf{w}_{t,j} \in C^{K_R\times 1}$

3 Problem Formulation

The objective is to maximize the EE of the overall CRN while satisfying the QoS requirement of the SUs and the interference constraint of the PU. The QoS requirement specifies the information rate, in bit/s/Hz, that each user should achieve. Therefore, it is related to SINR as follows,

$$\begin{aligned} \log_2(1 + SINR_t) &\geq \gamma_t, \\ \text{or,} \quad SINR_t &\geq 2^{\gamma_t} - 1 = \hat{\gamma}_t, \end{aligned} \quad (4)$$

where γ_t is the required QoS of t^{th} SU.

From Eq. (1), the SINR for the t^{th} SU is given by Eq. (3), given at the top of the page. This is the QoS constraint for the SUs. The interference constraint for a PU is the sum of the interference from the SBS and the RSs, and is given by,

$$\zeta_0 = \sum_{i=1}^{N} | \hat{\mathbf{g}}_{0,0}^H \mathbf{w}_{i,0} |^2 + \sum_{i=1}^{N}\sum_{j=1}^{R} | \hat{\mathbf{g}}_{0,j}^H \mathbf{w}_{i,j} |^2 . \quad (5)$$

With the SU interference limit denoted by ζ, this can be rewritten as,

$$\zeta_0 = \sum_{i=1}^{N}\sum_{j=0}^{R} | \hat{\mathbf{g}}_{0,j}^H \mathbf{w}_{i,j} |^2 \leq \zeta. \quad (6)$$

The total power consumption per sub-carrier C is the sum of the dynamic power and static power, as shown in Eq. (7),

$$P_{tot} = P_{dynamic} + P_{static}. \quad (7)$$

The dynamic power depends on the transmitted power and the amplifiers's inefficiency ρ. The static power depends on the number of the antennas (K_{BS} or K_R) which are used for serving the SUs and the total power dissipation η in each antenna [5]. The total power is thus given as,

$$P_{tot} = (\sum_{j=0}^{R} \rho_j \sum_{i=1}^{N} || \mathbf{w}_{i,j} ||^2) + (\frac{\eta_0}{C} K_{BS} + \sum_{j=1}^{R} \frac{\eta_j}{C} K_R), \quad (8)$$

where $\| \mathbf{w}_{i,j} \|^2$ is the norm-square of $\mathbf{w}_{i,j}$.

The maximum transmitted power has to be bounded. Since each antenna has its own power amplifier, it is common practice to use the per-antenna constraint on both the SBS and the RS [3]. Each SBS and RS is thus subject to L_j power constraints, such that,

$$\sum_{i=1}^{N} \mathbf{w}_{i,j}^{H} \mathbf{Q}_{j,l} \mathbf{w}_{i,j} \leq q_{j,l}, \quad l = 1, 2, .., L_j \tag{9}$$

where $\mathbf{Q}_{0,l} \in C^{K_{BS} \times K_{BS}}$; $\mathbf{Q}_{j,l} \in C^{K_R \times K_R}$ are the weighting matrices defining the per antenna power constraints for $j = 1, ..., R$ and are positive semi-definite. Each antenna is limited by a limit $q_{j,l} \geq 0$, where $q_{0,l} \gg q_{j,l}$ for $j = 1, ..., R$. The numerical simulation considers $L_0 = K_{BS}$, $L_j = K_R$ and $q_{j,l} = q_j \forall \ell$. $Q_{j,l} = 1$ at the l^{th} diagonal element and zero elsewhere [5].

The energy efficiency of the network is defined as the QoS requirement of each SU per unit of power consumed by the SBS and the RSs. Thus for user t it is defined as,

$$EE_t = \frac{B \log_2(1 + SINR_t)}{P_{tot}}. \tag{10}$$

The normalised energy efficiency (with respect to bandwidth B) for each user t is given by,

$$EE_t = \frac{\log_2(1 + SINR_t)}{P_{tot}} = \frac{\log_2(1 + \hat{\gamma}_t)}{P_{tot}}. \tag{11}$$

The objective of this paper is to maximise the EE of the overall network, thus the total EE of the network is given by,

$$EE = EE_1 + EE_2 + ... + EE_N, \tag{12}$$

$$EE = \frac{N \cdot \log_2(1 + \hat{\gamma})}{P_{tot}}, \tag{13}$$

where all SUs are assumed to have the same QoS requirement i.e. $\hat{\gamma}_1 = \hat{\gamma}_2 = \ldots = \hat{\gamma}_N = \hat{\gamma}$.

Thus, since it can be inferred that $\mathbf{w}^* \mathbf{R} \mathbf{w} = Tr\left[\mathbf{R}\mathbf{w}\mathbf{w^*}\right] = Tr\left[\mathbf{R}\mathbf{W}\right]$ and using Eq. (13) where $\mathbf{w}_{i,j}^H$ is replaced with $\mathbf{W}_{i,j}$ [3], the final optimisation problem is defined as follows,

$$\begin{aligned} \max_{\forall \mathbf{w}} \quad & EE = \frac{N \cdot \log_2(1 + \hat{\gamma})}{\sum_{j=0}^{R} \rho_j \sum_{i=1}^{N} Tr(\mathbf{W}_{i,j}) + (\frac{\eta_0}{C} K_{BS} + \sum_{j=1}^{R} \frac{\eta_j}{C} K_R)}, \\ \text{s.t.} \quad & \log_2(1 + SINR_t) \geq \gamma_t, \quad \forall t \\ & \sum_{i=1}^{N} \sum_{j=0}^{R} | \hat{g}_{0,j}^{H} \mathbf{w}_{i,j} |^2 \leq \zeta, \\ & \sum_{i=1}^{N} \mathbf{w}_{i,j}^{H} \mathbf{Q}_{j,l} \mathbf{w}_{i,j} \leq q_{j,l}. \quad \forall j, l \end{aligned} \tag{14}$$

The objective function can be expressed as,

$$\max_{\forall \mathbf{w}} \quad EE = \frac{1}{\psi} = \frac{\log_2(1+\hat{\gamma})}{P_{tot}}, \tag{15}$$

where ψ is the new objective function used to maximize the EE.

Eq. (14) above is a non-convex problem and thus needs to be converted into a convex problem in order to solve it. Since the matrix $\mathbf{W}_{i,j}$ is a correlation matrix, it is thus necessary to add a constraint to guarantee that it is Hermitian and positive semi-definite. Thus Eq. (14) reduces to,

$$\begin{aligned}
\min_{\forall \mathbf{w}} \quad & \psi, \qquad\qquad (16)\\
\text{s.t.} \quad & \psi \cdot \log_2(1+\hat{\gamma}) \geq \sum_{j=0}^{R} \rho_j \sum_{i=1}^{N} Tr(\mathbf{W}_{i,j}) + (\frac{\eta_0}{C} K_{BS} + \sum_{j=1}^{R} \frac{\eta_j}{C} K_R),\\
& \sum_{j=0}^{R} \mathbf{h}_{t,j}^H ((1+\frac{1}{\hat{\gamma}_t})\mathbf{W}_{t,j} - \sum_{i=1}^{N} \mathbf{W}_{i,j})\mathbf{h}_{t,j} \geq \mid \mathbf{g}_{t,0} \mid^2 + \sigma^2, \quad \forall t\\
& \sum_{i=1}^{N} \sum_{j=0}^{R} \hat{g}_{0,j}^H \mathbf{W}_{i,j} \hat{g}_{0,j} \leq \zeta,\\
& \sum_{i=1}^{N} Tr\left[\mathbf{Q}_{j,l} \mathbf{W}_{i,j}\right] \leq q_{j,l},\\
& \mathbf{W}_{i,j} \succeq 0,\\
& \mathbf{W}_{i,j} = \mathbf{W}_{i,j}^*.
\end{aligned}$$

$\mathbf{W}_{i,j}$ is positive semi-definite with rank $[\mathbf{W}_{i,j}] \leq 1$. With an additional constraint of rank $[\mathbf{W}_{i,j}] = 1$ [8], Eq. (16) is an exact equivalent of Eq. (14). Since that constraint is not included in Eq. (16), it is a relaxed solution for Eq. (14).

4 Numerical Results

Numerical results have been obtained for the scenario shown in Fig. 1. SUs were randomly distributed in the given area with at least one SU present in each femto cell. For the sake of simplicity, only one antenna was considered at the PBS (the results can easily be extended to the multi-antenna case at the PBS).

The solution to the optimisation problem was solved so as to determine the EE of the system (while adhering to the constraints shown in Eq. (15)). The channel model from [7] was adopted for $\mathbf{h}_{t,j}$. The parameter values used when performing the simulations are listed in Table 1 [5].

Simulation results for the case where the number of SUs in the network is small, i.e. 5, are shown in Fig. 3. The EE when femto cells are employed is compared to the EE when only a BS is employed (no RS). The EEs of two

Table 1. Channel Parameters for the numerical results [5].

Parameters	Values
Micro cell radius	500 m
Femto cell radius	50 m
Minimum distance between SUs and BS/relays	35m/3.5m
Number of SUs	5 and 12
Number of PU	1
Number of relays	2
Number of antennas at SBS	20 - 100
Number of antennas at relays	0, 1, 2, 3
QoS constraint of SU	2 - 3 bit/s/Hz
Interference Temperature (IT)	0.1 mW
Carrier frequency	2 GHz
Number of sub-carriers	600
Total bandwidth	10 MHz
Sub-carrier bandwidth	15 kHz
Standard deviation of log-normal shadowing	7 dB
Path and penetration loss, distance d (km), (Micro Cell)	$148.1 + 37.6 \log_{10}(d)$ dB
Path and penetration loss, distance d (km), (Femto Cell)	$127 + 30 \log_{10}(d)$ dB
Noise variance	-127 dBm
Noise figure	5 dB
Power amplifier efficiency	
- Micro BS	0.388
- Relay	0.052
Circuit power per antenna	
- Micro BS	66 mW
- Relay	0.08 mW
Per antenna constraints	
- micro BS	189 mW
- Relay	25.6 mW

different levels of QoS are also compared. When the number of SUs is small and their QoS requirements are low it is not very beneficial to use more antennas for the femto cells. When the QoS requirement of the SUs is 2 bit/s/Hz, the improvement in EE for 1 antenna per RS, 2 antennas per RS and 3 antennas per RS is almost identical. The case when the QoS requirement is 3 bit/s/Hz, is similar.

From the plot it is evident that when the number of antennas at the SBS is small ($K_{BS} < 30$) the EE increases with the number of SBS antennas and is also higher when femto cells are employed. The extent to which EE is improved by the use of femto cells is dependant on the QoS requirement of the SUs. For the scenario where $K_{BS} = 30$ antennas, a femto cell with three antennas is employed and the QoS requirement of the SUs is 2 bit/s/Hz (shown by the dashed lines), there is a 0.149 b/s/Hz/W improvement in EE. However, there is a 0.425 b/s/Hz/W improvement when the QoS requirement is 3 bit/s/Hz

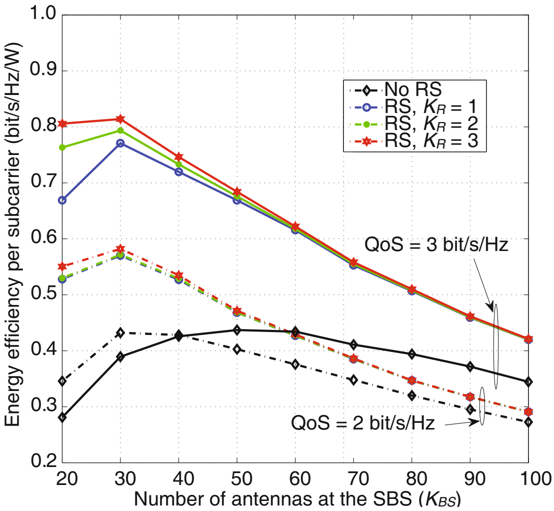

Fig. 3. Total energy efficiency of each BS when 5 SUs were considered (solid line: QoS of 3 bit/s/Hz; dashed line: QoS of 2 bit/s/Hz).

(shown by the solid lines). This improvement in EE is due to improved energy focusing, as a consequence of the large number of antennas used at the SBS, and also because the power gain due to a decrease in dynamic power is larger than the gain due to an increase in static power (caused by the addition of antennas).

When the number of antennas at the SBS becomes large ($K_{BS} > 30$) the improvement in EE begins to decrease and there is no further improvement to be gained by the addition of more antennas at the SBS, since the EE improvement steadily decreases due to an increase in the static power. Furthermore, the gain obtained from the deployment of femto cells, when compared to the case where no femto cells were deployed, becomes more distinguished as the QoS requirement of the SUs increases.

When no femto cells are employed, there is also an initial improvement in EE with the addition of antennas at the SBS. However, the improvement begins to decrease when $K_{BS} > 30$ for a QoS of 2 bit/s/Hz and when $K_{BS} > 50$ for a QoS of 3 bit/s/Hz.

Fig. 4 shows the energy efficiency of the system when the number of SUs is increased to 12. When no femto cells are deployed and when the SU QoS requirement is 2 bit/s/Hz (shown by the dashed line), then there is an improvement in EE when $K_{BS} < 80$ antennas, after which the gain in EE remains almost constant. When the QoS requirement increases to 3 bit/s/Hz, there is a continuous improvement in EE with an increment in the number of antennas at the SBS. When femto cells are deployed for the same scenario, the gain in EE increases with an increase in the number of femto cell antennas. This is due to a decrease in the propagation loss as a result of the use of femto cells, as well as an improvement in energy focusing due to the larger number of antennas.

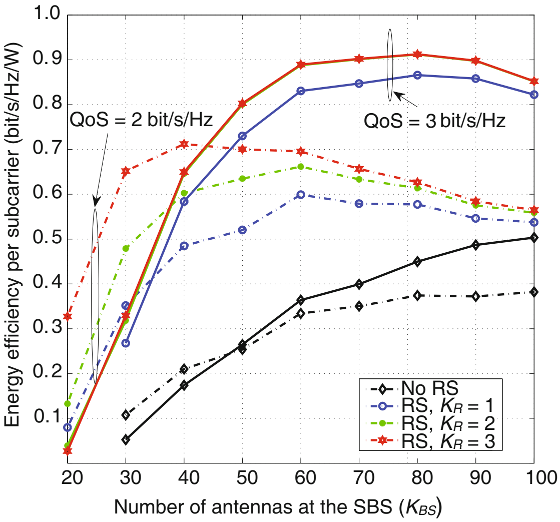

Fig. 4. Total energy efficiency of each station when 12 SUs are considered (solid line: Qos of 3 bit/s/Hz; dashed line: Qos of 2 bit/s/Hz).

The rate at which EE decreases, after the addition of a certain number of SBS antennas, varies according the SU QoS requirement. Similar to the 5 SUs case, the improvement in EE is larger for the higher QoS requirement.

The corresponding interferences per sub-carrier are listed in Table 2. It can be seen that the interference experienced by the PU, due to the SUs, decreases remarkably (by 22.2 %, from -10 dBm to -12.22 dBm) with the addition of femto cells. The result shows constant interference irrespective of the number of antennas used at either micro BS or femto cell. This is due to the fact that in the case of a micro BS, the problem is formulated according to the interference temperature (IT) limit. Thus, for a given IT (in this case 0.1 mW) the micro BS minimises its transmit power. For the case where femto cells are added to the network there is neither an increase nor a decrease in the interference experienced by the PU, since the PUs are located outside of the coverage of area of the RS. However, since the addition of femto cells divides the SUs into a micro BS region and a RS region, the number of users to be served by the BS is decreased; thereby decreasing the total interference to the PU. This result suggests that there would be a drastic decrease in the interference experienced by the PU if more users are served by the RS.

Table 2. Total interference to PU from each station (12 SUs with IT=0.1 mW).

Scenario	No RS	$K_R = 1$	$K_R = 2$	$K_R = 3$
ζ_0 (dBm)	-10.00	-12.22	-12.22	-12.22

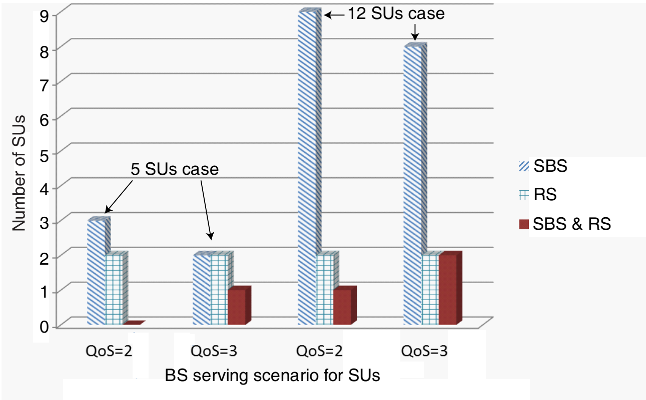

Fig. 5. Number of SUs served by different base stations and QoS requirements.

Fig 5 shows how the SUs are served by the different base stations. It explains the nature of the curves in Fig. 3 and Fig. 4. For the case of five SUs, when the QoS requirement is 2 bit/s/Hz, three SUs are served by the micro SBS and two SUs are served by the RS. When the QoS requirement is 3 bit/s/Hz, two SUs are served by the micro SBS, two SUs by the femto RS and the rest of the SUs by a combination of both. This suggests that when the SU QoS requirement increases it would be beneficial to serve the SUs using a combination of the SBS and the RS. Since the SUs are served in an efficient way, the rate at which EE decreases, after 40 antennas are added to the SBS, is similar for both QoS requirement scenarios. For the 12 SU case, when the QoS requirement is 2 bit/s/Hz, nine SUs are served by the micro BS, two SUs are served by the RS and one SU is served by both. When the QoS requirement of the SUs is 3 bit/s/Hz, eight SUs are served by the micro BS, two SUs are served by RS and two SUs are served by both.

5 Conclusion

From the results obtained it can be concluded that the gain in EE, obtained from the deployment of femto cells, decreases as the number of antennas at the SBS increases (when the number of SUs in the network is small). Thus, when the SU QoS requirement is small, the gain in EE is almost negligible when a large number of antennas is used at the SBS. The benefit of deploying femto cells becomes more pronounced as the number of SUs in the network increases, as well as when the SU QoS requirements are increased. Similarly, when the number of SUs and/or the network SU QoS requirements increase, it becomes more beneficial to increase the number of antennas at the femto cell RS. Irrespective of the number of SUs, the EE increases when the QoS requirement of the SUs increases. Massive MIMO is thus an effective approach for increasing the EE at the BS, for the case when the CRN needs to support a large number of users with a high QoS requirement. Furthermore, the inclusion of femto cells within the larger cell not only increases EE drastically, but also reduces the interference experienced by the PU. The coordinated secondary BS and RSs act in a cordial way to serve the SUs that produce the least interference to the PU, while still satisfying the SU QoS requirements.

In future work, small cell access points can be included within the micro cell to improve the performance of the CRN.

Acknowledgment. This research was supported by the Sentech Chair in Broadband Wireless Mobile Communication.

References

1. Report of the spectrum efficiency working group. Spectrum Policy Task Force (2002)
2. Bayhan, S., Alagoz, F.: Scheduling in centralized cognitive radio networks for energy efficiency. IEEE Trans. Veh. Technol. **62**(2), 582–595 (2013)
3. Bengtsson, M., Ottersten, B.: Optimal and suboptimal transmit beamforming. In: Handbook of Antennas in Wireless Communications (2001)
4. Björnson, E., Jorswieck, E.: Optimal resource allocation in coordinated multi-cell systems. Foundations Trends Commun. Inform. Theory **9**(2–3), 113–381 (2012)
5. Björnson, E., Kountouris, M., Debbah, M.: Massive MIMO and small cells: improving energy efficiency by optimal soft-cell coordination. In: 20th Int. Conf. Telecommun., Casablanca, Morocco, pp. 1–5 (2013)
6. Hasan, Z., Boostanimehr, H., Bhargava, V.K.: Green cellular networks: A survey, some research issues and challenges. IEEE Commun. Surveys Tuts. **13**(4), 524–540 (2011)
7. Hoydis, J., ten Brink, S., Debbah, M.: Massive MIMO in the UL/DL of cellular networks: How many antennas do we need? IEEE J. Sel. Areas Commun. **31**(2), 160–171 (2013)
8. Huang, Y., Palomar, D.P.: Rank-constrained separable semidefinite programming with applications to optimal beamforming. IEEE Trans. Signal Process. **58**(2), 664–678 (2010)
9. Islam, H., Liang, Y.C., Hoang, A.T.: Joint beamforming and power control in the downlink of cognitive radio networks. In: Proc. IEEE Wireless Commun. Netw. Conf., Kowloon, Hong Kong, pp. 21–26 (2007)
10. Marzetta, T.L.: Noncooperative cellular wireless with unlimited numbers of base station antennas. IEEE Trans. Wireless Commun. **9**(11), 3590–3600 (2010)
11. Mitola III, J., Maguire Jr, G.Q.: Cognitive radio: Making software radios more personal. IEEE Pers. Commun. **6**(4), 13–18 (1999)
12. Saker, L., Elayoubi, S.E., Chahed, T., Gati, A.: Energy efficiency and capacity of heterogeneous network deployment in LTE-advanced. In: Proc. 18th European Wireless Conf., Poznan, Poland, pp. 1–7 (2012)