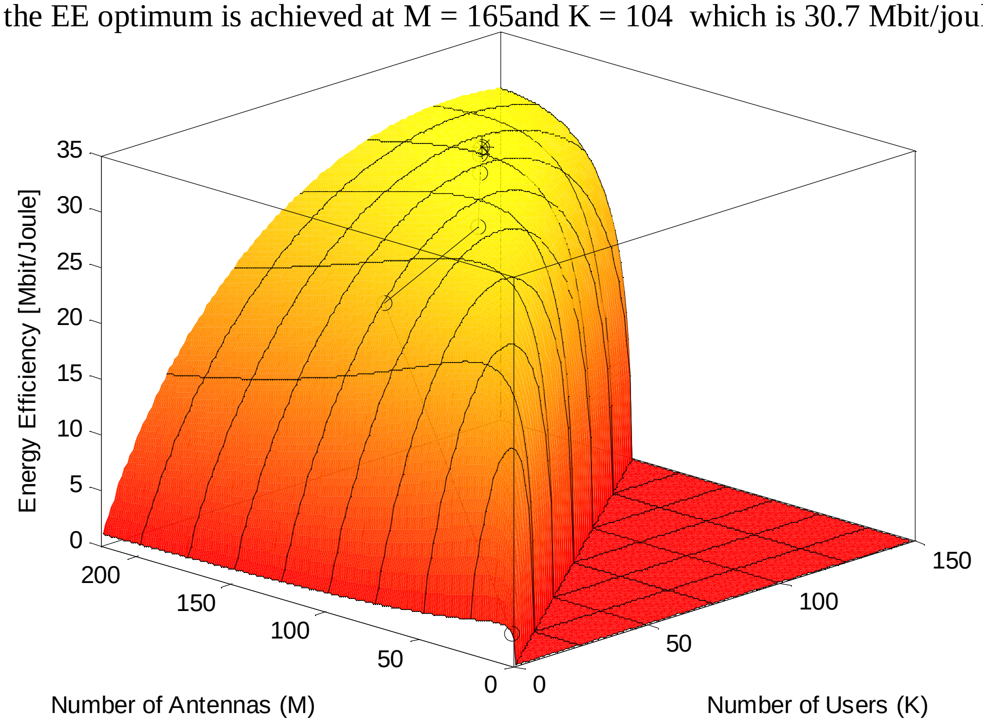
Chapter Four

4. Simulationresults and discussion

MATLAB simulation used to simulate the algorithms and equation founded in the previous chapter, we present numerical results to verify the theoretic analyses and simulation results of The Energy Efficiency (EE) which is measured in Mbit/Joule and is computed as the ratio between the average capacity sum rate
(bit/second) and the average total power consumption(Joule/second).

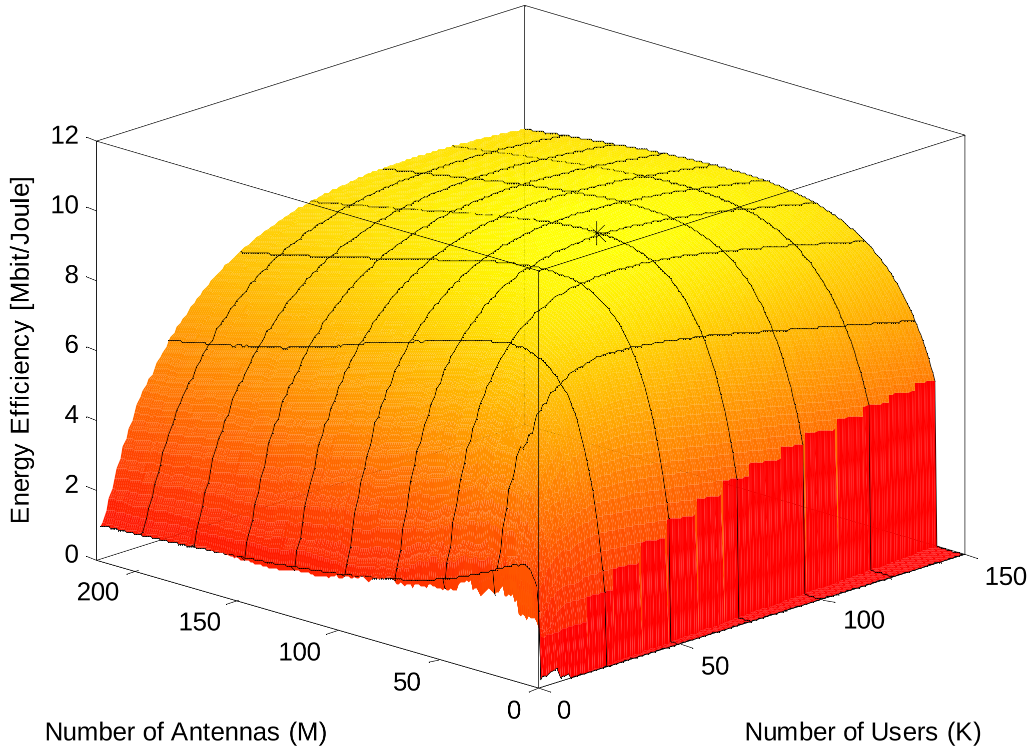
4.1 Single cell Scenario

Figure (4.1) shows set of achievable EE values with perfect CSI, single cell,ZF processing, and for differentvalues of M and K, the surface in figure(4.1) is concave and quite smooth; thus, there is a variety of system parameters that provides close-to-optimal EE. and the EE optimum is achieved at M = 165and K = 104 which is 30.7 Mbit/joule.



Figure(4.1) Energy efficiency (in M bit/Joule) with ZF processing in the single cell scenario.

Figure (4.2) shows the corresponding set ofachievable EE values under MRC processing Interestingly,MRC processing gives a very differentbehavior: the EE optimum is much smaller than with ZF and is achieved at M = 81 and K = 77 which is 9.86Mbit/joule.



Figure(4.2) Energy efficiency (in M bit/Joule) with MRC processing in the single cell Scenario

This can still be called a massive MIMO setup since there is a massive number of BS antennas, but it is a degenerative case where M and K are almost equal and thus the typical asymptotic massive MIMO properties from [7], [10] will not hold. The reason for $M \approx K$ is that MRC operates under strong inter-user interference, thus the rate per UE is small and it makes sense to schedule as many UEs as possible (to crank up the sum rate). The signal processing complexity is lower than with ZF for the same M and K, but the power savings are not big enough to compensate for the lower rates. To achieve the same rates as with ZF, MRC requires $M \gg K$ which would drastically increase the computational/circuit power and not improve the EE.

Despite its larger number of BS antennas and UEs, ZF processing only requires 3 times more operations than MRC,this is because the total complexity is dominated by performing precoding and receive combining on every vector of data symbols.

To further compare the different processing schemes, figure(4.3) shows the maximum EE as a function of the number of BS antennas.

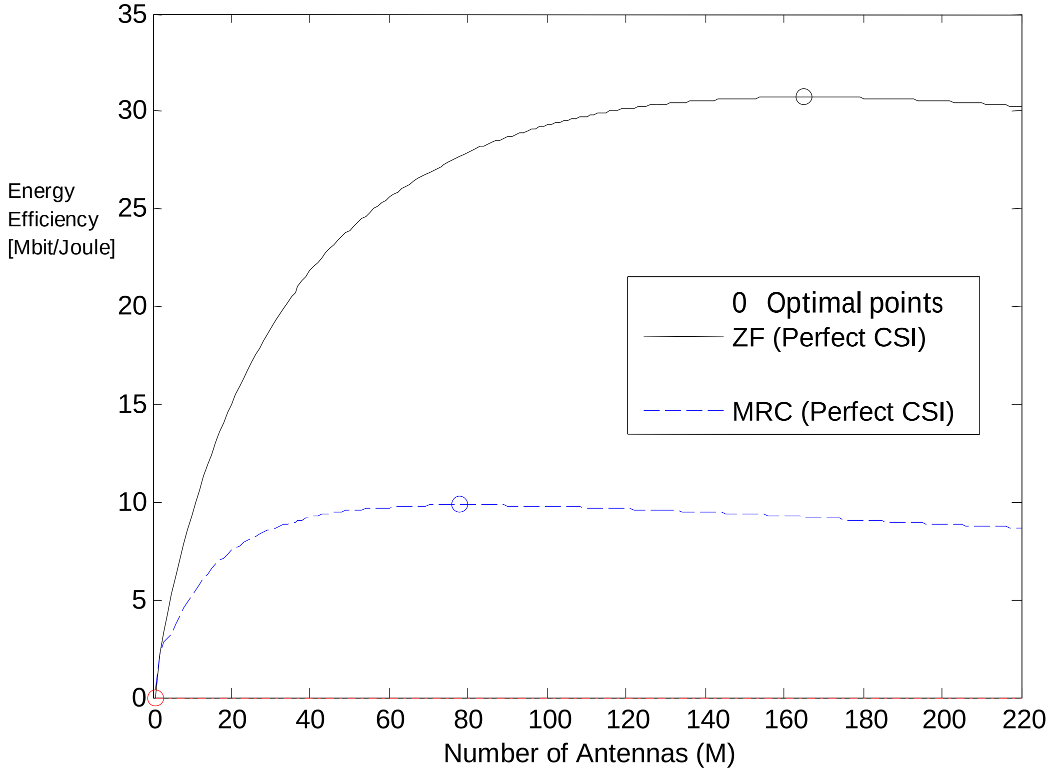
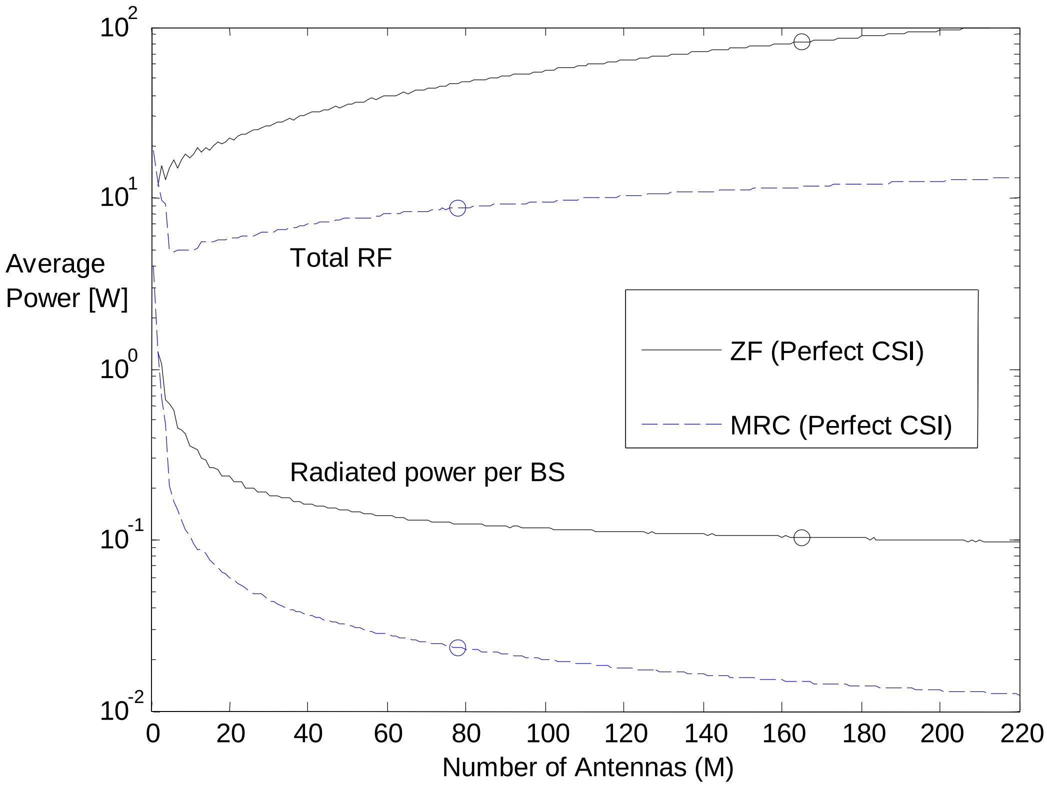


Figure (4.3)Maximal EE for different number of BS antennas and ZF, MRC processing scheme in the single-cell scenario.

Next, Figure(4.4) shows the total PA power that maximizes the EE for different M (using the corresponding optimal K). For all the considered processing schemes, the most energy efficient strategy is to increase the transmit power with M,it reveals that the EE optimal solution can be deployed with low-power UE-like RF

amplifiers. The downlink transmit power with ZF precoding is around 100mW/antenna, while it drops to 23 mW/antenna with MRC since it gives higher interference and thus makes the system interference-limited at lower power.



Figure(4.4) Total PA power at the EE-maximizing solution for different number of BS antennas in the single-cell scenario. The radiated power per BS antenna is also shown

Figure(4.5)shows the area throughput (in Gbit/s/km^2)that maximizes the EE for different M,itshows that massive MIMO with proper interference-suppressing precoding can achieve both great energy efficiency and unprecedented area throughput.

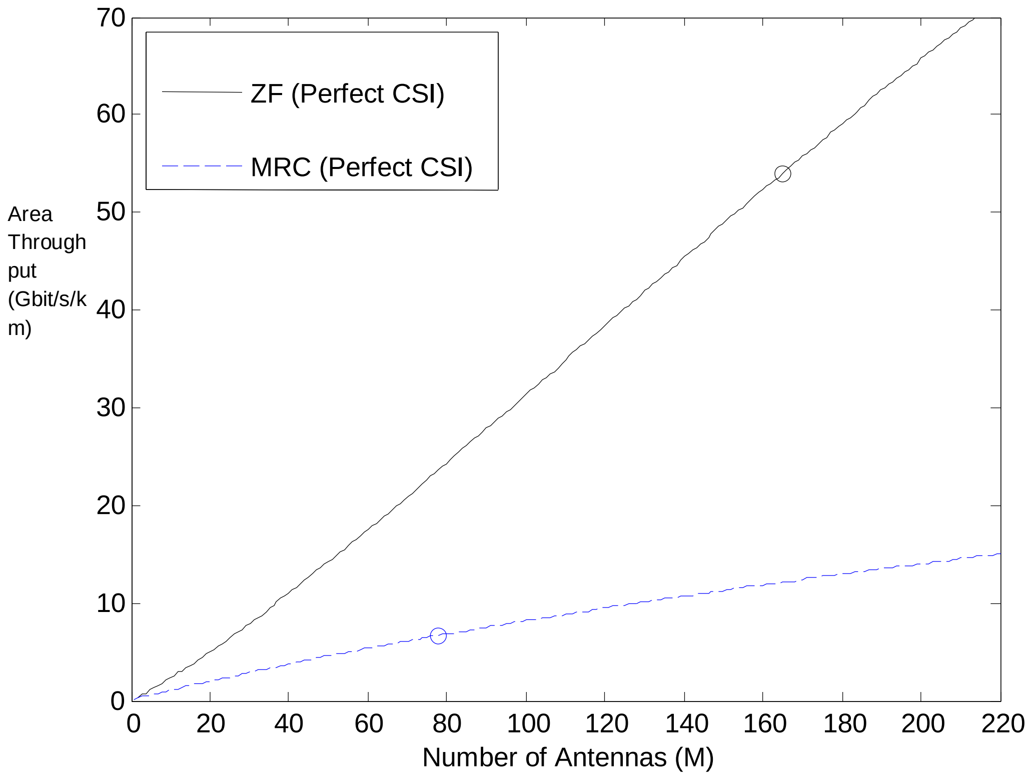


Figure (4.5)Comparison of area throughputat the EE-maximizing solution for different number of BS antennas in the single-cell scenario.

it is wasteful to deploy a large number of BS antennasand then co-process them using a MRC processingscheme that is severely limiting both the energy efficiencyand area throughput.

4.2Multi-Cell Scenario

Next, we consider the symmetric multi-cell scenario illustrated in figure(3.3) and concentrate on the cell in the middle. Each cell is a 500 ×500 square with uniformly distributed UEs, with the same minimum distance as in the single-cell

scenario. We consider only interference that arrives from the two closest cells (in each direction), thus the cell under study in figure (3.3)is representative for any cell in the system.

Motivated by the single-cell results, we consider only ZF processing and focus on comparing different pilot reuse patterns. As depicted in figure (3.3), the cells are divided into four clusters. Three different pilot reuse patterns are considered:

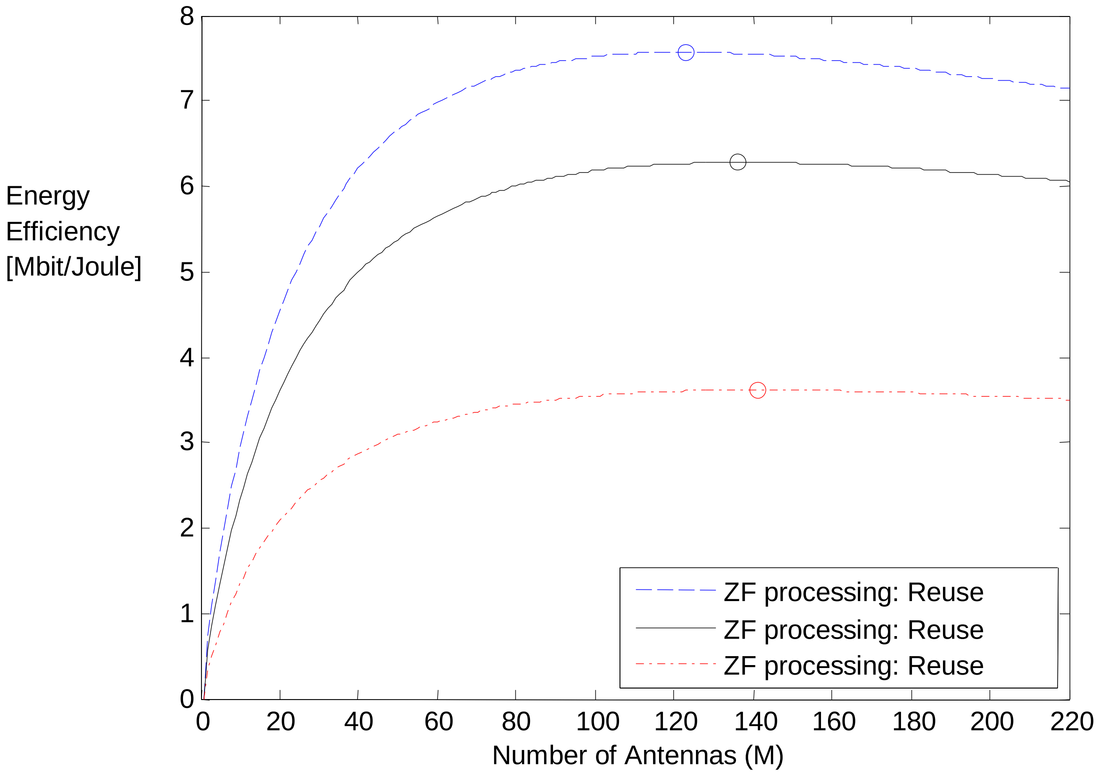
the same pilots in all cells (ƈ (ul) = 1), two orthogonal sets of pilots with Cluster 1 and Cluster 4 having the same (ƈ (ul) = 2), and all clusters have different orthogonal pilots (ƈ (ul) = 4). Numerical computations of the relative intercell

interference give (0:5288; 0:1163; 0:0214) where the values reduce with increasing reuse factor ƈ (ul).

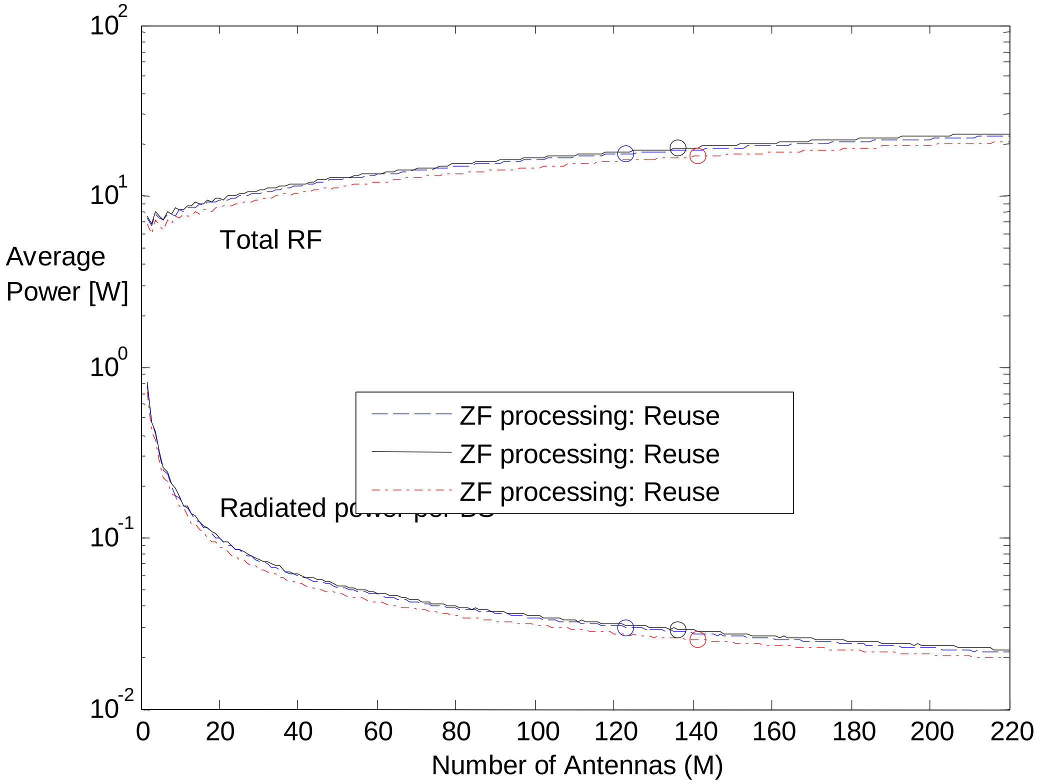
The maximal EE for different number of antennas is shown in figure(4.6)

while figure(4.7)shows the corresponding PA power (and power per BS antenna) and figure(4.8) shows the area throughput. These figures are very similar to the single-cell counterparts in figures(4.4)(4.5), but with the main difference that all the numbers are smaller. Hence, the inter-cell interference affects the system by reducing the throughput, reducing the transmit power consumption, and thereby also the EE. Interestingly, the largest pilot reuse factor (ƈ (ul) = 4) gives the

highest EE and area throughput. This shows the necessity of actively mitigating pilot contamination in multi-cell systems.



Figure(4.6)Maximal EE in the multi-cell scenario for different number of BS antennas and different pilot reuse factors.



Figure(4.7)Total PA power at the EE-maximizing solution in the multi-cell scenario, for different number of BS antennas. The radiated power per BS antenna is also shown.

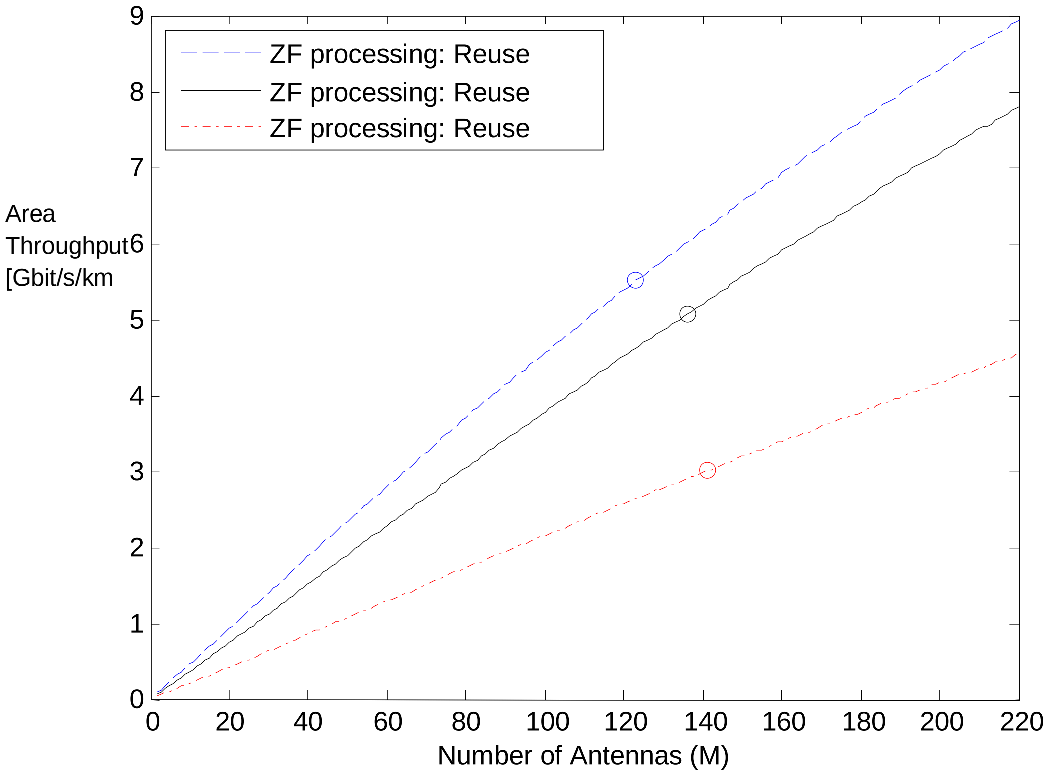


Figure (4.8)Area throughput at the EE-maximizing solution in the multi-cell scenario, for different number of BS antennas.