Area Spectral Efficiency of a Macro-Femto Heterogeneous Network for Cell-Edge Users under Shadowing and Fading Effects

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Abstract **–** The traditional macro-only network is not effective, especially when communication signal is required for users far away from the macrocell base station and located in the cell edge. The signal strength reaching these users is excessively attenuated due to fading and shadowing. The deployment of femtocells around the cell edge of this macrocell helps to reduce the effect of fading and shadowing thereby increasing the overall efficiency of the cellular network. This holds a great promise for adaptive space-based wireless sensor networks, formation-flying satellites and constellations.

Index Terms **–** Femtocells, heterogeneous networks, macrocells, spectral efficiency, uplink.

I. INTRODUCTION

Spectral efficiency is an important measure of the performance of a communication system that deals with the effective transmission of data. This efficiency must be optimized to match the available radio spectrum for mobile users to achieve a seamless communication. As the number of mobile users increases, the pressure on the available communication spectrum increases, leaving users in the cell-edge with extremely poor reception of the signal from the base station. The increase in mobile users is fast becoming higher than the spectral efficiency enhancements available to meet the required increase in the teledensity traffic.

To meet these challenging necessities in terms of coverage, capacity and deployment costs, heterogeneous network transmission techniques [1-3] are regarded to be one of the most promising solutions. A crucial part of these techniques will be how to significantly improve the capacity of users in the cell edge, coverage in rural areas due to the long distance between the traditional base stations and the mobile users in these areas as well as underground locations due to wall attenuation. One of the current heterogeneous network approaches is the deployment of low-power and low-cost femtocells within and around the main macro cellular infrastructure. This is referred to as two-tier heterogeneous network [4-6].

This paper considers the effect of shadowing and fading on the area spectral efficiency (ASE) of this two-tier heterogeneous network in uplink called the Macro-Femto Heterogeneous Network (MFHN).

From Fig. 1, the first tier of the case study heterogeneous network comprises of the macro-only network in which the carrier frequency is re-used at a minimum distance D[m]. This first tier comprises of a circular macrocell of radius R_m [m] with a base station made up of an omnidirectional antenna. The user is considered to be randomly located within the macro-cell bounded by R_0 and R_m, where R_0 is the minimum distance a user can be with reference to the macrocell base station.

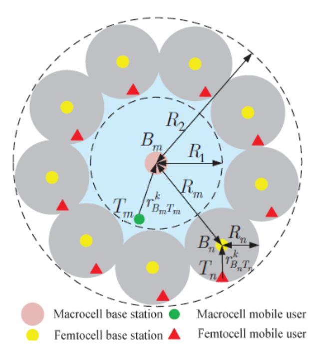

Fig. 1. Femtocells distribution at the cell edge in the Macro-Femto network [7].

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II. SYSTEM MODEL AND ANALYSIS

The second tier heterogeneous network is made up of N circular femtocells each of radius R_n [m] with low-powered low-cost user deployed femto base station at the center. The femtocells are deployed round the edge of the reference macrocell. This is also referred to as the femto-on-edge (FOE) configuration in [7]. For the simulation, the number of femtocells per macrocell, N, is given as:

$$N = \mu \frac{A_m}{A_n}, \quad (1)$$

where A_m is the area of the macrocell, A_n, the area of each of the femtocells and μ the femto population factor (FPF) [7] which controls the number of femtocells per macrocell. Simplifying this further, we obtain the following relationship:

$$N = \mu \frac{4 \times c}{R_n}. \quad (2)$$

A. Bandwidth allocation

In this paper, the co-channel allocation of the bandwidth is utilized where the users all share the same frequency channel without any partitioning. Hence the bandwidth for the macrocell and femtocell users are thus:

$$W_m = W_f = W, \quad (3)$$

where, W_m is the bandwidth for the macrocell users, W_f is the bandwidth for the femtocell users and W is the total available bandwidth. The macrocell and the femtocells share all the communication resources available. For simplicity, the channel is assumed to be serving only one user at a time for the both tier. The bandwidth is re-used throughout the macrocell network at a distance $D = R_u(R_m + R_n)$, where R_u is the network traffic load which has a value of 2 for a fully loaded cellular network [7].

B. Mobile user distribution

The mobile users in the macrocell, femtocell and interfering cells are assumed to be independent and uniformly distributed in their cells. The joint probability density function (PDF) of the macrocell users at any location (r, θ) from its serving macrocell base station is given by [7]:

$$p(r, \theta) = \frac{r - R_0}{\pi (R_1 - R_0)^2}, \quad (4)$$

where $R_0 \leq r \leq R_1$, $0 \leq \theta \leq 2\pi$ and $R_1 = R_m - R_n$.

For the femtocell users at any location $(\tilde{r}, \theta)$ from its serving femtocell base station, the PDF is given as:

$$p(\tilde{r}, \theta) = \frac{\tilde{r}}{\pi {R_n}^2}, \quad (5)$$

where $0 \leq \tilde{r} \leq R_n$ and $0 \leq \theta \leq 2\pi$.

C. Shadowing

The shadowing is modelled as a lognormal distribution with the probability density function (PDF) of the slowly varying received signal power given as [7]:

$$ps(P) = \frac{\varepsilon}{\sqrt{2\pi}\sigma P} exp(-\frac{(\varepsilon \, ln(P) - \mu)^2}{2\sigma^2}), \quad (6)$$

where ε=10/ln 10, $\mu = \varepsilon \ln(\bar{P})$ is the logarithmic mean power in dB, σ is the shadow standard deviation in dB.

D. Fading

This is modelled using the slow varying flat fading channel. It is assumed that the fading environment is characterized by a Nakagami-m distribution with the probability density function (PDF) of the received signal power given as [7]:

$$ps(P) = (\frac{m}{\Omega})^m \frac{P^{m-1}}{r(m)} \exp\left(-m\frac{P}{\Omega}\right), \quad (7)$$

where m is the Nakagami fading parameter, Ω is the mean received power related to path-loss and shadowing, $r(.)$ is the gamma function.

E. Area spectral efficiency

The area spectral efficiency is defined as the sum of the maximum available rates per bandwidth per unit macro-cell area. For the two tier network being considered, mathematically the ASE can be expressed as:

$$ASE = \frac{4(W_m C_m + N W_f C_f)}{\pi W {R_u}^2 (R_m + R_n)^2}, \quad (8)$$

W_m is the bandwidth of the macrocell, W_f is the bandwidth of the femtocell, C_m is the spectral efficiency (Capacity) of the macrocell, C_f is the capacity of the femtocell and N is the number of femtocell deployed.

From the earlier assumption in Equation (1), this equation reduces to:

$$ASE = \frac{4(C_m + N C_f)}{\pi {R_u}^2 (R_m + R_n)^2}. \quad (9)$$

III. SIMULATION PARAMETERS

A Monte-Carlo simulation procedure is established for the given system parameters in Table 1.

Table 1: Simulation parameters values

Simulation Parameters	Femtocell	Macrocell
System bandwidth	20 MHz	
Cell radius	30 m	100-600 m
Path-loss exponent	2	2
Additional path-loss exponent	2	2
BS antenna height	5 m	25 m
Mobile user antenna height	1.5 m	1.5 m
Femto population factor, μ	1	
Reference distance	100	
Path-loss constant, K	1	
Maximum transmit power	10 Watt	
Reference distance, Ro	-	100 m

A. Area spectral efficiency with shadowing

In this section, the effect of shadowing is investigated. Shadowing occurs due to objects obstructing the relative propagation path between the transmitter and receiver. For a long distance propagation, the received signal is modelled as a log-normal distribution with values in dB. A case of light shadowing (σ_d = 4 dB) and heavy shadowing (σ_d = 6 dB) are considered [8].

Figure 2 shows the effect on the area spectral efficiency for a shadowing parameter of 4 dB. From Fig. 2, a lognormal shadowing parameter of 4 dB reduces the ASE for the macro only. For the macro-femto network, shadowing effect is negligible. In Fig. 3, the increase in the shadowing parameter to 6 dB further reduces the area spectral efficiency of the macro-only network. The area spectral efficiency of the macro-femto network is minimally affected.

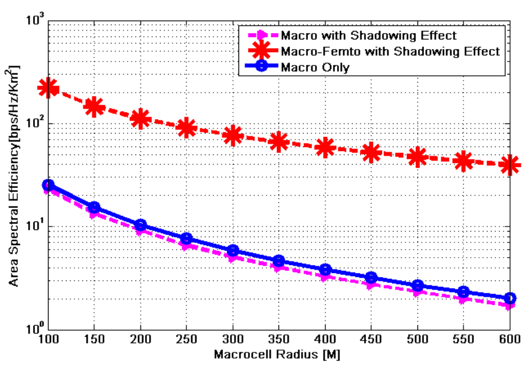

Fig. 2. Effect of shadowing on the area spectral efficiency for $\boldsymbol{\sigma_d}$ = 4 dB.

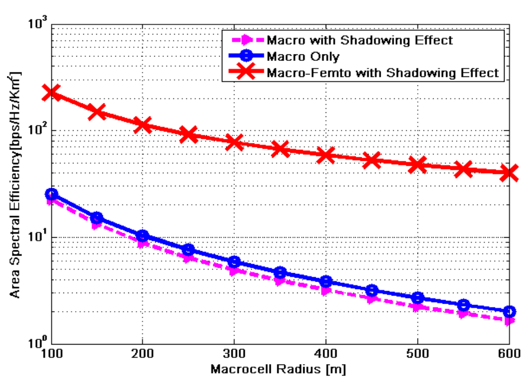

Fig. 3. Effect of shadowing on the area spectral efficiency for $\boldsymbol{\sigma_d}$ = 6 dB.

Comparing Figs. 2 and 3, the lower effect of shadowing on the macro-femto network can be attributed to the deployment of the low powered femtocells at the cell edge which provides the platform of signal reception for the cell-edge user rather than receiving communication signal directly from the traditional macro base station which is subject to more shadowing effect.

Furthermore, the deployment of the femtocells provides the medium for cell-edge users' connection to the network reducing the traffic on the traditional microcell network. This leads to less shadowing experienced over the macro-only distance; hence, improving the quality of the over-all macro-femto network.

The reported area spectral analysis of terrestrial macro-femto heterogeneous network can be extended to design and deploy small satellite missions operating as constellations, clusters and formation flying nodes in space. The categories for this application would span highly adaptive attosatellites, femtosatellites, picosatellites, nanosatellites and microsatellites in low Earth orbit [8, 9]. The feasible modes of operation are explained in [9], while [10] examines the operational times analysis of the payload subsystem for cost-effective mission, optimal operational margins and efficient power budgeting. This is an emerging trend for space-based macro-femto heterogeneous sensor networks.

B. Area spectral efficiency with fading

Fading is the distortion to communication signal as it is being propagated through certain propagation medium. This distortion may be as a result of multiple reflection of transmitted signal from various surfaces leading to a multipath propagation of the transmitted signal. This effect is considered for mobile users situated in the cell edge where they are prone to excessive fading on the communication signal from the traditional macrocell base station.

From Figs. 4 and 5, as the interfering mobile user increases from m_I=1 to m_I=3, the degradation on a Macro-only network reduces the spectral efficiency when compared with the macro-femto heterogeneous network. There is a negligible effect of the fading on the macro-femto heterogeneous network. In a deep fade scenario, the macro-femto network performs better than the Macro-only network as the radius of the macrocell is increased.

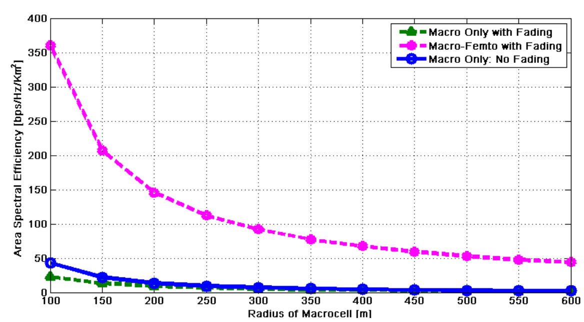

Fig. 4. Effect of fading on the area spectral efficiency for $\boldsymbol{m_I}$ = 1.

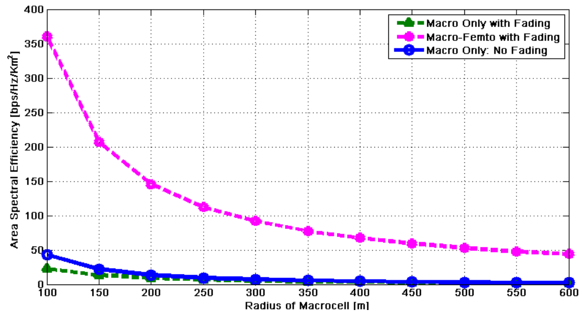

Fig. 5. Effect of fading on the area spectral efficiency for $\boldsymbol{m_I}$ = 3.

IV. CONCLUSION

A Monte-Carlo simulation process has been carried out to investigate the effect of fading and shadowing on the area spectral efficiency of a Macro-Femto Heterogeneous Network. This effect is compared with a macro-only network. The simulation result shows that the fading and shadowing effect in the macro-femto network is minimal when compared with the macro-only network. The immediate future works bordering on this research span the terrestrial and space communications networks. Firstly, the investigation of the effect of fading and shadowing between femto and femto cells located in the macro cell-edge is a core research area. Secondly, the energy efficiency of the macro-femto scheme discussed in this paper can be investigated further. Heterogeneous network hybrids such as a three-tier heterogeneous network form a key study niche that next-generation networks will depend on for a reliable seamless global communication. Furthermore, the study can be extended to validate the area spectral efficiency of space-based sensor nodes and small satellite constellations links in Earth orbits.

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