Enhancing the Performance of Cluster-based Networks through Energy Efficient MISO Techniques

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***Abstract*—Network clustering has been proposed as an efficient approach for addressing the problems arising from the continually increasing network density. Beside the congestion relieving and the coverage extension, cluster-based networks provide considerable energy savings, improving the sustainability of low-power networks. It has been shown that the energy efficiency and the network reliability are further enhanced by allowing the devices within a cluster to establish a communication link to the infrastructure through more than one cluster-heads (CHs). The performance improvement due to the diversity gain is important, but it may come at the cost of additional complexity, since the CHs have to continuously estimate the channel state information (CSI) for each device requiring access grant. In this paper, we are presenting an alternative scheme, aiming at reducing the hardware complexity by avoiding the CSI estimations, while maintaining the benefits from the CH selection scheme. The benefits of such an approach can be clearly identified in case that CH-based network operate in composite fading environments, where multipath fading coexists with shadowing. In our case, this composite environment has been modeled by the K distribution. The presented theoretical analysis, which is validated via extensive computer simulations shows that the performance of the low-complexity scheme is comparable to the CSI-based one.**

***Index Terms*—Cluster-based networks, wireless internet, K composite fading, shadowing.**

I. Introduction

The vision of sustainable wireless internet is based on the assumption of a global infrastructure providing internetworking between human users and/or machines. Cellular systems are considered to be a fundamental part of the wireless internet, offering substantial benefits, such as ubiquitous coverage and global internetworking [1]. The demand for reliable communication between machines without the intervention of humans has rendered the energy efficiency of devices as a primary research field, since most of the connected objects (e.g. sensors) are subject to physical limitations, including power consumption or hardware complexity. Toward this problem which hinders the direct link of such devices to the cellular infrastructure, cluster-head (CH) based networks have been introduced, providing coverage extension, which facilitates the connectivity of those objects [2], [3] (see Fig. 1).

With the energy efficiency being the primary goal, complemental techniques have been proposed aiming to enhance it, by enabling the users (devices) within a cluster to select between two ore more CHs for the communication link to the infrastructure [4], [5]. Following a similar concept, we propose a communication protocol for CH-based networks, where the nodes can select a CH to be connect to, according to the corresponding signal strength, in order to maintain a predefined Quality of Service (QoS) constraint. More specifically, the user selects the CH with the highest signal to noise ratio (SNR). Following such an approach, the network reliability significantly increases, especially for these mobile scenarios, where the connection to a CH may be not possible, due to shadowing effects. In contrast to previous works, we relate the CH failure with the wireless channel between the infrastructure (e.g. base station), the CH and the node, which is subject to multipath random fading and shadowing. Additionally, we assume that the CHs are equipped with multiple antennas, enhancing further the performance and the reliability of the network. More specifically, two diversity techniques are going to be investigated, namely maximal ratio transmission (MRT) and equal gain transmission (EGT) for the downlink and maximal ratio combining (MRC) and equal gain combining (EGC) for the uplink case. EGT at the transmitter (or EGC at the receiver) have already been considered as low-cost alternatives to maximal ratio transmission and combining, respectively, providing similar performances [6]. In terms of performance, MRT/MRC are considered to be the optimal solutions, at the expense of increased complexity, and thus, power consumption. On the other hand, EGT/EGC allow the use of inexpensive amplifiers at the antennas, since the antenna amplifiers do to modify the amplitudes of the transmit signal, which means that no estimations of the channel state information (CSI) are necessary. Moreover, the absence of CSI estimations results in lower demands for signal processing and thus energy consumption (see Fig. 2).

II. System Model and Mode of Operation

We consider a communication network, where an access point (e.g., a base station in a cellular network) broadcasts a message to a set of mobile nodes (Fig. 1). The nodes are divided in M CH overlays, each consisting of N CHs [5]. The CHs are equipped with a single antenna for the link to the access point and L antennas for the link to the mobile nodes. The CHs receive the broadcast message, via an error

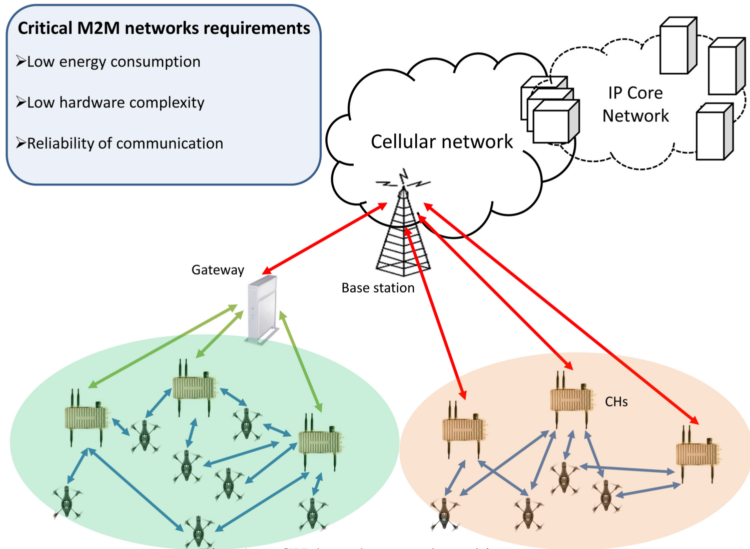

Fig. 1. CH based network architecture.

free channel, and then retransmit it to the mobile nodes, using either MRT or EGT techniques, depending on the availability of perfect CSI knowledge at the CHs. For the uplink case, the nodes transmit their data and the CHs combine the received signal at each antenna in terms of MRC or EGC.

A. Received Signal Statistics

Let $X_{\ell,n}$ $(\ell = 1, 2, \ldots, L_n)$ represent the fading amplitude between the ℓth antenna of the nth CH $(n \in N)$ and the end node, following the $\mathcal{K}$ distribution with PDF given by [7, eq. (2)]

$$f_{X_{\ell,n}}(x) = \frac{4x^{k_{\ell,n}}}{\Gamma\left(k_{\ell,n}\right)} \left(\frac{1}{\Omega_{\ell,n}}\right)^{(k_{\ell,n}+1)/2} K_{k_{\ell,n}-1}\left(2\frac{x}{\sqrt{\Omega_{\ell,n}}}\right) \tag{1}$$

where $k_{\ell,n} \geq 0$ is the shaping parameter of the distribution related with the severity of the shadowing, $\Omega_{\ell,n}$ is the average fading power given as $\Omega_{\ell,n} = \mathbb{E}\langle X^2_{\ell,n}\rangle / k_{\ell,n}$, with $\mathbb{E}\langle\cdot\rangle$ denoting expectation, $K_{\alpha}\left(\cdot\right)$ is the modified Bessel function of the second kind and order α [8, eq. (8.407/1)] and $\Gamma\left(\cdot\right)$ is the Gamma function [8, eq. (8.310/1)]. By using different values for k_{ℓ}, (1) describes various shadowing conditions, from severe shadowing, e.g., $k_{\ell} \to 0$, to no shadowing, e.g., $k_{\ell} \to \infty$.

Furthermore, the total instantaneous SNR of the received signal at a mobile node from the nth CH (downlink with EGT or MRT), or the combined signal at the CHs (uplink with EGC or MRC), is given by [9, eq. (9.51)]

$$\gamma_{\mathrm{out_n}} = \theta_{\delta,1} \frac{E_s}{N_0} \left(\sum_{\ell=1}^{L} X_{\ell,n}^{-\delta+2}\right)^{\delta+1} \tag{2}$$

where $\theta_{\delta,a} = \left(2^{-a} - 1\right)\delta + 1$, $a \in \mathbb{N}$. It is noted in (2) for $\delta = 0$ and $\delta = 1$, γ_{out} represents the output for MRC and EGC diversity receivers, respectively. It can be proved that in case of identical fading conditions, the PDF of $\gamma_{\mathrm{out_n}}$ can be obtained as

$$f_{\gamma_{\mathrm{out_n}}}(\gamma) = \frac{2k_{\ell,n}^{\frac{L-k_{\ell,n}}{2}+1} \gamma^{\frac{k_{\ell,n}+L}{2}-1}}{\Gamma(L)\Gamma(k_{\ell,n})\left(\beta\overline{\gamma}\right)^{\frac{k_{\ell,n}+L}{2}}} K_{k_{\ell,n}-L}\left(2\sqrt{\frac{k_{\ell,n}}{\beta\overline{\gamma}}\gamma}\right) \tag{3}$$

where $\beta = 1$ for MRC (in the downlink) or MRT (in the uplink), $\beta = 4/5$ for EGC (in the downlink) or EGT (in the

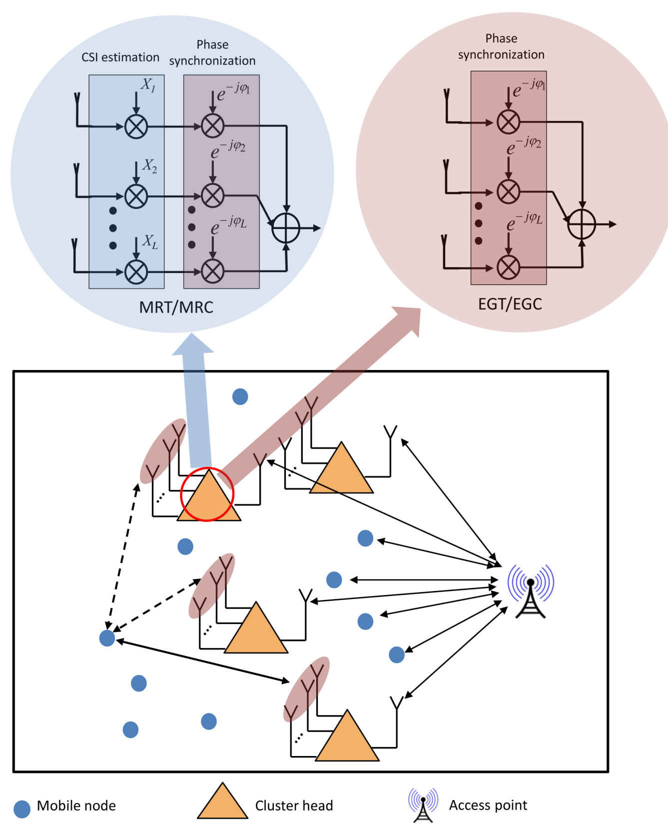

Fig. 2. System model.

uplink), while $K_\nu(\cdot)$ is the modified Bessel function of the second kind and order ν [8, eq. (8.407/1)]. It is noted that for MRC (or MRT) (3) represents an exact expression, while for EGC (or EGT) (3) represents an approximated expression. Furthermore, the corresponding expressions for the CDF are the following

$$F_{\gamma_{\text{out}_\text{n}}}(\gamma) = \frac{k_{\ell,n}^{\frac{L-k_{\ell,n}}{2}+1} \gamma^{\frac{k_{\ell,n}+L}{2}}}{\Gamma(L)\Gamma(k_{\ell,n}) (\beta\overline{\gamma})^{\frac{k_{\ell,n}+L}{2}}} \times \mathcal{G}_{1,3}^{2,1}\left(\frac{k_{\ell,n}\,\gamma}{\beta\overline{\gamma}}\middle|\begin{matrix}1-\frac{k_{\ell,n}+L}{2}\\ \frac{k_{\ell,n}-L}{2}, -\frac{k_{\ell,n}-L}{2}, -\frac{k_{\ell,n}+L}{2}\end{matrix}\right) \quad (4)$$

where $\mathcal{G}_{p,q}^{m,n}[\cdot|\cdot]$ is the Meijer's G-function [8, eq. (9.301)].

B. Proposed Technique

For the CH selection strategy that is adopted in this analysis, the CH providing the link with the highest instantaneous SNR is selected for the connection between the nodes and the AP, i.e., the criterion for selecting the CH is $\gamma_{\text{out}} = \max(\gamma_{\text{out}_1}, \gamma_{\text{out}_2}, \ldots, \gamma_{\text{out}_\text{N}})$. In that case and by considering identical distributed fading conditions the CDF of γ_{out} can be expressed as [10],

$$F_{\gamma_{\text{out}}}(\gamma) = F^N_{\gamma_{\text{out}_\text{n}}}(\gamma). \quad (5)$$

Based on (5) closed-form expressions for the outage probabiliy can be readily evaluated. The OP is defined as the probability that the final node's SNR falls below a predetermined outage threshold γ_{th}. By employing (5), the OP can be obtained by replacing γ with γ_{th} in these equations as $P_{\text{out}}(\gamma_{\text{th}}) = \mathcal{F}_{\gamma_{\text{out}}}(\gamma_{\text{th}})$.

III. Numerical Results and Discussion

In this section, some preliminary numerical performance evaluation results are presented and discussed. These results include performance comparisons of several communication scenarios, employing different fading and shadowing channel conditions. The performance criterion that will be studied is the outage probability, that was studied in the previous section.

In Fig. 3, considering three communication scenario, namely a) the node is connected to a single antenna CH, b) the node is connected to a CH that supports MRT c) the node is connected to the CH with the highest SNR that supports MRT. The performance criterion is the outage probability, while the number of antennas (in case of multiple antennas scenarios) is $L = 2$ and the number of CHs (in case of CH selection) is $N = 3$. In this figure, it is clearly depicted that the best outage probability performance can be obtained when the CH selection algorithm is employed, for both weak and strong shadowing conditions. In other words, the reliability of a CH-based network significantly increases if the network nodes are able to choose among three CHs to connect to. We also observe that the performance of CH that supports MRT is quite improved as compared to single CH, which is proves the advantages of supporting multiple antennas in CHs. In Fig. 4, considering also three communication scenario, namely the node is connected to the CH that provides the highest instantaneous SNR and supports a) MRC, b) EGC, c) single antenna. Considering also outage probability as a performance indicator, varying number of antennas (in case of multiple antennas scenarios), $k = 1.5$ and $N = 3$. In this figure, it is depicted that the performance considerable improves in case that the CHs support multiple antennas. Another interesting observation is that CH with EGC provide

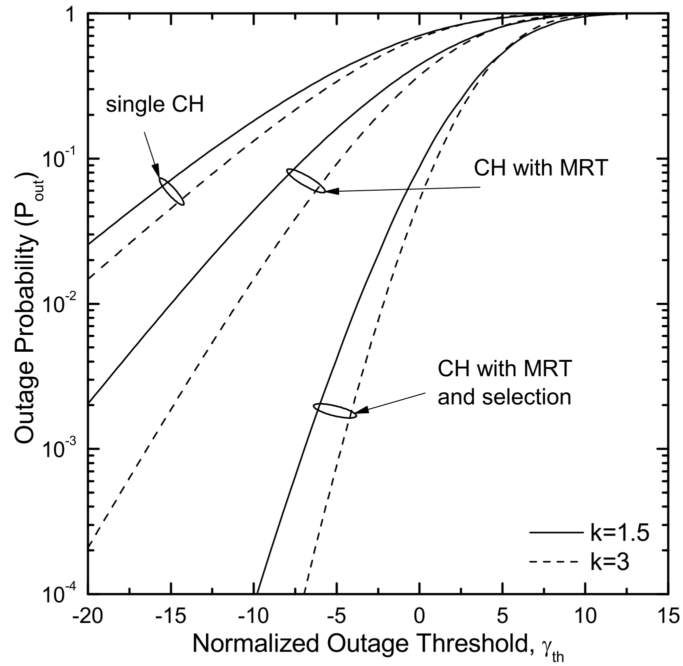

Fig. 3. The OP versus the normalized outage threshold, $\gamma_{\text{th}}/\overline{\gamma}$, for several values of k.

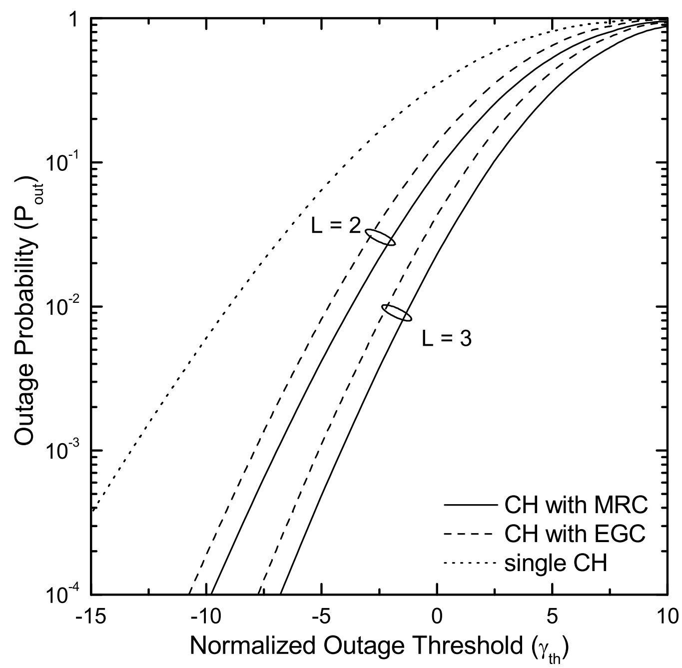

Fig. 4. The OP versus the normalized outage threshold, $\gamma_{\text{th}}/\overline{\gamma}$, for several values of L.

quite similar performance as compared to the CH with MRC. Specifically, in the latter case the performance is slightly better with the non negligible cost of higher receiver complexity

IV. Conclusions

In this paper, we proposed two CH selection algorithms, where the nodes can select a CH to be connected to, according to the corresponding signal strength, in order to maintain a predefined QoS constraint. The first scheme achieves the optimum performance in terms of outage probability at the cost of complexity, since it requires full CSI estimation. On the other hand, we propose an alternative scheme, where CSI estimations are not necessary, aiming at providing a similar performance compared to the optimum one, but with lower hardware complexity. Employing the proposed schemes, we showed that the reliability of CH-based networks significantly increases, while the power consumption decreases, especially when considering mobile scenarios, where the connection to a CH may be not possible, due to shadowing effects. The performance of this scheme was theoretically examined over composite K fading channels.

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References

[1] O. Vermesan, M. Harrison, H. Vogt, K. Kalaboukas, M. Tomasella, and et al. (Eds), "The internet of things - strategic research roadmap," *Cluster of European Research Projects on the Internet of Things*, 2009.

[2] M. Chatterjeo, S. K. Das, and D. Turgut, "WCA: A weighted clustering algorithm for mobile ad-hoc networks," *Cluster Computing*, pp. 193–204, July 2002.

[3] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," *IEEE Trans. Wireless Commun.*, vol. 1, no. 4, pp. 660–670, October 2002.

[4] O. Younis, S. Fahmy, and P. Santi, "Robust communications for sensor networks in hostile environments," *The Twelfth International Workshop on Quality of Service (IWQoS'04)*, 2004.

[5] ——, "An architecture for robust sensor network communications," *International Journal of Distributed Sensor Networks*, vol. 1, no. 3, pp. 4305–327, July 2005.

[6] K.-K. Leung, C. W. Sung, M. Khabbazian, and M. Safari, "Optimal phase control for equal-gain transmission in mimo systems with scalar quantization: Complexity and algorithms," *IEEE Trans. Inf. Theory*, vol. 56, no. 7, pp. 3343 –3355, Jul. 2010.

[7] A. Abdi and M. Kaveh, "Comparison of DPSK and MSK bit error rates for K and Rayleigh-Lognormal fading distributions," *IEEE Commun. Lett.*, vol. 4, no. 4, pp. 122–124, Apr. 2000.

[8] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 6th ed. New York: Academic Press, 2000.

[9] M. K. Simon and M.-S. Alouini, *Digital Communication over Fading Channels*, 2nd ed. New York: Wiley, 2005.

[10] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*, 2nd ed. New York: McGraw-Hill, 1984.