Energy Efficient Cooperative HAP-Terrestrial Communication Systems

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Abstract. In this paper we study the energy efficiency of hybrid high altitude platform (HAP) and terrestrial communication systems in the uplink. The applications of HAPs in the recent years have gained significant interest especially for telecommunications. A cooperative relay based communication strategy on the ground with a single source-relay pair is considered for the hybrid HAP-terrestrial system. We show that cooperation on ground between the terrestrial terminals could improve the energy efficiency in the uplink depending on the temporal behavior of the channels. Thus by having cognitive context aware capabilities in the ground terminals one could exploit the spatial domain to improve the energy efficiency. The energy efficiency can be further improved by means of proper power allocation between the terrestrial source and relay nodes. We consider the decode and forward based cooperative system for our study with a constraint on the overall bit error probability to achieve a predefined quality of service. Results show that considerable gain in the energy can be attained by exploiting the spatial domain by means of cooperation.

Keywords: Hybrid HAP terrestrial systems, high altitude platform, energy efficiency, cooperative communications.

1 Introduction

The rapid growth of bandwidth-hungry telecommunication applications has pushed wireless infrastructure providers and network operators under continuous pressure to exploit the limit of radio spectrum as efficiently as possible. Further, the costs related to rolling out and operation of broadband wireless networks in emerging and Greenfield environments have increased considerably. Notwithstanding, new requirements for flexible network access have emerged within the telecommunications community, spurred by the vision of optimal connectivity, anywhere, anytime. In this context, high-altitude platforms (HAPs) are increasingly being cited as having an important role to play in future systems and applications capable of providing efficient broadband wireless access at lower costs [12]. HAPs as new solutions for delivering wireless broadband, have recently been proposed for the provision of fixed, mobile and broadcast services in the stratosphere at an altitude of 17 km to 22 km [13],[14], [15], [16].

G. Giambene and C. Sacchi (Eds.): PSATS 2011, LNICST 71, pp. 151–164, 2011.

The HAP systems have features of both terrestrial and satellite communications and thus shares the advantages of both the communication systems. The International Telecommunication Union (ITU) suggests that footprints larger than 100 km radius can be served from HAPs [18]. This would technically allow a single HAP station to effectively replace several terrestrial base stations with a cost-effective and time-efficient deployment and ease of integration to existing networks. The ever increasing cost of infrastructure deployment and the intricacies in site acquisitions and renting have stepped up the complexity in the deployment of next generation broadband wireless networks, particularly in emerging markets. In these areas, HAP systems will be an effective solution to provide the necessary network infrastructure at lower CAPEX and OPEX costs for incumbent and new entrant network operators. Moreover, HAP systems could also be exploited in applications of environment and disaster surveillance to support long-period data transmission and mobile deployments apart from such applications like remote sensing, radio monitoring, weather monitoring etc. These additional applications, along with the savings in physical infrastructure costs could even out the operational expenditures related to terrestrial network deployments. In order to aid the eventual deployment of HAPs, the ITU has allocated spectrum in the 3G band for HAPs, as well as in the mm-wave bands for broadband services at around 48 GHz worldwide and 31/28 GHz for certain Asian countries [17].

The use of HAPs has been proposed in many communication applications [18]. 3G and 4G services are recently considered as principal application of HAPs [17], which offer the possibility of being part of the current 3G networks and services, and also as complementary access solution for 4G networks and its mobile and multimedia services. Multimedia broadcast and multicast services (MBMS) also can be provided by the HAP layer of 3G/4G in order to achieve higher system capacity and lower costs. 3G base stations, integrated on the HAP systems, with wide beamwidth antennas could provide service over large sparsely populated areas. In addition to this, in urban areas, where a higher capacity is needed, smaller cells can be deployed with integrated directional antennas (antenna arrays). All this include exceptional benefits such as offering coverage in a large area, direct propagation paths without obstacles and elimination of the expensive resources spent in ground station installations, maintenance and wire installations.

In the case of a HAP system planned to operate on a given coverage area integrated with a base network already operating as part of the terrestrial network, such hybrid HAP-terrestrial system can be partially or completely deployed as a complementary network, for instance, depending on higher traffic requirements or power/equipment related failures. The notion of HAP platform components deployed as a substitution network will provide for improved balance between the complexity and costs related to operating a large fleet of HAP platforms and the ever increasing traffic requirements in future broadband communication networks. Such consideration will also ease the heavier payload demands and thereby lower the power consumption on the platform improving the overall energy efficiency of the system. Moreover, as the HAPs platform could potentially be linked to multiple ground stations and relay nodes, coordination and cooperation between these stations is an important consideration for reducing the communication energy costs within the system.

In this paper, we consider a cooperative networking scenario based on decode and forward mechanism on the ground between the terrestrial radios for the uplink hybrid HAP-terrestrial system. The terrestrial source node with a bad uplink channel will cooperate with a neighboring terrestrial node in order to transmit its data to the HAP station. The terrestrial node acting as the relay node poses a good uplink channel with the HAP station. For a bit error rate (BER) constraint requirement, we show that depending on the channel gains cooperation can lead to energy efficient communications. We present some numerical results to show the improvement in the energy efficiency. Moreover, we provide an optimization strategy to select the source relay transmission power levels for the cooperative relay link in order to minimize the overall energy consumption due to transmission. The proposed strategy and the related study not only improves the energy efficiency of the overall communication system but also provides seamless connectivity to the terrestrial user when the direct uplink channel is very poor. Having these two potential benefits in mind we present our study in the rest of the paper.

The rest of the paper is organized as follows. In Section 2 we present the hybrid HAP-Terrestrial network model and the corresponding channel models. In Section 3 we present the decode and forward cooperative system followed by the energy efficiency study in Section 4. The optimum power allocation for energy efficiency is presented Section 5. In Section 6 we present numerical results with some concluding remarks in Section 7.

2 The Hybrid HAP-Terrestrial Network Model

In this section, we present the integrated HAP - terrestrial radio network model. We consider an integrated HAP and multiple terrestrial radio system as depicted in Figure-1. The aerial HAP platform is considered to act as a macro cell surrounded by cells served by terrestrial base stations, including the possibility of several ground relay stations. The integrated terrestrial-HAP system enables the network operator to serve high-mobility users characterized with low bit rates and at the same time, serving users with high bit rates with the terrestrial stations. The HAP network will be connected to the terrestrial networks through a series of ground gateway stations. Though, we limit the study to a single HAP system (with a single aerially deployed HAP station) in this paper, it could be conveniently extended for a multiple HAP system (multiple interconnected HAP stations) linked with multiple terrestrial radios. The scenario presented here is motivated by the work conducted in the C2POWER project for power efficient cooperation in multi-radio platforms [21]. In our network model we also assume context awareness meaning that the channel, communications and networking parameters corresponding to the participating nodes are known to each other.

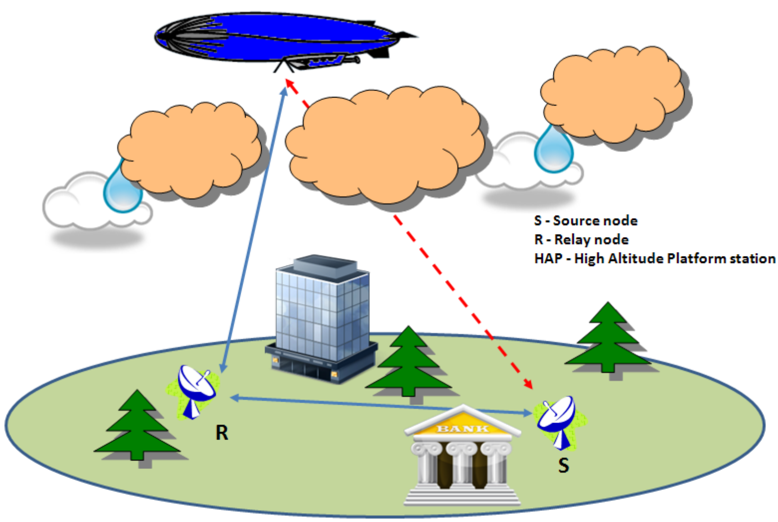

Fig. 1. The hybrid HAP-Terrestrial communication system with cooperative relay link

The cognition can be provided by means of learning or by means of signalling mechanisms, the treatment of such however are not addressed in this paper but simply assume that context aware capabilities are present (which is infact a valid assumption considering the next generation terrestrial systems [21]). The terrestrial nodes are also aware of the neighboring nodes by means of spectrum sensing and cognitive learning capabilities embedded in the radios [9], [10], [11].

2.1 The Channel Models

Theoretical channel models have been proposed in the literature for the uplink terrestrial to HAP communication channel [7]. In our work for the convenience of theoretically studying the energy efficiency we consider a Rayleigh channel model with free space pathloss for the uplink communications having different small scale channel gains with spatial separations. In other words the uplink channel gains for the S $\rightarrow$ HAP and the R $\rightarrow$ HAP can vary due to its spatial separation. The Rayleigh channel model for the uplink clearly describes that no line of sight communication exist due to the position of the mobile terrestrial nodes (in an urban environment) and the stratospheric rain fading conditions. It is also possible to extend our analytical work presented in this paper to a Ricean channel for the uplink however we consider the Rayleigh channel as an example for simplicity.

The channel model between the terrestrial radios is also considered to be a Rayleigh fading channel with a pathloss exponent of α_2, as we present subsequently. Figure-2 depicts the channel models and the related parameters for the hybrid Terrestrial-HAP system, where h_i with $i \in \{1, 2, 3\}$ are the small scale Rayleigh fading channel gains, d_i are the T-R distances, α_i are the pathloss

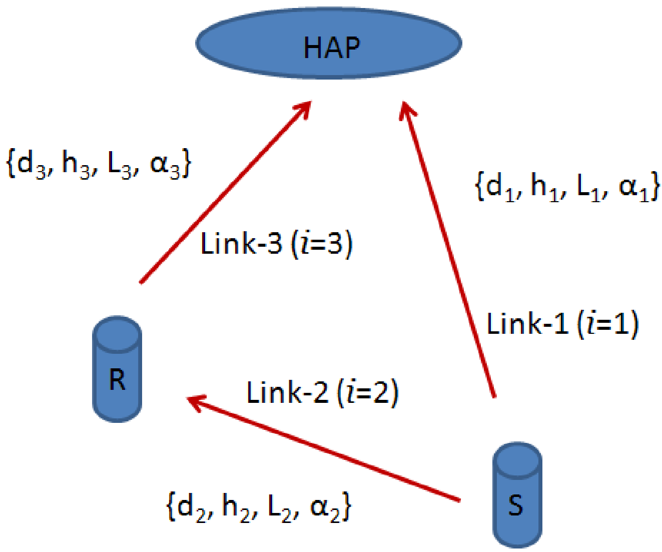

Fig. 2. The channel parameters for the hybrid HAP-Terrestrial system

exponents, and L_i are the mean pathloss for the respective links. The pathloss is given by,

$$L_i(d_i) = L_i(d_0)\left(\frac{d_i}{d_0}\right)^{\alpha_i} \tag{1}$$

where, $L_i(d_0)$ is the pathloss at a reference distance d_0 which is given by the free-space pathloss [8] $L_i(d_0) = (4\pi f_i d_0/c)^2$, where f_i is the carrier frequency and $c = 3 \times 10^8$ is the speed of light. Moreover, we also define the average power gains of the channels given by $\gamma_i = \frac{1}{t}\int_0^t h_i^2(t)dt$. With the assumption of context awareness, the above mentioned parameters such as the T-R separations d_i, the channel power gains h_i, the pathloss exponent α_i are all known to the terrestrial nodes. Note that since the uplink communication has a free space pathloss model, from the terrestrial node to the HAP, we have $\alpha_1 = \alpha_3 = 2$, where as α_2 would vary with time and the positions of the terrestrial nodes. As mentioned before, the positions and the channel parameters are all assumed to be known to the nodes S and R by means of cognitive learning features in the respective radios.

3 Decode and Forward Cooperative Relay Communications

For the cooperative network model in Figure-2 the received signals for the communications from $S \rightarrow HAP$, $S \rightarrow R$, and $R \rightarrow HAP$ (i.e. for $i = 1, 2$ and 3 respectively) can be expressed in the form of,

$$r_i(t) = \frac{1}{L_i(d_i)}h_i(t)s_i(t) + \upsilon_i(t) \tag{2}$$

where, $s_i(t)$ are the transmitted signal components and $v_i(t)$ are the additive Gaussian noise components at the receivers with a double-sided power spectral density of $N_0(i)/2$. Moreover, we consider a BPSK communication system for all the links in our example corresponding to the signal components $s_i(t)$ in equation (2). The bit error probability under Rayleigh fading with additive Gaussian noise channels for all the links is given by [8],

$$\Pi_i = 0.5\left(1 - \sqrt{\frac{\Gamma_i}{(1+\Gamma_i)}}\right) \tag{3}$$

where $\Gamma_i = E_b(i)\gamma_i/N_0(i)$ is the average received SNR for the i^{th} link, $E_b(i)$ is the received bit energy given by $E_b(i) = P_t(i)G_i^t G_i^r/[\Delta_i L_i(d_i)]$, $P_t(i)$ is the transmitted signal power, G_i^t and G_i^r are the transmit and receive antenna gains, and Δ_i(bits/s) is the data rate for link i. Note that according to our notations we have $G_1^t = G_2^t, G_2^r = G_3^t, G_1^r = G_3^r$.

Based on the decode and forward strategy for the cooperative relay link the relay node will receive the signal $r_2(t)$ from the source node, detect it, and transmit it to the HAP. The HAP will then receive the signal $r_3(t)$ from the terrestrial relay node and decode it. On the other hand in the direct link transmission the HAP will directly receive the signal $r_1(t)$ from the terrestrial source node. In the subsequent sections we study the energy efficient way for the source node to communicate with the HAP, by choosing between the relay and the direct links, depending on the communication channel conditions to achieve the same bit error probability ξ.

3.1 Overall Bit Error Probability

In this section we present the overall bit error probability for the relay link based on the decode and forward cooperative strategy. If Π_2 and Π_3 are the bit error probabilities respectively of the concatenated two-hop relay link with decode and forward protocol, then the overall bit error probability of the relay link is given by $\overline{\Pi} = \Pi_2(1-\Pi_3) + \Pi_3(1-\Pi_2)$. By expanding this expression we have,

$$\overline{\Pi} = \Pi_2 + \Pi_3 - 2\Pi_2\Pi_3 \tag{4}$$

and since the probability values are less than one (small), the last term of the above expression can be ignored, giving us a final expression of,

$$\overline{\Pi} = \Pi_2 + \Pi_3 \tag{5}$$

Then using (3) in (5), we have

$$\overline{\Pi} = 1 - 0.5\left[\left(\sqrt{\frac{\Gamma_2}{(1+\Gamma_2)}}\right) + \left(\sqrt{\frac{\Gamma_3}{(1+\Gamma_3)}}\right)\right] \tag{6}$$

In the following sections we will analyze the energy efficiency associated with the cooperative relay link for a given BER constraint of $\overline{\Pi} = \Pi_1 = \xi$.

4 Energy Efficient Communications with BER Constraint

In this section we study the relative energy efficiency of the relay link and the direct link. For the direct communication link from $S \rightarrow HAP$, with a given BER constraint of ξ, and considering the BER expression in (3), the transmit power requirement $P_t(1)$ at the source node S can be computed as,

$$P_t(1) = \frac{\Delta_1 L_1(d_1) N_0(1)(1-2\xi)^2}{G_1^t G_1^r \gamma_1 [1-(1-2\xi)^2]} \tag{7}$$

Likewise, for the relay link from $S \rightarrow R \rightarrow HAP$ the transmit power pair $\{P_t(2), P_t(3)\}$ requirement at the source node and the relay node respectively for the same BER constraint ξ, using the BER expression (6), can be computed as,

$$P_t(3) = \frac{\lambda^2}{G_3^t G_3^r \gamma_3 (1-\lambda^2)} L_3(d_3) N_0(3) \Delta_3 \tag{8}$$

where λ is a function of $P_t(2)$, and is given by,

$$\lambda = \sqrt{\frac{K_1 P_t(2)}{1 + K_1 P_t(2)}} - 2\xi \tag{9}$$

with $K_1 = \frac{G_2^t G_2^r \gamma_2}{L_2(d_2) N_0(2) \Delta_2}$. From equations (7), (8) and (9) we have the transmit power requirements at the source and relay nodes for the direct and relay transmissions for a given bit error rate constraint. Now, let us define an energy efficiency factor β to compare the energy efficiency between the direct and the relay links, given by,

$$\beta \triangleq \frac{[P_t(2) + P_t(3)]}{P_t(1)} \tag{10}$$

Then, based on the definition of β, one may conclude that direct link is more efficient than the relay link if $\beta > 1$ (or β(dB)> 0), or the relay link is more efficient than the direct link if $\beta < 1$ (or β(dB)< 0), or both relay and direct links are equally energy efficient if $\beta = 1$ (or β(dB)$= 0$) but considering the overhead due to cooperation the direct link is preferred when $\beta = 1$. Note that in our work we ignore the energy consumptions due to processing at the nodes. As we observe from the above expressions it is very clear that the value of β depends on several parameters such as the pathloss exponent α_2, terrestrial T-R separation d_2, and the small scale channel gains γ_i, etc. With the context aware capabilities at the terrestrial nodes by means of cognitive functionalities the source node could adopt its transmissions between the direct and relay links for improved energy efficiency. In Section 6 we present numerical results for the analysis presented in this section.

5 Optimum Source-Relay Power Allocation for Maximum Energy Efficiency

Suppose the cooperative relay link exhibits better efficiency compared to the direct uplink, in other words when $\beta < 1$ (or $\beta(dB) < 0$), then the source and the relay node transmit power levels need to be carefully chosen in order to minimize the total energy utilization for the transmission. It is observed that the efficiency factor β exhibits a convex property which could be then minimized to have better energy efficiency. From the numerical results presented in the next section we observe the convex property of β clearly. Suppose $X = P_t(2) + P_t(3)$, then the optimal source-relay transmit power levels are given by,

$$\{\hat{P}_t(2), \hat{P}_t(3)\} = \arg\min_X \{\beta\} \tag{11}$$

or equivalently, given by,

$$\{\hat{P}_t(2), \hat{P}_t(3)\} = \arg\min_X \{P_t(2) + P_t(3)\} \tag{12}$$

The optimum transmit power values for the source and relay nodes are then given by taking the first derivative of X with respect to $P_t(2)$ and equating it to zero. The first derivative therefore is given by,

$$\frac{dX}{dP_t(2)} = 1 + \frac{dP_t(3)}{dP_t(2)} \tag{13}$$

Then, by using equations (8) and (9), we arrive at the following expression for $\frac{dX}{dP_t(2)}$, given by,

$$\frac{dX}{dP_t(2)} = 1 + \frac{K_0 K_1^{\frac{1}{2}} \lambda}{P_t^{\frac{1}{2}}(2)(1 + K_1 P_t^{\frac{3}{2}}(2))(1 - \lambda^2)^2} \tag{14}$$

where, $K_0 = \frac{L_3(d_3) N_0(3) \Delta_3}{G_3^t G_3^r \gamma_3}$. The optimum transmit power at the source node is then given by solving the following equation,

$$\left(\frac{dX}{dP_t(2)}\right)_{P_t(2)=\hat{P}_t(2)} = 1 + \frac{K_0 K_1^{\frac{1}{2}} \lambda}{\hat{P}_t^{\frac{1}{2}}(2)(1 + K_1 \hat{P}_t^{\frac{3}{2}}(2))(1 - \lambda^2)^2} = 0 \tag{15}$$

Solving the above equation for $P_t(2)$ is not trivial and hence we use the Gradient Descent method to find $\hat{P}_t(2)$. The gradient descent algorithm for some $\epsilon > 0$ to compute the optimum source power is then given by,

$$\hat{P}_{t_{n+1}}(2) = \hat{P}_{t_n}(2) - \epsilon \left(1 + \frac{K_0 K_1^{\frac{1}{2}} \lambda_n}{\hat{P}_{t_n}^{\frac{1}{2}}(2)(1 + K_1 \hat{P}_{t_n}^{\frac{3}{2}}(2))(1 - \lambda_n^2)^2}\right) \tag{16}$$

where, $\lambda_n = \sqrt{\frac{K_1 P_{t_n}(2)}{1 + K_1 P_{t_n}(2)}} - 2\xi$. The above iteration converges to $\hat{P}_{t_{n+1}}(2) \rightarrow \hat{P}_t(2)$ for sufficiently large n depending on the value of ϵ. The corresponding optimum relay transmit power can then be computed by using equations (8) and (9), which is given by,

$$\hat{P}_t(3) = \frac{\hat{\lambda}^2}{G_3^t G_3^r \gamma_3 (1 - \hat{\lambda}^2)} L_3(d_3) N_0(3) \Delta_3 \tag{17}$$

where $\hat{\lambda}$ is given by,

$$\hat{\lambda} = \sqrt{\frac{K_1 \hat{P}_t(2)}{1 + K_1 \hat{P}_t(2)}} - 2\xi \tag{18}$$

Therefor, by using equations (16) and (17), one could compute the optimum source-relay transmit power levels for minimum energy consumption in the co-operative relay link.

6 Numerical Results

In this section we present numerical results to analyze the relative energy efficiency of cooperative relay link with the direct link. First, we consider the analytical results obtained in Section 4. The following simulation parameters are considered for our analysis;

Link-1: From S to HAP (Direct Uplink)
$\Delta_1 = 100e3(\text{bps}), \gamma_1 = 5e-1, d_1 = 20.0025e3(\text{m}), f_1 = 3.5e9(\text{Hz}), \alpha_1 = 2,$
$G_1^t = 30(\text{dB}), G_1^r = 25(\text{dB}).$

Link-2: From S to R (Relay Terrestrial Link)
$\Delta_2 = 100e3(\text{bps}), \gamma_2 = 20, d_2 = 2.5e3(\text{m}), f_2 = 3.5e9(\text{Hz}), \alpha_2 = 2.3,$
$G_2^t = 30(\text{dB}), G_2^r = 30(\text{dB}).$

Link-3: From R to HAP (Relay Uplink)
$\Delta_3 = 100e3(\text{bps}), \gamma_3 = 1, d_3 = 20.0035e3(\text{m}), f_3 = 3.5e9(\text{Hz}), \alpha_3 = 2,$
$G_3^t = 30(\text{dB}), G_3^r = 25(\text{dB}).$

Common parameters
$\xi = 1e^{-3}, N_0(i) = -140(\text{dBw/Hz}).$

Note that some of the parameters above are varied in the results presented subsequently, in this case the varied parameters are explicitly mentioned appropriately.

Figure-3 depicts the power requirements for the direct and relay links for the above given parameters. In the figure we have plotted the required direct uplink power for a BER of $1e^{-3}$ together with the terrestrial relay-node power in dBw, the total relay link transmit power (sum of link-2 and link-3) in dBw, and the energy efficiency factor β(dB). From the figure we observe that when the total relay-link power exceeds the direct uplink transmit power then the direct transmission becomes energy efficient and when the total relay-link power is lower than the direct uplink transmit power then the relay-link transmission becomes energy efficient. This is also observed by looking at the β curve in Figure-3, that is the relay link becomes efficient when β(dB)< 0 and the direct uplink becomes efficient when β(dB)> 0. Furthermore, we observe that the total transmission power for the relay link (or equivalently the energy efficiency factor

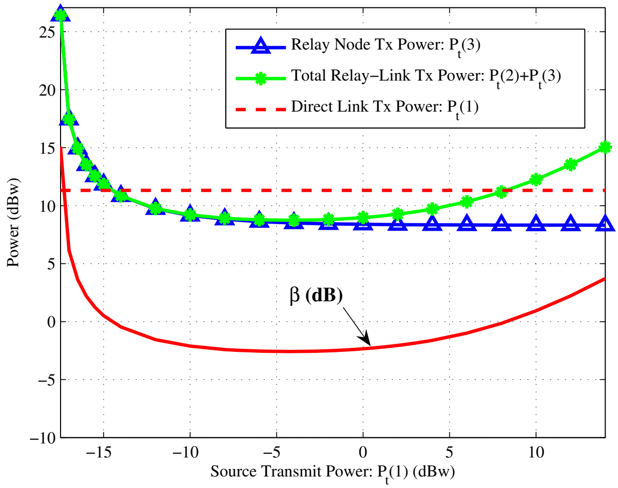

Fig. 3. Comparing the direct and relay links for energy efficiency, for a BER constraint of $\xi = 1e^{-3}$

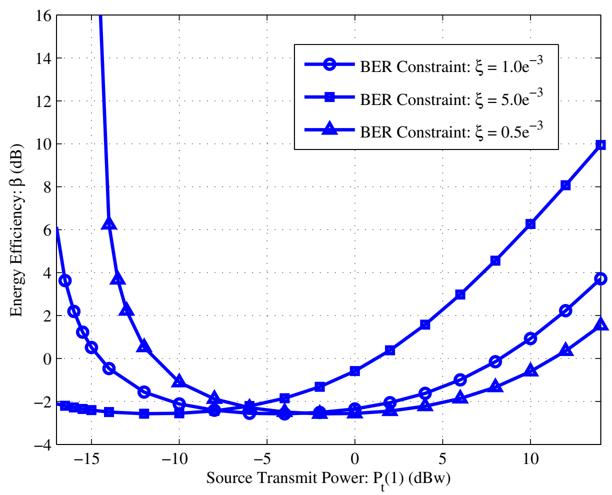

Fig. 4. The energy efficiency factor comparing the direct and relay links, for varying BER constraints

β) exhibits a convex property in the domain of the source transmit power $P_t(1)$. This is a desirable feature to optimize the power consumption by choosing the appropriate source-relay transmit power levels if the relay link is chosen to be the energy efficient link, as discussed in Section 5.

Figure-4, Figure-5 and Figure-6 show the variations on the energy efficiency factor β for varying BER constraint ξ, the direct uplink fading gain γ_1, and the terrestrial channel gain γ_2. As observed in Figure-4, when the BER constraint

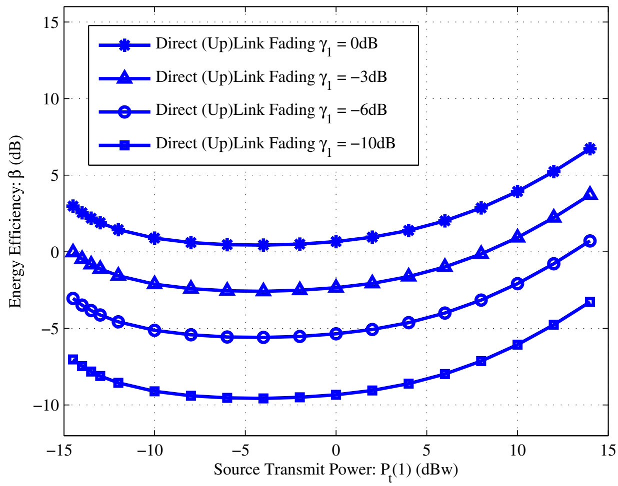

Fig. 5. The energy efficiency factor comparing the direct and relay links, for varying direct up-link channel gain γ_1

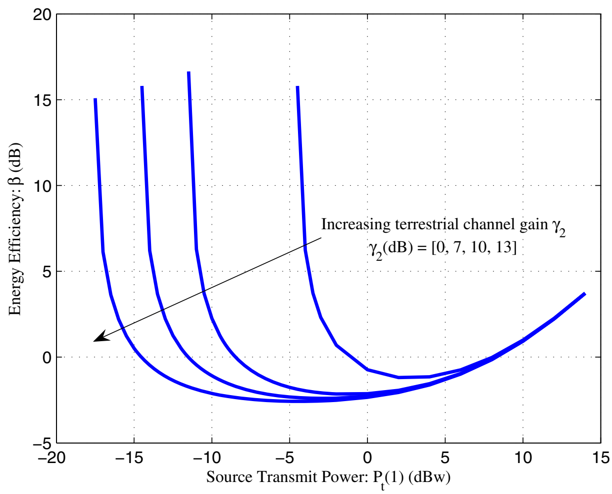

Fig. 6. The energy efficiency factor comparing the direct and relay links, for varying terrestrial link channel gain γ_2

ξ reduces, the source transmit power requirement also reduces for the values of β(dB)< 0. In Figure-5, we observe that the range of source transmit power levels such that β(dB)< 0 increases when the direct uplink gain reduces (i.e. when fading gets severe), this is because when γ_2 reduces the cooperative relay link becomes more and more energy efficient compared to the direct uplink. In Figure-6, we observe that the source transmit power requirement reduces for the case of β(dB)< 0 when the terrestrial channel gain γ_2 increases, as expected.

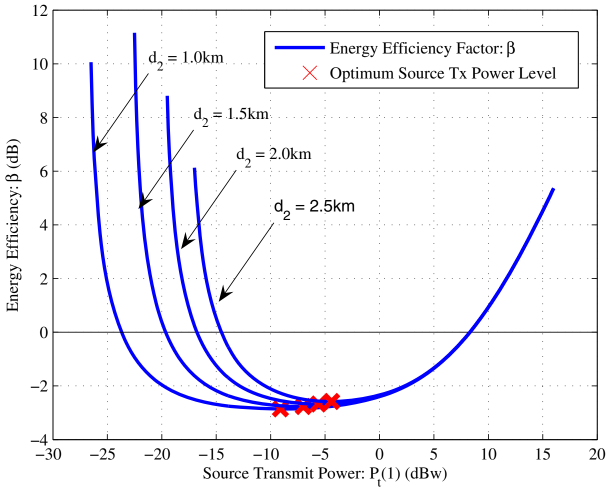

Fig. 7. Optimum source power for the cooperative relay link, for varying terrestrial T-R distance d_2

Finally, we present the results for the optimum power allocation between the source and the relay nodes when β(dB)< 0. Figure-7 depicts the variations in β for varying T-R separation d_2 between the terrestrial nodes. In the figure we also depict the optimum source power selection for minimizing the total energy consumption in the cooperative relay link as described in Section-5. As observed in the figure, the optimum source power level increases with increasing d_2 as expected for the same channel condition γ_2.

7 Conclusion

In this paper, we consider energy efficiency of a cooperative HAP and terrestrial communication system. For Rayleigh fading channels, we analyze the energy efficiency for the cooperative relay link and the direct uplink. Our analysis shows that for poor direct uplink channels the cooperative relay link provides better energy efficiency. Numerical results were presented to show the comparative energy efficiency between the cooperative relay link and the direct uplink for various network and channel parameters. We had also presented an optimization framework to select the optimum source and relay transmit power levels for the cooperative relay link based on a Gradient Descent iterative method for the Rayleigh fading channels. Our future work in this area include similar analysis with Ricean and other fading channels for the uplink and also consider cooperation between multiple HAP stations communicating and coordinating through inter-platform links.

Acknowledgment. The authors would like to thank Dr. Francesco Rossetto and Dr. Sandro Scalise from the German Aerospace Centre (DLR), Germany for their valuable comments on the manuscript.

References

1. Djuknic, G.M., Freidenfelds, J., Okunev, Y.: Estabilishing wireless communications services via high altitude platforms: A concept whose time has come? IEEE Communications Magazine, 128–135 (September 1997)
2. AragonZavala, A., Cuevas-Ruz, J.L., Delgado-Penin, J.A.: High-Altitude Platforms for Wireless Communications. John Wiley and Sons, Chichester (2008)
3. Karapantazis, S., Pavlidou, F.: Broadband Communications Via High-Altitude Platforms: A Survey. IEEE Communications Surveys, First Quarter 7(1) (2005)
4. Grace, D., et al.: LMDS from High Altitude Aeronautical Platforms. In: Proceedings of Global Telecommun. Conf. 1999 (GLOBECOM 1999), Rio de Janeiro, Brazil, December 5-9, vol. 5, pp. 2625–2629 (1999)
5. Grace, D., Tozer, T.C., Daly, N.E.: Communications from High Altitude Platforms - A Complementary or Disruptive Technology? IEE Colloquium New Access Network Technologies (October 31, 2000)
6. Grace, D., et al.: Providing Multimedia Communications Services from High Altitude Platforms. Int'l. J. Satellite Commun., 19(6), 559–580 (2001)
7. Dovis, F., Fantini, R., Mondin, M., Savi, P.: Small-Scale Fading for High-Altitude Platform (HAP) Propagation Channels. IEEE journals on Selected Areas in Communications 20(3), 641–647 (2002)
8. Rappaport, T.S.: Wireless Communications: Principles and Practice. Prentice-Hall, Englewood Cliffs (1996)
9. Mitola, J., Maguire, G.Q.: Cognitive Radio: Making Software Radios More Personal. IEEE Personal Communications 6(4), 13–18 (1999)
10. Haykin, S.: Cognitive Radio: Brain-Empowered Wireless Communication. IEEE Journal on Selected Areas in Communications 23(2), 201–220 (2005)
11. Kandeepan, S., De Nardis, L., Di Benedetto, M.G., Guidotti, A., Corazza, G.E.: Cognitive Satellite Terrestrial Radios. In: IEEE Globecom 2010, Florida (2010)
12. Karapantazis, S., Pavlidou, F.-N.: Broadband Communications via High Altitude Platforms (HAPs) - A Survey. IEEE Commun. Surveys and Tutorials, 1st Qtr (2005), `http://www.comsoc.org/livepubs/surveys`
13. Tozer, T.C., Grace, D.: High-altitude platforms for wireless communications. IEE Electronics and Communications Engineering Journal 13, 127–137 (2001)
14. Grace, D., Thornton, J., Konefal, T., Spillard, C., Tozer, T.C.: Broadband communications from high altitude platforms - The HeliNet solution. In: Wireless Personal Mobile Conference, Aalborg, Denmark (2001)
15. Mohammed, A., Arnon, S., Grace, D., Mondin, M., Miura, R.: Advanced communications techniques and applications for high-altitude platforms. Editorial for a special issue in EURASIP Journal on Wireless Communications and Networking (2008)
16. Mohammed, A., Yang, Z.: Broadband communications and applications from High Altitude Platforms. International Journal of Recent Trends in Engineering 1(3) (May 2009)

17. Fourth Generation Wireless Communications from High Altitude Platforms, Vodafone Market Report (May 2010)
18. Gerla, M., et al.: Communications via High Altitude Platforms: Technologies and Trials. International Journal of Wireless Information Networks 13(1) (January 2006)
19. Lähdekorpi, P., Isotalo, T., Kylä-Liuhala, K., Lempiäinen, J.: Replacing Terrestrial UMTS Coverage by HAP in Disaster Scenarios. In: European Wireless Conference (April 2010)
20. Araniti, G., Iera, A., Molinaro, A.: The Role of HAPs in Supporting Multimedia Broadcast and Multicast Services in Terrestrial-Satellite Integrated Systems. Wireless Pers. Commun., 32(3-4), 195–213 (2005)
21. URL of C2POWER Project, `http://www.ict-c2power.eu`
22. Holis, J., Pechac, P.: Penetration Loss Measurement and Modeling for HAP Mobile Systems in Urban Environment. EURASIP Journal on Wireless Communications and Networking 2008 (2008)