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Energy Efficiency Maximization of the Fifth Generation (5G) Mobile Networks in High Speed Trains

Abstract. *This paper presents an optimized algorithm to enhance energy efficiency in 5th generation mobile networks, specifically in high-speed train environments. It targets users accessing in-train access points and 5G macro cells, optimizing bit rate, power usage, and interference mitigation. Through dual decomposition techniques, it significantly improves energy efficiency, particularly with dynamic power allocation. This research offers crucial insights for efficient mobile network deployments in dynamic settings like high-speed trains.*

Streszczenie. *W artykule przedstawiono zoptymalizowany algorytm zwiększający efektywność energetyczną sieci mobilnych piątej generacji, szczególnie w środowiskach pociągów dużych prędkości. Jest skierowany do użytkowników uzyskujących dostęp do punktów dostępu w pociągu i makrokomórek 5G, optymalizując przepływność, zużycie energii i łagodząc zakłócenia. Dzięki technikom podwójnego rozkładu znacznie poprawia efektywność energetyczną, szczególnie przy dynamicznej alokacji mocy. Badanie to dostarcza kluczowych informacji na temat wydajnych wdrożeń sieci mobilnych w dynamicznych warunkach, takich jak pociągi dużych prędkości.* ***(Maksymalizacja efektywności energetycznej sieci mobilnych piątej generacji (5G) w pociągach dużych prędkości)***

Keywords: energy efficiency, in-train access points, 5G-MC-gNBs, high-speed train.
Słowa kluczowe: efektywność energetyczna, punkty dostępu w pociągu, gNodeB makrokomórek 5G, pociąg dużych prędkości.

Introduction

Each mobile technology from first generation (1G) to fourth generation (LTE) has been driven by the need to fill new requirements. For example, the enabling of internet in mobile devices was expected to happen in the transition from the second generation (2G) to the third generation (3G), even the 3G added data connectivity, the expected transition didn't occur till to 3.5G when a huge jump happened as an expression of consumer experience, as a result of combination of smart mobile devices and broadband mobile networks. Mobile broadband network has brought a large number of benefits starting from email, social media, music, video streaming and applications for controlling our homes, in this manner changing our lives providing services by broadband mobile service operators and by third party players.

Furthermore, the transition from 3.5G to 4G has brought to users access to the bigger data rates and lower data latency, and the way that mobile users use and access the internet service on mobile devices is changing rapidly. Mobile service operators all around the world report that 4G users are consuming two times to three times more data than non-4G customers. As the main factor that has indicated in increasing the level of consumed data in 4G networks is video streaming.

The Internet of Things (IoT) also has been mentioned as a key distinctive from 4G service. With the development of internet of things and of mobile internet rapidly, the needs for data applications with high-speed, like social networking, wireless video streaming with high-quality and machine-to-machine communication, have been increased exponentially lately. It is supposed that the total daily of mobile traffic in the Western European states will be 67 times higher by 2010 to 2020 from 186 TB (terabyte) to 12540 TB, and the total worldwide of mobile traffic will grow 1.74 times from 202 EB (exabyte) to 351 EB through 2020 to 2025 [1] and [2]. At present, including all existing mobile service generation (first, second, third and fourth generation) are so far away from providing the substantial traffic increases and the energy efficiency (EE) because the most power of 5G macro cell's gNodeBs (5G-MC-gNBs) is used to exceed path loss, which in other side cause interference to other users.

The fifth generation has been planned to provide from 1Gbps to 10 Gbps data rates, and nine times saving up of energy expense compared with LTE mobile networks. In 5G system is planned to provide 1000% more of battery life time's mobile devices, more than a thousand $Gbit/s/km^2$ spectral capacity in dense urban areas, and five times less end-to-end latency [3] and [4].

In order to reach all these objectives of 5G systems, it has been needed that new radio access technologies and architecture of internet networks based on all-IP (all-internet protocol) to evolve softly from 4G. Also, to achieve these objectives, more bandwidth has been required and more integrated access nodes (ultra-dense deployment of small cells) had been installed compared with previous deployed access nodes [5] and [6].

The increasing number of access nodes has led to a substantial surge in total energy consumption, with a significant proportion of this energy expenditure attributed to the radiation from antennas. As consequent, optimizing antenna radiation is essential to curbing energy consumption and enhancing the efficiency of the 5G mobile network [7].

For this reason, in this paper we have shown the algorithm and given the solutions to optimize the energy efficiency maximization in terms of transmission rate and assigned power for high speed train's users served by 5G mobile networks considering a practical scenario (case study). In this case study, the users are located inside the high speed train and are served by in-train access points (ITAPs) and 5G-MC-gNBs.

The paper is organized as follows. The geometry of the network cell model which presents the criteria for user classification based on the threshold value of in-train path loss model, and path loss models with their settings that expose the properties of wireless channel are introduced in Section II. Further, we draw up the problem of energy efficiency maximization and solve utilizing Water-Filling-Like approach for power assignment in Section III. In Section IV we carry out the network simulation to show the algorithm for optimal power assignment with the aim to maximize the energy efficiency. Section V presents the conclusions of paper.

Network Cell Model

In the following, we consider a network cell model with seven 5G-MC-gNBs, where each of them has three section antennas, i.e. there are twenty one (21) cells, and each section has its own section antenna. High-speed trains move through them, which are equipped with in-train access points (ITAPs). The users classified as in-train users are served by ITAPs (which are inside the high-speed train), and these users are denoted with X^{ITAP}. The users classified as in-out-train users are served by 5G-MC-gNBs (which also are inside the high-speed train), and these users are denoted as X^{gNB}. I.e. both in-train and in-out-train users are into high-speed train. The model is presented in Figure 1.

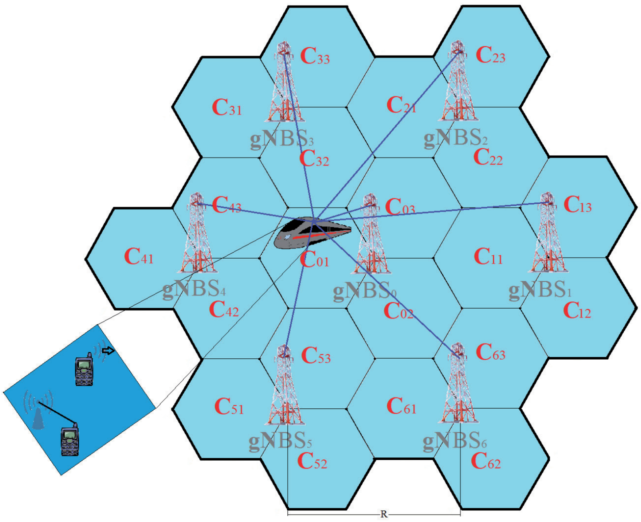

Fig. 1. System cell model

The system cell model shown in Figure 1, in order to categorize a user, use the in-train path loss model's (IT-PLM) threshold. If the value of user's IT-PLM is lower than the specified threshold then that user is categorized like an in-train user, contrarily a user is categorized like an in-out-train user. In the network cell model, X^{ITAP} users, known as in-train users, are served by in-train access points, and X^{gNB} users, known as in-out-train users, are served by 5G-MC-gNBs.

The cluster contains seven 5G-MC-gNBs, where each 5G-MC-gNB comprises three section antennas. On the center of cluster is the three sections 5G-MC-gNB $gNBS_0$, where its sections are expressed by C_{01}, C_{02} and C_{03}. Index 0 stands for $gNBS_0$ and indexes 1, 2 and 3 stand for first, second and third sections, respectively. In-out-train users which resides to section C_{01} of 5G-MC-gNB $gNBS_0$ receive power from C_{01} section antenna, and interference from two other section's antennas (C_{02} and C_{03}) of their 5G-MC-gNB ($gNBS_0$) and from all section's antennas (C_{j1}, C_{j2} and C_{j3}) of other 5G-MC-gNBs, $gNBS_k$, where $j = 1, 2, 3, 4, 5, 6$. Assuming that transmission power of ITAP is lower, in-out-train users don't receive interference from them. Energy efficiency of an in-out-train user x located in section C_{01} is defined in the following equation [8]

$$\phi_x^{gNB} = \frac{R_x^{gNB}}{\rho_0^{gNB}} \tag{1}$$

In equation (1), ϕ_x^{gNB} is the energy efficiency, R_x^{gNB} is the transmission speed (bit rate), and ρ_0^{gNB} is the power allocated to an in-out-train user x.

The transmission rate achieved by an in-out-train user x located in section C_{01} is defined in the following equation

$$R_x^{gNB} = \beta_x^{gNB} \log_2 \left(1 + \frac{G_{0x}^{gNB} \rho_0^{gNB}}{N_0 \beta_x^{gNB} + \sum_{j=1}^{6} G_{jx}^{gNB} \rho_j^{gNB}} \right) \tag{2}$$

In equation (2), β_x^{gNB} is the bandwidth assigned to the in-out-train user x, N_0 is the power density of noise, and ρ_j^{gNB} is the power of interference. The direct channel's path loss model is symbolized by G_{0x}^{gNB}, while the interference channels' PLM are symbolized by G_{jx}^{gNB}. The PLM for these two kind of channels (direct and interference channels) are defined in Equation (5). In-train users which resides to section C_{01} of 5G-MC-gNB $gNBS_0$ receive power from ITAP located in section C_{01} of 5G-MC-gNB $gNBS_0$, and interference from all sections' antennas (C_{j1}, C_{j2} and C_{j3}) of 5G-MC-gNBs, $gNBS_k$, where $j = 0, 1, 2, 3, 4, 5, 6$. Assuming that transmission power of ITAP is lower, we admit that in-train users don't receive interference from other in-train access points. Energy efficiency maximization of an in-train user x located in section C_{01} is defined in the following equation

$$\phi_x^{ITAP} = \frac{R_x^{ITAP}}{\rho_0^{ITAP}} \tag{3}$$

In equation (3), ϕ_x^{ITAP} is the energy efficiency, R_x^{ITAP} is the transmission bit rate, and ρ_0^{ITAP} is the transmitted power allocated to an in-train user x.

The transmission bit rate attained by an in-train user x located in section C_{01} is defined in the following equation

$$R_x^{ITAP} = \beta_x^{ITAP} \log_2 \left(1 + \frac{G_{0x}^{ITAP} \rho_0^{ITAP}}{N_0 \beta_x^{ITAP} + \sum_{j=0}^{6} G_{jx}^{ITAP} \rho_j^{ITAP}} \right) \tag{4}$$

In equation (4), β_x^{ITAP} is the bandwidth assigned to the in-train user x, N_0 is the noise spectral density, and ρ_j^{ITAP} is the interference power from 5G-MC-gNBs. The PLM of the direct channel is denoted by G_{0x}^{ITAP}, while the PLM for the interference channels is denoted by G_{jx}^{ITAP}. The PLM for direct channel is determined by Equation (6), while the interference channels' PLM is specified in Equation (5).

Path-loss Models

The path loss model for in-train users' interference channels, and in-out-train users' direct and interference channels is shown in Equation 5, which takes into account the Doppler effect caused by high speed train movement [9]:

$$G_{jx}^{i} = -[5 \log_{10} f_d + 39.2 \log_{10} d + 20 \log_{10} f + 41.45 - A^i] \tag{5}$$

The index (^{i}) stands for in-out-train users (^{gNB}) or in-train users (^{ITAP}), G_{jx}^{i} is in dB, f is the center frequency in MHz, d is the distance between in-train/in-out-train user and 5G-MC-gNB in km, and A^i is the sum of in-train/in-out-train user antenna gain and 5G-MC-gNB antenna gain in dBi. The frequency variation f_d caused by Doppler effect is denoted by $f_d = v \frac{f}{c} \cos\theta$, where v is the movement speed of train, c is the light speed in vacuum, and θ is the angle between 5G-MC-gNB and user.

The PLM for a direct channel of in-train users is expressed by following equation [10]

$$G_{0x}^{ITAP} = -[20 \log_{10} f + \Omega_f(\omega) + N \log_{10} d - 28] \tag{6}$$

where G_{0x}^{ITAP} is in dB, f is the center frequency in MHz, N is the distance power loss coefficient expressed as natural number, d is the distance between in-train user and in-train access point in x, $\Omega_f(\omega)$ is the train cabin loss factor in dB, ω is the number of cabins between in-train user and in-train access point expressed as natural number.

Algorithm for Energy Efficiency Maximization

In the following, we show the algorithm for classifying the users as in-train users or as in-out-train users using the in-train path loss model's threshold criteria. The algorithm to classify the users is shown by Algorithm 1.

Algorithm (1) for Classification of Users (Xs)

Estimate: $IT - PLM_{threshold}$

if $IT - PLM < IT - PLM_{threshold}$ **then**

ITAP-X $\rightarrow$ **ITAP**

otherwise

gNB-X $\rightarrow$ **5G-MC-gNB**

Compute:

$\rho_0^{ITAP}, \rho_j^{ITAP}, \rho_0^{gNB}, \rho_j^{gNB}$

using Equation (7) for optimal power assignment.

If the Algorithm 1 classifies a user as an in-train user then it will be associated to an in-train access point, otherwise if the Algorithm 1 classifies a user as an in-out-train user then the user will be connected to a 5G-MC-gNB. In final, the power is assigned to the user in the way that minimize the energy consumption.

The bandwidth and power assignment problem, with the aim to maximize the energy efficiency is written by the following equation by utilizing a matrix approach [11]:

$$\text{(7a)} \quad \underset{\boldsymbol{\phi},\boldsymbol{\beta}}{\text{maximize}} \quad \mathbf{1}^T\boldsymbol{\phi}^{gNB} + \mathbf{1}^T\boldsymbol{\phi}^{ITAP}$$

$$\text{(7b)} \quad \text{subject to} \quad \alpha_{ITAP}\boldsymbol{\rho}_0^{gNB} + \alpha_{gNB}\boldsymbol{\rho}_0^{ITAP} \leq \rho^{MAX}$$

$$\text{(7c)} \quad \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} \boldsymbol{\rho} \\ \boldsymbol{\beta} \end{bmatrix} = \begin{bmatrix} \rho^{MAX} \\ \beta^{MAX} \end{bmatrix}$$

$$\text{(7d)} \quad \boldsymbol{\rho} \geq \mathbf{0}$$

$$\text{(7e)} \quad \boldsymbol{\beta} \geq \mathbf{0}$$

where $\mathbf{R}^{gNB}$ and $\mathbf{R}^{ITAP}$ are the vector elements of in-train and in-out-train user rates, $\boldsymbol{\phi}^{gNB}$ is energy efficiency (EE) for in-out-train users defined as $\boldsymbol{\phi}^{gNB} = \frac{\mathbf{R}^{gNB}}{\boldsymbol{\rho}_0^{gNB}}$, $\boldsymbol{\phi}^{ITAP}$ is EE for in-train users defined as $\boldsymbol{\phi}^{ITAP} = \frac{\mathbf{R}^{ITAP}}{\boldsymbol{\rho}_0^{ITAP}}$, while $\boldsymbol{\rho}_0^{gNB}$ and $\boldsymbol{\rho}_0^{ITAP}$ are the vector elements of the in-train and the in-out-train user assigned powers, respectively. The coefficients α_{ITAP} and α_{gNB}, in constrain (7b), are utilized to represent the portion of power radiated from in-train access point and 5G-MC-gNB, respectively. Transmission rate and transmitted power are characterized as:

$$\text{(8)} \quad \begin{aligned} \mathbf{R}^{gNB} &= [R_1^{gNB}, R_2^{gNB}, ..., R_{X^{gNB}}^{gNB}], \\ \mathbf{R}^{ITAP} &= [R_1^{ITAP}, R_2^{ITAP}, ..., R_{X^{ITAP}}^{ITAP}], \\ \boldsymbol{\rho}_0^{gNB} &= [\rho_{0_1}^{gNB}, \rho_{0_2}^{gNB}, ..., \rho_{0_{X^{gNB}}}^{gNB}] \\ \boldsymbol{\rho}_0^{ITAP} &= [\rho_{0_1}^{ITAP}, \rho_{0_2}^{ITAP}, ..., \rho_{0_{X^{ITAP}}}^{ITAP}] \end{aligned}$$

The notation ρ^{MAX} shows the maximum power while the notation β^{MAX} shows the maximum allocated bandwidth of the assigned cell. Bandwidth's and power's vectors are defined like in the following

$$\text{(9)} \quad \boldsymbol{\rho} = \begin{bmatrix} \rho^{gNB} \\ \rho^{ITAP} \end{bmatrix} \qquad \boldsymbol{\beta} = \begin{bmatrix} \beta^{gNB} \\ \beta^{ITAP} \end{bmatrix}$$

The constraints (7b), (7c), (7d) and (7e), in the Equation (7), are linear and so they are convex. Since the energy efficiency maximization is determined by the problem specified in Equation (7), in standard power control as a particular case, the energy efficiency maximization problem is not convex. Supposing that both in-train and in-out-train users are handled by cells that use equal powers $\rho_0^{gNB} = \rho_j^{gNB}$ and $\alpha_{gNB}\rho_0^{ITAP} = \rho_j^{ITAP}$, we present that the problem of energy consumption minimization is solvable via Water-Filling-Like approach since it turn into a convex problem.

All formulated problems and algorithms can be utilized for the situation of multiple users along multiple cells, but for simplicity we take into account the case of users located over one cell. It can be presented that the second derivative of ϕ_x^{gNB} with respect to ρ_0^{gNB} is concave. As a result we get that $\hat{\phi}^{gNB}(\beta_x^{gNB}, \rho_0^{gNB}) = \beta_x^{gNB}\phi_x^{gNB}(\rho_0^{gNB}/\beta_x^{gNB})$ is concave since it is the prospect of a concave function [12]. Moreover, as ϕ_x^{ITAP} is also concave due to its form as ϕ_x^{gNB}'s, the optimization problem (8) is concave too.

Power Assignment with Water-filling-like approach

It is so difficult to find an analytic solution for optimization problem (7). But, if we assume that bandwidth assignment is invariable, then an algorithm for power assignment can be acquired from Kuhn-Karush-Tucker (KKT) optimality prerequisites [12]. To simplify, we rewrite $G_{0x}^{gNB} = s_x$, $\sum_{j=1}^{6} G_{jx}^{gNB} = t_x$, $G_{0x}^{ITAP} = u_x$ and $\sum_{j=0}^{6} G_{jx}^{ITAP} = v_x$ in the following equations. We formulate the optimization problem (7) through the Lagrangian like presented in equation (10)

$$\text{(10)} \quad (\boldsymbol{\rho}, \boldsymbol{\epsilon}, \boldsymbol{\gamma}) = \mathbf{1}^T\boldsymbol{\phi}^{gNB} + \mathbf{1}^T\boldsymbol{\phi}^{ITAP} - \boldsymbol{\epsilon}^T(\mathbf{1}^T\boldsymbol{\rho} - \rho^{MAX}) + \boldsymbol{\gamma}^T\boldsymbol{\rho}$$

The notations $\boldsymbol{\gamma} = [\gamma^{gNB}, \gamma^{ITAP}]$ and $\boldsymbol{\epsilon}$ are the Lagrange multipliers, where $\boldsymbol{\gamma}$ is the positivity constraints and $\boldsymbol{\epsilon}$ is the sum-power. We take the following identities considering that

$$\text{(11)} \quad \begin{aligned} &\log_2\left(1 + \frac{s_x\rho_0^{gNB}}{N_0\beta_x^{gNB} + t_x\rho_0^{gNB}}\right) \approx \log_2\left(1 + \frac{s_x\rho_0^{gNB}}{t_x\rho_0^{gNB}}\right) \\ &\log_2\left(1 + \frac{u_x\rho_0^{ITAP}}{N_0\beta_x^{ITAP} + \alpha_{gNB}v_x\rho_0^{ITAP}}\right) \approx \\ &\approx \log_2\left(1 + \frac{u_x\rho_0^{ITAP}}{\alpha_{gNB}v_x\rho_0^{ITAP}}\right) \end{aligned}$$

and applying the Kuhn-Karush-Tucker prerequisites [12] [13]:

(12a)

$$\boldsymbol{\rho} \geq \mathbf{0},$$

(12b)

$$\mathbf{1}^T \boldsymbol{\rho} - \rho^{MAX} \leq 0,$$

(12c)

$$\boldsymbol{\gamma} \geq \mathbf{0},$$

(12d)

$$\gamma^{gNB} \rho^{gNB} = 0,$$

(12e)

$$\gamma^{ITAP} \rho^{ITAP} = 0,$$

$$\frac{\partial L}{\partial \rho_0^{gNB}} = -\sum_{x=1}^{X^{gNB}} \frac{\beta_x^{gNB}}{\rho_0^{gNB} \ln 2} \frac{1}{(N_0 \beta_x^{gNB} + t_x \rho_0^{gNB})} \times \frac{s_x N_0 \beta_x^{gNB}}{[N_0 \beta_x^{gNB} + (s_x + t_x) \rho_0^{gNB}]} + \frac{\beta_x^{gNB}}{(\rho_0^{gNB})^2} \log_2 \left(1 + \frac{s_x}{t_x}\right) + \epsilon - \gamma^{gNB}$$

(12f)

$$= \psi^{gNB}(\rho_0^{gNB}) - \gamma^{gNB} = 0,$$

$$\frac{\partial L}{\partial \rho_0^{ITAP}} = -\sum_{x=1}^{X^{ITAP}} \frac{\beta_x^{ITAP}}{\rho_0^{ITAP} \ln 2} \times \frac{1}{(N_0 \beta_x^{ITAP} + \alpha_{gNB} v_x \rho_0^{ITAP})} \times \frac{u_x N_0 \beta_x^{ITAP}}{[N_0 \beta_x^{ITAP} + (u_x + \alpha_{gNB} v_x) \rho_0^{ITAP}]} + \frac{\beta_x^{ITAP}}{(\rho_0^{ITAP})^2} \log_2 \left(1 + \frac{u_x}{\alpha_{gNB} v_x}\right) + \epsilon - \gamma^{ITAP}$$

(12g)

$$= \psi^{ITAP}(\rho_0^{ITAP}) - \gamma^{ITAP} = 0,$$

The identities (12f, 12g) are the first derivative with respect to ρ_0^{gNB} and ρ_0^{ITAP} of the Lagrangian approach presented in Equation (11), inferred from the KKT prerequisites [14] and [15]. We demonstrate that efficiently calculating the optimally assigned power is feasible under the condition that the variable ϵ remains unchangeable. By deriving the optimal ρ_0^{gNB} and ρ_0^{ITAP} as functions of ϵ, while taking into account the constraints (12c-12g), we determine these values from the roots of the functions $\psi^{gNB}(\rho_0^{gNB})$ and $\psi^{ITAP}(\rho_0^{ITAP})$, respectively. The roots of these functions can be computed using the Ferrari-Lagrange methodology [16]. Given that $\epsilon^{gNB} = \sum_{x=1}^{X^{gNB}} [(s_x/(N_0 ln2)]$ and $\epsilon^{ITAP} = \sum_{x=1}^{X^{ITAP}} [(u_x/(N_0 ln2))]$, we ascertain the optimal power assignment for both in-train and in-out-train users as follows:

(13)
$$\rho_0^{gNB} = \begin{cases} \rho_0^{gNB}(\epsilon), & \text{if } \frac{1}{\epsilon} \geq \frac{1}{\epsilon^{gNB}}, \\ 0, & \text{otherwise}, \end{cases}$$

(14)
$$\rho_0^{ITAP} = \begin{cases} \rho_0^{ITAP}(\epsilon), & \text{if } \frac{1}{\epsilon} \geq \frac{1}{\epsilon^{ITAP}}, \\ 0, & \text{otherwise}, \end{cases}$$

If $X^{gNB} = X^{ITAP} = 1$, then the equations given above can be computed analytically and yield the optimal power allocated to in-out-train user as follows:

(15)
$$\rho_0^{gNB} = \begin{cases} -\frac{\xi_{31}}{4\xi_{41}} + \nu_1 + \frac{1}{2}\sqrt{-4Z_1^2 - 2\zeta_1 - \frac{\eta_1}{\nu_1}}, & \text{if } \frac{1}{\epsilon} \geq \frac{1}{\epsilon^{gNB}}, \\ 0, & \text{otherwise}. \end{cases}$$

The variables ζ_1, η_1, ν_1, τ_1, δ_{01}, δ_{11}, ξ_{01}, ξ_{11}, ξ_{21}, ξ_{31} and ξ_{41} are shown as follows:

$$\zeta_1 = \frac{8\xi_{41}\xi_{21} - 3k_{31}^2}{8k_{41}^2}$$

$$\eta_1 = \frac{k_{31}^3 - 4\xi_{41}\xi_{31}\xi_{21} + 8k_{41}^2\xi_{11}}{8k_{41}^3}$$

$$\nu_1 = \frac{1}{2}\sqrt{-\frac{2}{3}\zeta_1 + \frac{1}{3\xi_{41}}\left(\tau_1 + \frac{\delta_{01}}{\tau_1}\right)}$$

$$\tau_1 = \sqrt[3]{\frac{\delta_{11} + \sqrt{\delta_{11}^2 - 4\delta_{01}^3}}{2}}$$

$$\delta_{01} = k_{21}^2 - 3\xi_{31}\xi_{11} + 12\xi_{41}\xi_{01}$$

$$\delta_{11} = 2k_{21}^3 - 9\xi_{31}\xi_{21}\xi_{11} + 27k_{31}^2\xi_{01} + 27\xi_{41}k_{11}^2 - 72\xi_{41}\xi_{21}\xi_{01}$$

$$\xi_{01} = \beta_1^{gNB}(N_0\beta_1^{gNB})^2 \log_2\left(1 + \frac{s_1}{t_1}\right)$$

$$\xi_{11} = \beta_1^{gNB}(N_0\beta_1^{gNB})\left[(s_1 + 2t_1)\log_2\left(1 + \frac{s_1}{t_1}\right) - \frac{s_1}{\ln 2}\right]$$

$$\xi_{21} = t_1(s_1 + t_1)\beta_1^{gNB}\log_2\left(1 + \frac{s_1}{t_1}\right) + (N_0\beta_1^{gNB})^2\epsilon$$

$$\xi_{31} = N_0\beta_1^{gNB}(s_1 + 2t_1)\epsilon$$

$$\xi_{41} = t_1(s_1 + t_1)\epsilon$$

The optimal power allocated to in-train user is given as follows:

(16)
$$\rho_0^{ITAP} = \begin{cases} -\frac{\xi_{32}}{4\xi_{42}} + \nu_2 + \frac{1}{2}\sqrt{-4Z_2^2 - 2\zeta_2 - \frac{\eta_2}{\nu_2}}, & \text{if } \frac{1}{\epsilon} \geq \frac{1}{\epsilon^{ITAP}}, \\ 0, & \text{otherwise}, \end{cases}$$

with variables ζ_2, η_2, ν_2, τ_2, δ_{02}, δ_{12}, ξ_{02}, ξ_{12}, ξ_{22}, ξ_{32} and ξ_{42}, which are presented below:

$$\zeta_2 = \frac{8\xi_{42}\xi_{22} - 3k_{32}^2}{8k_{42}^2}$$

$$\eta_2 = \frac{k_{32}^3 - 4\xi_{42}\xi_{32}\xi_{22} + 8k_{42}^2\xi_{12}}{8k_{41}^3}$$

$$\nu_2 = \frac{1}{2}\sqrt{-\frac{2}{3}\zeta_2 + \frac{1}{3\xi_{42}}\left(\tau_2 + \frac{\delta_{02}}{\tau_2}\right)}$$

$$\tau_2 = \sqrt[3]{\frac{\delta_{12} + \sqrt{\delta_{12}^2 - 4\delta_{02}^3}}{2}}$$

$$\delta_{02} = k_{22}^2 - 3\xi_{32}\xi_{12} + 12\xi_{42}\xi_{02}$$

$$\delta_{12} = 2k_{22}^3 - 9\xi_{32}\xi_{22}\xi_{12} + 27k_{32}^2\xi_{02} + 27\xi_{42}k_{12}^2 - 72\xi_{42}\xi_{22}\xi_{02}$$

$$\xi_{02} = \beta_1^{ITAP}(N_0\beta_1^{ITAP})^2 \log_2\left(1 + \frac{u_1}{\alpha_{gNB}v_1}\right)$$

$$\xi_{12} = \beta_1^{ITAP}(N_0\beta_1^{ITAP})\left[(u_1 + 2\alpha_{gNB}v_1) \times \right.$$

$$\left. \times \log_2\left(1 + \frac{u_1}{\alpha_{gNB}v_1}\right) - \frac{u_1}{\ln 2}\right]$$

$$\xi_{22} = \alpha_{gNB}v_1(u_1 + \alpha_{gNB}v_1)\beta_1^{ITAP} \log_2\left(1 + \frac{u_1}{\alpha_{gNB}v_1}\right)$$

$$+(N_0\beta_1^{ITAP})^2\epsilon$$

$$\xi_{32} = N_0\beta_1^{ITAP}(u_1 + 2\alpha_{gNB}v_1)\epsilon$$

$$\xi_{42} = \alpha_{gNB}v_1(u_1 + \alpha_{gNB}v_1)\epsilon$$

By employing a straightforward bisection search, the water-filling level $\frac{1}{\epsilon}$ reaches its optimal value.

Network Simulation

In the following, we show the results through simulations for two users, both of them located inside the train that moves with a very high speed, where one of them is served by in-train access point while the other is served by a 5G-MC-gNB. In simulations, we have taken into account 200 channel realizations. In Table I are shown the simulation quantities.

Table 1. Simulation quantities: High-speed train scenario

Parameters	Values
5G-MC-gNB maximum power	10 W
In-train access point maximum power	0.025 W
Maximum bandwidth β^{MAX}	1 GHz
Center carrier frequency f_c	30GHz
Train speed v	340 Km/h
in-out-train power coefficient α_{OST}	48
In-train power coefficient α_{IST}	0.018
in-out-train user position in (r, θ)	(140 m,$145°$)
In-train user position in (r, θ)	(161 m,$161°$)
In-train access point position in (r, θ)	(166 m,$166°$)
Inter 5G-MC-gNB distance R	350 m

Considering Equations (15) and (16) for searching the optimal water-filling-level $\frac{1}{\epsilon}$ via simple bisection searching the power allocated optimally for the in-out-train user and the in-train user have been simulated.

The energy efficiency for the in-out-train user (located in train) served by a 5G-MC-gNB is shown in Figure 3. It is presented as function of assigned power to user x for static and optimal power allocation. From Figure 3 we remark an energy efficiency growth in case of optimal power assignment compared with fixed one.

The in-train user energy efficiency, which is located in train too, connected by an in-train access point is shown in Figure 4. The energy efficiency is given as function of allocated power to user x for optimal and static power cases. From Figure 4 we see an energy efficiency rise with optimal power assignment compared with static case.

Comparing Figure 3 and Figure 4, we ascertain that the in-train user energy efficiency is much higher than the in-out-train user EE.

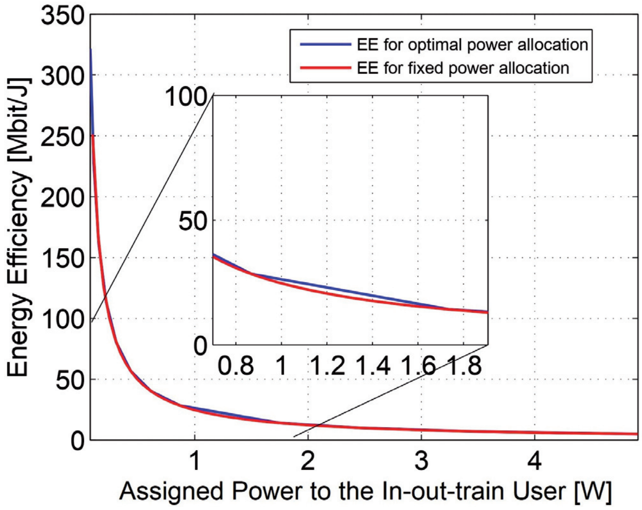

Fig. 2. Energy efficiency for the in-out-train user

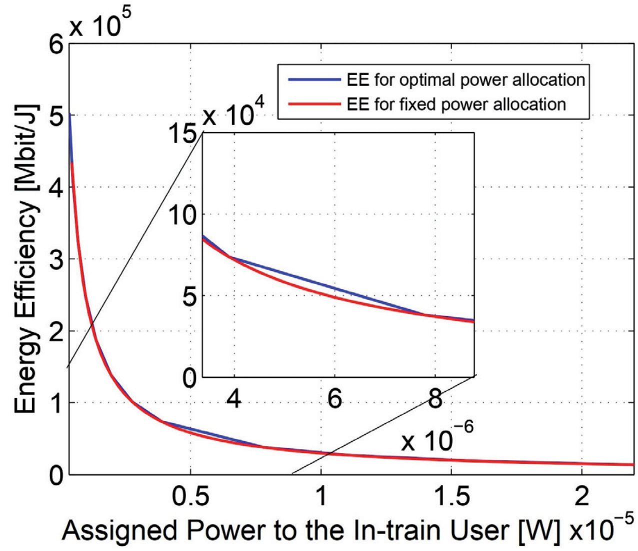

Fig. 3. Energy efficiency for the in-train user

In Figure 5 is presented the energy efficiency versus bit rate and allocated power optimally to the in-out-train user in high-speed train.

The energy efficiency as function of bit rate and assigned power optimally to the in-train user in high-speed train is shown in Figure 6.

By seeing at Figure 5 and Figure 6 we notice that more power is assigned to users when the channel conditions are becoming worse in order to ensure the required transmission rate. The energy efficiency decreases with the increase of power consumption. By comparing Figure 5 and Figure 6 we see that much less power is required when the user is served by in-train access point than it is served by 5G-MC-gNB for the same bit rate. So, the energy efficiency is much higher for the in-train user than for the in-out-train user in high-speed train.

Conclusion

In this study, we address the scenario of users situated within high-speed trains, introducing a novel cell cluster system to accommodate their mobility. To delineate user classification, we employ an in-train path loss model (IT-PLM) threshold.

We propose an algorithm and formulate an optimization problem aimed at enhancing energy efficiency while considering power allocation and bit rate. These challenges

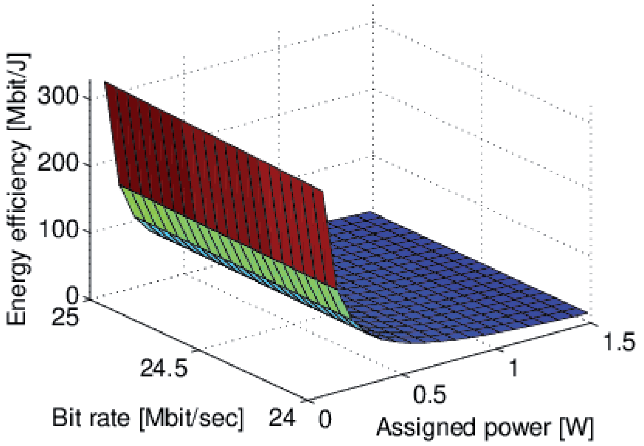

Fig. 4. Energy efficiency versus bit rate and assigned power for the in-out-train user

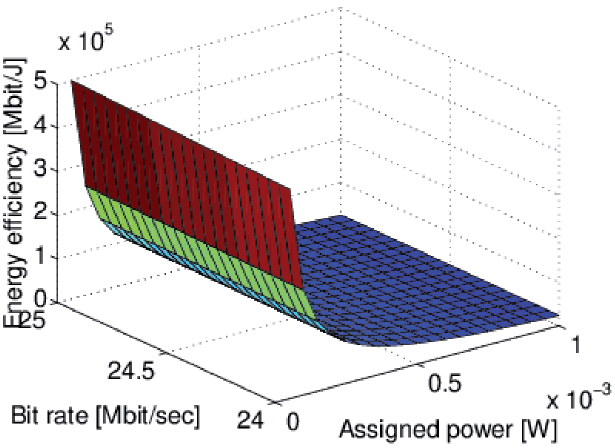

Fig. 5. Energy efficiency versus bit rate and assigned power for the in-train user

are compounded by the non-convex nature of the problems. However, by assuming equal power allocation between in-train and in-out-train users, we transform the non-convex optimization problem for energy efficiency maximization into a convex one.

Leveraging dual decomposition techniques, we derive optimal power assignments for in-train and in-out-train users within a fixed bandwidth. This optimal power assignment effectively enhances energy efficiency and bit rate simultaneously.

Simulation results demonstrate that our optimal power assignment algorithm significantly reduces energy consumption compared to static power assignment methods, with a remarkable 69% increase in energy efficiency observed when users are served by 5G macro cell gNodeBs, and a 6.8% improvement when served by in-train access points (ITAPs). Notably, energy efficiency is substantially higher with ITAPs compared to gNodeBs. Furthermore, our analysis reveals that under deteriorating channel conditions, increased power allocation is necessary to maintain required bit rates, albeit at the expense of energy efficiency.

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