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Abstract—**In this paper we apply constrained optimization techniques to optimally allocate bandwidth and transmit power to the users in a cellular network. We utilize partial frequency reuse as inter-cell interference mitigation technique considering two users uniformly located in full and partial frequency reuse regions. Bandwidth and power are allocated to the users based on their large-scale path-loss attenuation. Moreover, an efficient algorithm is used to solve the problem of power assignment for fixed bandwidth allocation when one user is in the full reuse region and one in the partial reuse region. We further demonstrate by simulations that allocation of the bandwidth and power to the users depending on the threshold for large-scale path-loss attenuation, results in a significantly increased sum-rate.**

I. INTRODUCTION

Next generation mobile communication systems use Orthogonal Frequency Division Multiple Access (OFDMA) as their modulation scheme in the downlink [1], [2]. Since cell edge users may suffer severely from Inter-Cell Interference (ICI), several schemes have been proposed for ICI mitigation. One of those schemes is Partial Frequency Reuse (PFR), which is applied for example in [3], [4], [5].

The characteristics of the optimal power allocation for two base stations, employing also scheduling schemes, has been studied in [6] under frequency reuse-1.

Additionally to the sum-rate maximization power control problem, in [7] the authors also investigate the maximization of the minimum rate for two users. An efficient algorithm for solving the sum-rate maximization problem in convex form for PFR under the assumption that all Full frequency Reuse (FFR) user are served with equal power is developed in [8]. In this study the authors have shown that the maximization of the minimum rate and the minimization of the sum-power can be transformed in convex optimization problems and solved efficiently. In [3], [9] the authors have mentioned that the cell edge bandwidth can be re-used as cell center bandwidth whenever the cell edge user is idle. A study about the utilization of the cell edge (outer) bandwidth as cell center (inner) bandwidth considering the user density is done in [5]. In this study the authors have shown how the cell edge bandwidth can be reused as cell center bandwidth while optimizing over the optimal frequency partitioning radius. In [10] a static method is used for sum-rate maximization by bandwidth re-allocation dependent on the user's distance from their serving base station. In this study the authors have shown that almost all of the cell outer bandwidth can be re-allocated as cell inner bandwidth whenever we have only inner users active. To the best of our knowledge, there are currently no studies considering the maximization of the sum-rate by bandwidth re-allocation depending large-scale path-loss attenuation.

Our contributions can be summarized as follows. In Section II we show the realistic system model including the bandwidth allocation scheme for PFR. In Section III we study the allocation of the bandwidth and power to the users depending on the large-scale path-loss attenuations. A threshold for large-scale path-loss attenuation is used in order to decide when a user is inner or outer user. The large-scale path-loss attenuation threshold is defined as the mean over all large-scale path-loss attenuation of all users [11]. For a fixed bandwidth allocation we even use a simple water-filling-like power allocation algorithm [8] to optimally allocate the power to the inner and outer user. Furthermore, we present in Section IV simulation results which confirm the rate gains by applying the proposed dynamic method for power and bandwidth allocation. The simulation results show that allocation of the power and bandwidth to the users depending on their large-scale path-loss attenuation result in a significant increased sum-rate for each random user's positions and also the average sum-rate compared with a static case. Conclusions are drawn in Section V.

II. SYSTEM MODEL

In our realistic system we consider one user located in the inner region of the cell (the full frequency reuse region) and one user located in the outer region of the cell (the partial frequency reuse region), as indicated in Fig. 1. Based on the users' large-scale path-loss attenuation a user is considered to be an inner user or an outer user. The frequency reuse pattern [3] applied in our system model is shown Fig. 2. The frequency pattern shows that frequency reuse-1 is used to serve the inner users and frequency reuse-3 is used to serve the outer

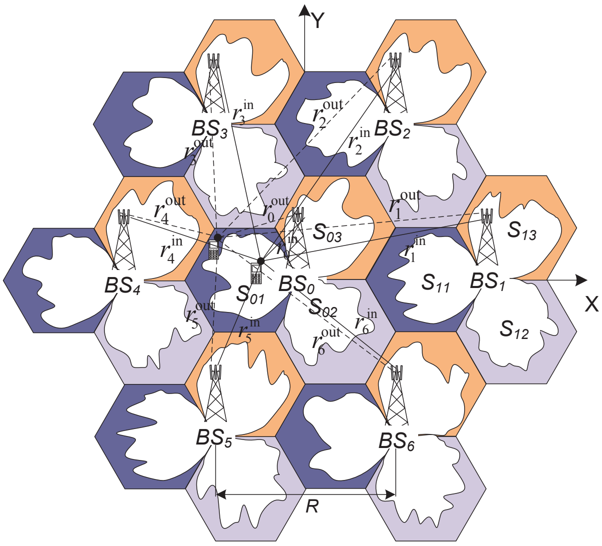

Fig. 1. Partial frequency reuse cell cluster

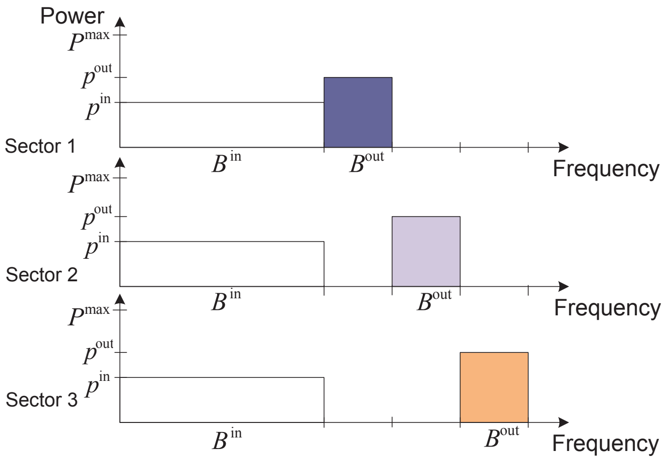

Fig. 2. Frequency reuse pattern

users. The user who is located in the inner region of the cell, S_{01} receives power from its own sector antenna of base station BS_0 and also interference from all other base stations BS_k, $k = 0 \ldots 6$. More distant base stations are not considered in our system model but all our results can be easily extended to consider also interference from non-neighboring base stations. The rate achieved by the user in the inner region is given by

$$R^{\mathrm{in}} = B^{\mathrm{in}} \log_2 \left(1 + \frac{G_0^{\mathrm{in}} p_0^{\mathrm{in}}}{N_0 B^{\mathrm{in}} + \sum_{k=1}^{6} G_k^{\mathrm{in}} p_k^{\mathrm{in}}} \right), \tag{1}$$

where B^{in} is the bandwidth utilized in the inner region and N_0 is the noise spectral density. The large-scale path-loss attenuation G_k is in dB including antenna gain, penetration loss, shadowing and fast fading is expressed in the form [12]

$$G_k = -[128.1 + 10\alpha \log_{10}(r_k) + A_k + L_p + X_\sigma + F] \tag{2}$$

where α the path-loss exponent, r_k the distance between the mobile station and the base station BS_k in km, A_k the sum of user antenna gain and base station antenna gain in dB, L_p the penetration loss in dB, X_σ the log-normal shadowing in dB, and F the fast fading channel coefficient in dB. The antenna gain A_k is defined by a horizontal antenna pattern [12]. The large-scale path-loss attenuation of directed channels G_0^{in} is defined by Equation (2). The large-scale path-loss attenuation of interference channels G_k^{in} is also defined by Equation (2) except for the fast fading, which is not taken into account here. The transmit power assigned to the user in the inner region is denoted by p_0^{in} and the interference power from the other base stations is denoted by p_k^{in}, $k = 1 \ldots 6$, with k denoting the index of the interfering base stations. The user located in the outer region of the cell receive also interference from all non-neighboring sectors that use the same frequency band. The transmit power assigned to the user in the outer region is denoted by p_0^{out} and the interference power from the other base stations is denoted by p_k^{out}, $k = 1 \ldots 6$. Thus, the rate achieved by the user in the outer region is given by

$$R^{\mathrm{out}} = B^{\mathrm{out}} \log_2 \left(1 + \frac{G_0^{\mathrm{out}} p_0^{\mathrm{out}}}{N_0 B^{\mathrm{out}} + \sum_{k=1}^{6} G_k^{\mathrm{out}} p_k^{\mathrm{out}}} \right) \tag{3}$$

where B^{out} denotes the bandwidth utilized in the outer region and G_0^{out} and G_k^{out} denotes the large-scale path-loss attenuation for the direct and interference channels of the outer user.

III. BANDWIDTH AND POWER ALLOCATION DEPENDENT LARGE-SCALE PATH-LOSS

In this section we show the bandwidth and power utilization. By considering the large-scale path-loss attenuation of the users and comparing with a pre-defiend threshold denoted by G_{tgt}, we have three cases of allocating the bandwidth and power.

A. One user located in the inner cell region and one user located in the outer cell region

If the user's large-scale path-loss attenuation is higher than G_{tgt}, than that user is considered to be an inner user, otherwise an outer user. When we have one inner and one outer user, the bandwidth assignment to them is based on the frequency reuse pattern shown for sector S_{01} in Fig. 3. The inner bandwidth denoted by B^{in} is allocated to the inner user and the outer bandwidth denoted by B^{out} is allocated to the outer user. The optimal power assignment to the inner and outer user is calculated by using an efficient algorithm [8] as water filling-like power allocation. The optimal power assigned to the inner

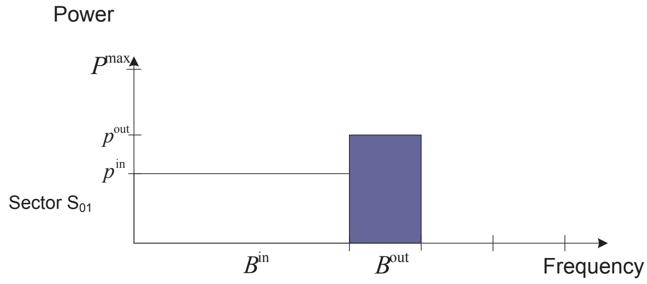

Fig. 3. Frequency reuse pattern for sector S_{01}

user is given by the Equation (4).

$$p_0^{\text{in}} = \begin{cases} \dfrac{-(a+2b)N_0 B^{\text{in}} + \sqrt{\Delta^{\text{in}}}}{2(a+b)b}, & \text{if } \dfrac{1}{\mu} \geq \dfrac{N_0 \log(2)}{a}, \\ 0, & \text{otherwise,} \end{cases} \tag{4}$$

where $a = G_0^{\text{in}}$, $b = \sum_{k=1}^{6} G_k^{\text{in}}$ and Δ^{in} under the square root in Equation (4) is given by

$$\Delta^{\text{in}} = (aN_0 B^{\text{in}})^2 + 4ab\,(a+b)\,\frac{N_0 (B^{\text{in}})^2}{\mu \log(2)},$$

where μ is the Lagrange multiplier [13]. A simple bisection method [14] is used for searching the optimal water-level $1/\mu$. The optimal assigned power to the outer user is analogously given by

$$p_0^{\text{out}} = \begin{cases} \dfrac{-(d+2e)N_0 B^{\text{out}} + \sqrt{\Delta^{\text{out}}}}{2(d+e)e}, & \text{if } \dfrac{1}{\mu} \geq \dfrac{N_0 \log(2)}{d}, \\ 0, & \text{otherwise,} \end{cases} \tag{5}$$

where $d = G_0^{\text{out}}$, $e = \sum_{k=1}^{6} G_k^{\text{out}}$ and Δ^{out} under the square root in Equation (5) is given by

$$\Delta^{\text{out}} = (dN_0 B^{\text{out}})^2 + 4de\,(d+e)\,\frac{N_0 (B^{\text{out}})^2}{\mu \log(2)}.$$

B. Both users are located in the inner cell region

If the large-scale path-loss attenuations of both considered users are higher than G_{tgt}, both users are considered to be inner users. Since, we have only inner users they have to share the inner bandwidth. The maximum base station power is assigned to both inner users. The transmission rate for User 1 is given as follows:

$$R_1^{\text{in}} = \frac{B^{\text{in}}}{2} \log_2 \left(1 + \frac{G_{01}^{\text{in}} P^{\max}}{N_0 \frac{B^{\text{in}}}{2} + \sum\limits_{k=1}^{6} G_{k1}^{\text{in}} P^{\max}} \right) \tag{6}$$

and the transmission rate of the inner User 2 is:

$$R_2^{\text{in}} = \frac{B^{\text{in}}}{2} \log_2 \left(1 + \frac{G_{02}^{\text{in}} P^{\max}}{N_0 \frac{B^{\text{in}}}{2} + \sum\limits_{k=1}^{6} G_{k2}^{\text{in}} P^{\max}} \right) \tag{7}$$

The large-scale path-loss attenuations of direct channels G_{01}^{in}, G_{02}^{in} are defined by Equation (2). The large-scale path-loss attenuation of interference channels G_{k1}^{in}, G_{k2}^{in} are defined also by Equation (2) with F=0 dB. The outer bandwidth is less interfered than the inner bandwidth because it is interfered only by non-neighboring sectors. We therefore re-allocate that bandwidth to the inner users. The bandwidth re-allocation scheme consists of using the outer bandwidth as inner bandwidth. The way of re-allocating the outer bandwidth and using it as inner bandwidth is shown in Fig. 4. The parameter t describes how much of outer bandwidth is re-allocated to be used as inner bandwidth. In order to account for the bandwidth re-allocation we modify Equation (6) for the inner User 1 as follows:

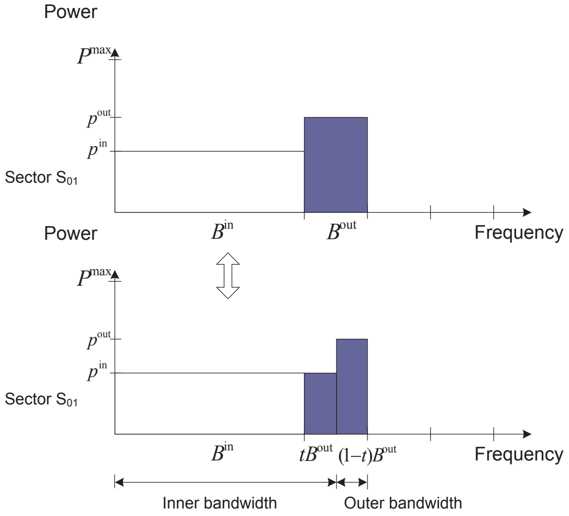

Fig. 4. Partial bandwidth re-allocation for inner user

$$\begin{aligned} R_1^{\text{in}} = & \frac{B^{\text{in}}}{2} \log_2 \left(1 + \frac{G_{01}^{\text{in}} P^{\max}}{N_0 \frac{B^{\text{in}}}{2} + \sum\limits_{k=1}^{6} G_{k1}^{\text{in}} P^{\max}} \right) + \\ & + t\frac{B^{\text{out}}}{2} \log_2 \left(1 + \frac{G_{01}^{\text{out}} P^{\max}}{N_0 t\frac{B^{\text{out}}}{2} + \sum\limits_{k=1}^{6} G_{k1}^{\text{out}} P^{\max}} \right) \end{aligned} \tag{8}$$

Equation (7) for the rate of the inner User 2 is modified accordingly:

$$\begin{aligned} R_2^{\text{in}} = & \frac{B^{\text{in}}}{2} \log_2 \left(1 + \frac{G_{02}^{\text{in}} P^{\max}}{N_0 \frac{B^{\text{in}}}{2} + \sum\limits_{k=1}^{6} G_{k2}^{\text{in}} P^{\max}} \right) + \\ & + t\frac{B^{\text{out}}}{2} \log_2 \left(1 + \frac{G_{02}^{\text{out}} P^{\max}}{N_0 t\frac{B^{\text{out}}}{2} + \sum\limits_{k=1}^{6} G_{k2}^{\text{in}} P^{\max}} \right) \end{aligned} \tag{9}$$

C. Both users located in the outer cell region

Both users are considered as outer users if their large-scale path-loss attenuation is lower than G_{tgt}. In this case, the inner bandwidth is not used at all and can not be re-used since this bandwidth experiences high interference at the cell edge. Since we have only outer users, the outer bandwidth is shared among them. The transmission rate of the first outer user is:

$$R_1^{\mathrm{out}} = \frac{B^{\mathrm{out}}}{2} \log_2 \left(1 + \frac{G_{01}^{\mathrm{out}} P^{\max}}{N_0 \frac{B^{\mathrm{out}}}{2} + \sum\limits_{k=1}^{6} G_{k1}^{\mathrm{out}} P^{\max}} \right) \quad (10)$$

The Equation for the transmission rate of the outer User 2 is:

$$R_2^{\mathrm{out}} = \frac{B^{\mathrm{out}}}{2} \log_2 \left(1 + \frac{G_{02}^{\mathrm{out}} P^{\max}}{N_0 \frac{B^{\mathrm{out}}}{2} + \sum\limits_{k=1}^{6} G_{k2}^{\mathrm{out}} P^{\max}} \right) \quad (11)$$

The large-scale path-loss attenuations of direct channels G_{01}^{out}, G_{02}^{out} are defined by Equation (2). The large-scale path-loss attenuation of interference channels G_{k1}^{out}, G_{k2}^{out} are defined also by Equation (2).

IV. SIMULATION RESULTS

In this simulation we consider uniform user's positions. A realistic urban scenario is considered with its parameters shown in Table I.

TABLE I
SIMULATION PARAMETERS

parameters	value
Maximum base station power $P^{\max}$	$5\,\mathrm{W}$
Maximum base station bandwidth $B^{\max}$	$20\,\mathrm{MHz}$
Noise spectral density N_0	$-174\,\mathrm{dBm/Hz}$
Center frequency f	$2.0\,\mathrm{GHz}$
Pathloss exponent α	3.75
Penetration loss L_p	$20\,\mathrm{dB}$
Shadowing X_σ	$\mathcal{N}(0,8)$ dB
Fast Fading F	$\mathcal{CN}(0,1)$ dB,
Inter base station distance R	$700\,\mathrm{m}$
Maximum cell range r	$(2/3)R\,\mathrm{m}$
Large-scale path-loss threshold G_{tgt}	$-106.4\,\mathrm{dB}$,
Number of channel realizations	100
Number of uniform user's positions	100

The large-scale path-loss attenuation results for two users depending on their distance for each uniform user's positions are shown in Fig. 5.

To show the values of large-scale path-loss attenuations depending on their random user distances from base station, we used the Equation (2). For the simulation setup we have considered 100 uniform user's positions where per each positions users have experiences different channels. For each specific channel realization of random user's positions we have compared the large-scale path-loss attenuation of users with G_{tgt} and based on that we have decided for user's power and bandwidth assignment. During simulations we have noticed that the case that both users are located in the inner region occurs with a probability of 16 %. The case when one user is located in the inner region and the other one located in the outer region occurs with a probability of 48 %. The last case when both users are located in the outer region occurs with a probability of 36 %. From the simulation results shown in Fig. 5 we see that because of fast fading and shadowing, sometimes the user which is far from base station has a better large-scale path-loss attenuation (better channel) than a user which is near the base station. By selecting the users as inner user and outer user depending on the threshold for large-scale path-loss attenuation we are able to assign the power and bandwidth resources in the optimal way to the users, incease the sum-rate gain and decrease the inter-cell interference. In Fig. 6 is shown the sum-rate gain for dynamic method compared with a static method.

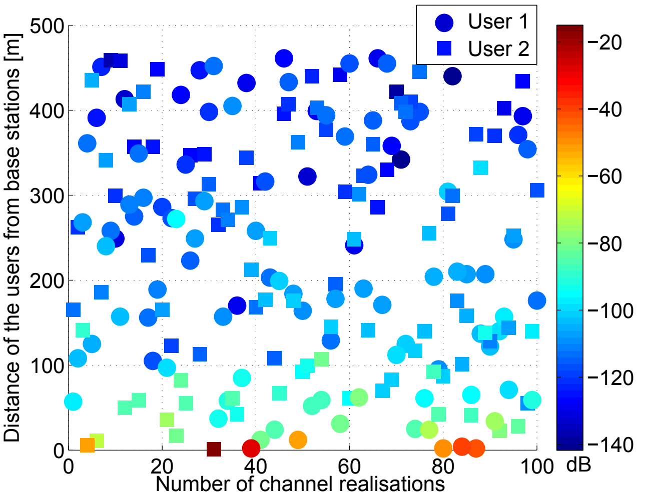

Fig. 5. Large-scale path-loss attenuations for uniform users positions

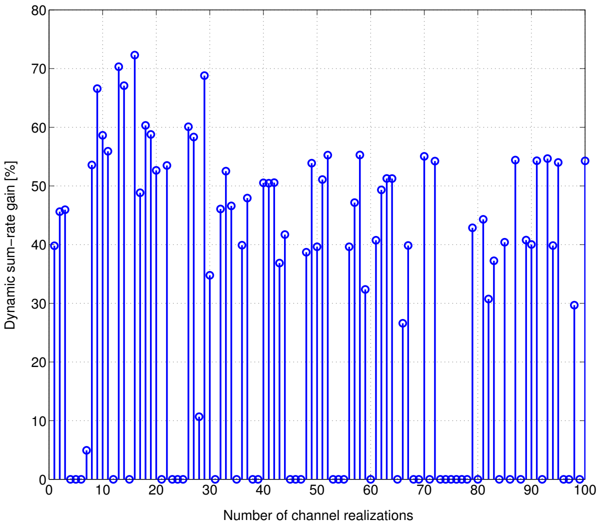

Fig. 6. Sum-rate gain for dynamic method compared with static method

With dynamic method we mean that the selection of the users is done based on their threshold for large-scale path-loss attenuation. With static method we mean that the selection of the users is done based on their distance from their serving base station. For our simulation setup the static method defines a user as inner user if its distance from its serving base station is in the range $0 < r_0^{\mathrm{in}} \leq 0.70 \cdot r$. Analogously the definition for a user as outer user is if its distance is in the range $0.70 \cdot r < r_0^{\mathrm{out}} \leq r$. Looking the simulation results shown in Fig. 6 one can see that in some cases the dynamic method outperform the static method (the sum-rate gain is positive), while in some cases both methods perform the same (the sum-rate gain is zero). This happens because the dynamic method selects the users with bad channels to be as outer user which experience less ICI, while the static method the same user selects as inner user which experience higher ICI. In all other cases when those methods perform the same means that they have done the same selection. For all distance thresholds from $(0.70 \cdot r - r)$ the dynamic method outperform the static method in all uniform user's positions. In Fig. 7 we show the simulation results for average sum-rate taken over uniform user's positions in the inner and outer regions versus maximum base station power. The lower curve represents the average of all sum-rates when no re-allocation of the outer bandwidth to the inner users is carried out for the static method used. A better performance in terms of average sum-rate is achieved when we consider the dynamic method. It is shown by simulation results that a performance increase of approximately 16.4 Mbit/s is achieved when dynamic method is used. Considering also the outer bandwidth re-allocation to the inner users a performance increase of 3.1 Mbit/s is achieved when dynamic method is used.

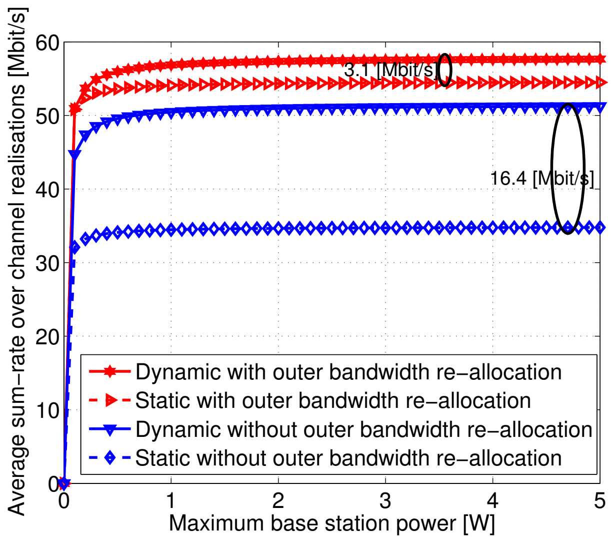

Fig. 7. Maximum average sum-rate for uniform users positions

V. CONCLUSIONS

In this paper we formulated the sum-rate maximization problem for two users in partial frequency reuse cellular networks. We showed analytical expressions for the optimal power assignment to the inner user (full frequency reuse region) and the outer user (partial frequency reuse region) when one inner user and one outer user are present. Furthermore, we demonstrated that for a 20 MHz bandwidth system, allocation of the bandwidth and power to the users dependent on their large-scale path-loss attenuations increases the sum-rate gain as well as the average sum-rate by 16.4 Mbit/s when no re-allocation is considered and by 3.1 Mbit/s when reallocation is considered.

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