Maximization of Link Capacity by Joint Power and Spectrum Allocation for Smart Satellite Transponder

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***Abstract*—The contradiction between ever increasing satellite communication traffic and limited satellite transponder resources motivates a more dynamic allocation and more effective utilization of satellite transponders' resources. In this paper, the link capacity for a smart satellite transponder is maximized with limited available power and spectrum resource at satellite transponder. Specifically, given that the satellite transponder broadcasts the signals from the gateway station to the multiple satellite terminals with minimum transmission rate requirement, the satellite transponder needs to provide as large link capacity as possible to gateway station for the amount data transmission of special demands. The problem is formulated with aim of maximizing link capacity, and subject to minimum transmission rate requirement of link to satellite terminals and available resource allocation. The finely-matched dynamic power and spectrum allocation scheme is proposed to achieve maximization of both target link capacity and transponder resource utilization. Simulations results demonstrate that the proposed scheme outperforms tradition schemes and the superiority is even more remarkable in multi-constrained situations.**

***Index Terms*—satellite transponder, power allocation, spectrum allocation**

I. Introduction

Satellite communications have been rapidly developed and widely applied in the past years. Due to the fact that every signal must go through a single satellite, the amount of usable radio resources (e.g. the satellite transponder bandwidth and satellite transmission power [1]) is limited to the amount of satellite available resources. Therefore, the system capacity crucially depends on satellite resources and their utilization. To enhance the system capacity of satellite communications, ongoing developments [2] [3] have been carried out in different aspects, including high power satellites, multi-beam systems, high-frequency systems [4], multi-carrier decomposition, the adaptive modulation and coding and user scheduling optimization [5] [6]. However, some of these techniques require new communication satellites launched which lead to extremely high costs, and some enable only satellite bandwidth resource to be used more effectively [7].

Various dynamic resource allocation schemes for satellite communications have been studied. Weerackody *et al.* [8] examine the bandwidth and power allocation problem for a multi-frequency time division multiple access (MF-TDMA) to optimize the use of bandwidth and power at the satellite transponder. They present an optimization method to allocate the bandwidth and power among a given set of terminals so that the aggregate data rate from the system is maximized under resource limitations. The authors in [9] have considered to use satellite bandwidth and satellite power together, and they propose a channel allocation algorithm for a demand assigned multiple access (DAMA) controller, which is based on multi-carrier transmission and adaptive modulation methods. It optimizes channel elements such as the number of sub-carriers, modulation level and forward error correction (FEC) coding rate. However, the assumption that the transponder is simple amplified and re-transmitted in the afore mentioned papers is not compatible with the rapidly development of transponder technology [10] [11]. The authors in [12] study a delay-aware power and bandwidth allocation algortihm to maximize the throughput of multiuser satellite downlink system.

Focusing on satellite downlinks' asymmetry for return links to ground station and forward links to satellite terminals, this paper presents an optimization method to achieve the maximum capacity by determining the allocation of bandwidth and spectrum between a forward downlink and a return downlink. Our proposed scheme can be applied on top of the previous ones, providing additional performance gain. What we focus is that given the available bandwidth in each transponder and the minimum reachable transmission rate of the forward link (from the gateway to remote satellite terminals), the capacity of reverse link could be maximized by jointly allocating power and bandwidth for different links. A simple method is derived for selecting the best combination of power and spectrum. The proposed algorithm can be used for adaptively adjustment of accessing number of satellite terminals based on the change of link conditions in terms of forward link channel condition, return link channel condition, and requirement of forward link transmission. This algorithm can be applied as a middleware software/processor in a transponder to make it smart and adaptive, allowing communication satellite operators to maximize their space segment capacity. The performance evaluation results allow the systems designer to achieve the trade-offs between the terminal power, satellite power, satellite bandwidth and transmission link capacity.

The rest of this paper is organized as follows. Section II describes and formulates the problem. Section III derives the problem and develops the algorithm. In Section IV, the performance evaluation results are demonstrated.

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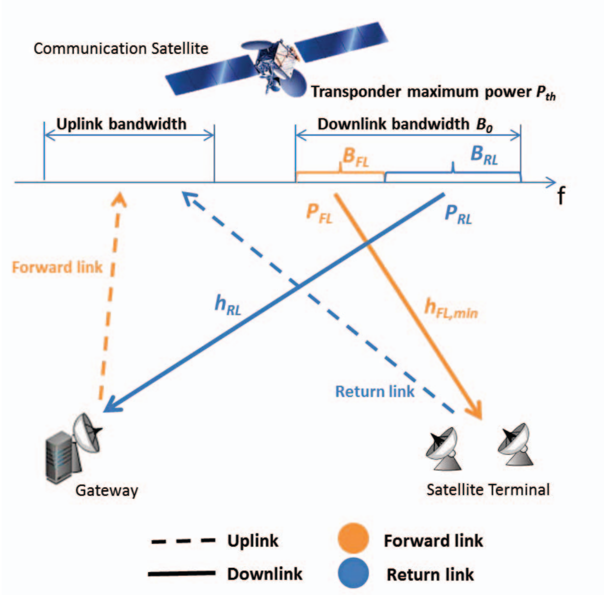


Figure 1. System model.

II. System Model and Problem Formulation

A. System Model

The considered system is depicted in Figure 1. The system consists of a communication satellite, a gateway station, and a number of satellite terminals. The signals are transmitted from the gateway station to remote terminals (forward link) and transmitted from the terminals to gateway station (return link) combining with other data (such as remotely sensed data) for different services. Instead of operating on a bent pipe principle, the transponder in this system use on-board processing, where the signal is demodulated, decoded, re-encoded and modulated aboard on satellite for more efficient resource utilization. Thus, as the signals from forward link and signals from return link reach the transponder, the transponder resources (transmission power and bandwidth) are allowed to be adjusted and allocated adaptively regarding to the required transmission quality.

Within assigned spectrum, the total downlink bandwidth of the transponder is B_0 and the transponders' maximum available transmission power is P_{th}. In a satellite communication system (e.g. VSAT), the transmission rate of broadcast data from gateway station is essentially required. Thus, downlink bandwidth B_{FL} and transmission power P_{FL} are assigned to guarantee the minimum transmission rate. Benefiting from the smart regenerative transponder, the rest resources B_{RL} and P_{RL} could be dynamically adjusted in order to provide maximum accessible return link terminals. This is attributed to that different combination of transmission power and spectrum allocation can be used to achieve the same system capacity. Hence, given the guaranteed transmission rate of forward downlink, how to jointly allocate the transmission power and spectrum to achieve the maximum capacity of return downlink is the focus of this paper.

In order to make the studied more vivid, for example, the simple analysis is elaborated as shown in Figure 2.

- The maximum return link capacity is investigated with constraint of satisfying forward link rate (In this example, assume as R_1) by optimal allocation scheme of power and spectrum (In this example, assume as P_1 and B_1 respectively for forward link rate requirement), as shown in Figure 2(a).
- When R_1 increases to R_2 ($R_1 < R_2$), as shown in Figure 2(b), the maximum return link capacity C is bound to deduce. How much does it deduce is closely related to the power and spectrum adjustment. Then, two aspects problem is needed to consider.
  1) Turn on ON/OFF functionality of spectrum splitter and power splitter? Case 1: If the B_1 is increased to B_2 with the fixed P_1 to satisfy the requirement R_2, then the deduction ΔC_1 for C can be obtained with corresponding computation. Case 2: If the P_1 is increased to P_2 with the fixed B_1 to satisfy the requirement R_2, then the deduction ΔC_2 for C can be obtained with corresponding computation.
  2) However, the value of ΔC_1 and ΔC_2 are often different under different parameters. It is a nice choice that B_1 and P_1 increase in the meantime. The question that how many times power increment and power increment made to achieve the deduction minimization for C should be noticed, and then the maximum return link capacity is obtained with constraint of satisfying R_2.

In the following, the mathematical model is built in the following with optimization tools.

B. Problem Formulation

The capacity of return link is

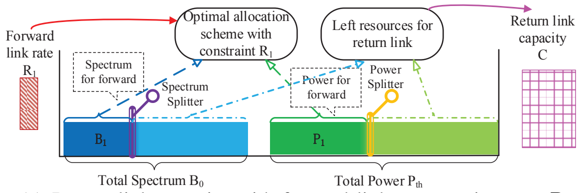
$$C_{RL}(B_{RL}, P_{RL}) = B_{RL}\log_2(1 + P_{RL}h_{RL}/B_{RL}\sigma_{GW}^2) \quad (1)$$

where $h_{RL} = G_T A_{Re}/(4\pi d_{RL}^2 L_{TF} L_{TP} L_P L_{RP} L_{RF})$ [14], G_T, L_{TF}, and L_{TP} are the antenna gain, the feeder loss, and pointing loss of transmit antenna, respectively, for the communication satellite. d_{RL} and L_P are the propagation distance and polarization mismatch loss of transmit and receive antennas, respectively, between the communication satellite and the gateway (ground master station), A_{Re}, L_{RF}, and L_{RP} are the effective area of receiving antenna, the feeder loss of receiving system, and pointing loss of transmit antenna, respectively, for the gateway. σ_{GW}^2 is the noise power density of the gateway.

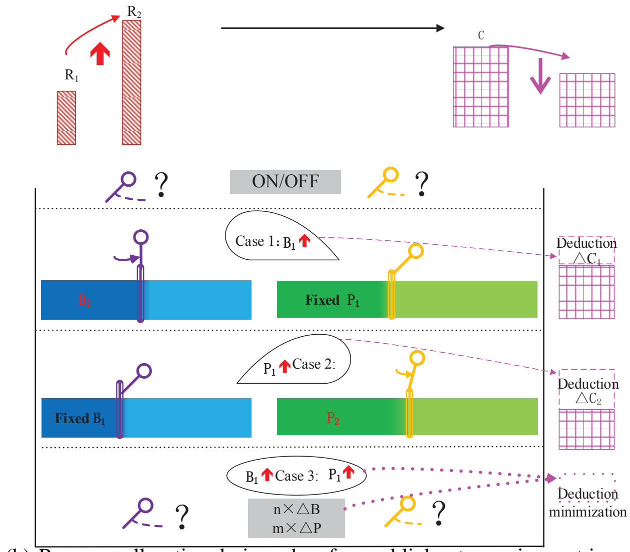
On one hand, the minimum transmit rate requirement that the gateway broadcasts data to satellite terminals should be satisfied

$$\mathcal{C}_1 : C_{FL,min}(B_{FL}, P_{FL}) \geq R_{FL} \quad (2)$$

where $C_{FL,min}(B_{FL}, P_{FL}) = B_{FL}\log_2(1 + P_{FL}h_{FL,min}/B_{FL}\sigma_{ST}^2)$ with channel gain $h_{FL,min} =$



(a) Return link capacity with forward link rate requirement R_1



(b) Resource allocation design when forward link rate requirement increases as R_2

Figure 2. Illustration of considered problem.

$\min\{h_{TP,STi}\}$, $h_{TP,STi}$ is the channel gain between communication satellite and satellite terminal i (including transceiver's antenna gain, path loss, etc.), σ_{ST}^2 is the noise power density at each satellite terminal (assume that the noise power density at each satellite terminal is equal).

On the other hand, some practical engineering application constraints should be taken into account. That is, Firstly, it constrains the maximum transmit power P_{th} at communication satellite

$$\mathcal{C}_2 : P_{FL} + P_{RL} \leq P_{th} \tag{3}$$

Secondly, the maximum available bandwidth B_0 at communication satellite is used for forwarding gateway's broadcast information and returning satellite terminal's data

$$\mathcal{C}_3 : B_{FL} + B_{RL} \leq B_0 \tag{4}$$

Thirdly, the minimum transmit power $P_{FL,min}$ from communication satellite and satellite terminal is described as

$$\mathcal{C}_4 : P_{FL} \geq P_{FL,min} \tag{5}$$

Fourthly, the minimum transmit power $P_{RL,min}$ from communication satellite and gateway is described as

$$\mathcal{C}_5 : P_{RL} \geq P_{RL,min} \tag{6}$$

Therefore, aiming to maximize the return link capacity, joint power and spectrum optimization problem is formulated as

$$\mathcal{OP}: \max_{\substack{B_{RL},B_{FL},\\ P_{FL},P_{RL}\geq 0}} \quad C_{RL}(B_{RL},P_{RL})$$
$$\text{s.t.} \quad \mathcal{C}_1 \sim \mathcal{C}_5.$$

III. Power and Spectrum Allocation Scheme

A. Optimal Power and Spectrum

It is easy to find that the problem $\mathcal{OP}$ is concave with respect to $\{P_{FL}, P_{RL}, B_{RL}, B_{FL}\}$, and hence, an optimal solution can be derived by the primal-dual method [13]. Specifically, by using primal-dual method, the optimal power allocation and spectrum for forward link and return link equip the following relations.

$$\begin{cases} P_{FL}^* = B_{FL}^* \cdot \chi_{FL}(\beta_{FL}, \rho, \mu_{FL}) \\ P_{RL}^* = B_{RL}^* \cdot \chi_{RL}(\rho, \mu_{RL}) \end{cases} \tag{7}$$

with
$$\begin{cases} \chi_{FL}(\beta_{FL}, \rho, \mu) = \left[\frac{\beta_{FL}}{(\rho-\mu_{FL})\ln 2} - \frac{\sigma_{ST}^2}{h_{FL,min}}\right]^+ \\ \chi_{RL}(\rho, \mu_{RL}) = \left[\frac{1}{(\rho-\mu_{RL})\ln 2} - \frac{\sigma_{GW}^2}{h_{RL}}\right]^+ \end{cases}$$

where β_{FL}, ρ, μ_{FL} and μ_{RL} are Lagrange multipliers for constraints 1, 2, 4 and 5, respectively, and $[z]^+ = \max\{z, 0\}$.

Moreover, power and spectrum used for forward link do not contribute to the objective function. The optimal strategy for the communication satellite is to meet rightly the forward link's minimum rate requirement, and save as many resources as possible into the return link transmission. Therefore, the optimal spectrum allocation should satisfy

$$\begin{cases} B_{FL}^* = \frac{R_{FL}}{\log_2(1+\chi_{FL}(\beta_{FL},\rho,\mu_{FL})h_{FL,min}/\sigma_{ST}^2)} \\ B_{RL}^* = B_0 - B_{FL}^* \end{cases} \tag{8}$$

Since the problem $\mathcal{OP}$ is concave with respect to $\{B_{RL}, B_{FL}, P_{FL}, P_{RL}\}$, the optimal solution that satisfies Karush-Kuhn-Tucker (KKT) conditions can be derived by the primal-dual method, where a local maximum is also the global maximum [13]. For brevity, the derivation procedure of (7) and (8) stops drilling here and the reader can refer to literature [16].

B. Parameters: Lagrange Multipliers

The dual problem considered to provide the dual multipliers for the optimal solution can be expressed as

$$\begin{aligned} &\min_{\beta_{FL},\rho,\nu,\mu_{FL},\mu_{RL}} \mathcal{D}(\beta_{FL}, \rho, \nu, \mu_{FL}, \mu_{RL}) \\ = &\min_{\beta_{FL},\rho,\nu,\mu_{FL},\mu_{RL}} \max_{B_{RL}\geq 0, B_{FL}\geq 0, P_{FL}\geq 0, P_{RL}\geq 0} \\ &\mathcal{L}(B_{RL}, B_{FL}, P_{FL}, P_{RL}, \beta_{FL}, \rho, \nu, \mu_{FL}, \mu_{RL}) \end{aligned} \tag{9}$$

It can be solved by sub-gradient method [15], and the Lagrange multipliers are deduced as follows

$$\beta_{FL}[t] = \Big[\beta_{FL}[t-1] - \varepsilon_{FL}\Big(B_{FL}\log_2\big(1 \qquad (10)$$

$$+P_{FL}[t]h_{FL,min}/B_{FL}\sigma_{ST}^2\big) - R_{FL}\Big)\Big]^+ \qquad (11)$$

$$\rho[t] = \Big[\rho[t-1] - \varepsilon_P\big(P_{th} - P_{FL}[t] - P_{RL}[t]\big)\Big]^+ \qquad (12)$$

$$\nu[t] = \Big[\nu[t-1] - \varepsilon_B\big(B_0 - B_{FL}[t] - B_{RL}[t]\big)\Big]^+ \qquad (13)$$

$$\mu_{FL}[t] = \Big[\mu_{FL}[t-1] - \kappa_{FL}\big(P_{FL} - P_{FL,min}\big)\Big]^+ \qquad (14)$$

$$\mu_{RL}[t] = \Big[\mu_{RL}[t-1] - \kappa_{RL}\big(P_{RL} - P_{RL,min}\big)\Big]^+ \qquad (15)$$

where ε_{FL}, ε_P, ε_B, κ_{FL} and κ_{RL} are non-negative steps to control iteration steps.

C. Algorithm Design

According to above derivation, a finely-matched joint power and spectrum allocation algorithm (FMA) is proposed for optimization problem shown in Return Link Capacity Maximization. Steps of Return Link Capacity Maximization are elaborated in Algorithm 1.

Algorithm 1. Return Link Capacity Maximization

Input:

1: P_{th}, R_{FL}, $h_{FL,min}$, h_{RL}, B_0, ε_{FL}, ε_P, ε_B, κ_{FL}, κ_{RL}, σ_{GW}^2, σ_{ST}^2, ϵ, and Δ ($\Delta > \epsilon$).

Initialization:

2: $t = 0$, $\beta_{FL}[0], \rho[0], \nu[0], \mu_{FL}[0], \mu_{RL}[0]$.

Iteration:

3: **while** $\Delta > \epsilon$ **do**

4: Compute $B_{FL}[t]$ according to equation (8);

5: Compute $P_{FL}[t]$ according to equations (7) and the newfound $B_{FL}[t]$ in Step 3;

6: Determine $B_{RL}[t]$ and $P_{RL}[t]$ following relations (8) and (7), respectively;

7: $t \leftarrow t + 1$, Update;

8: Calculate $\Delta = \mid \beta_{FL}[t] - \beta_{FL}[t-1] \mid + \mid \rho[t] - \rho[t-1] \mid + \mid \nu[t] - \nu[t-1] \mid + \mid \mu_{FL}[t] - \mu_{FL}[t-1] \mid$;

9: **end while**

IV. Performance Evaluation

In this section, simulations are performed to demonstrate the performance of our proposed finely-matched algorithm - FMA. The simulation setting is based on the VSAT satellite communication system, where practically a minimum transmission performance for forward link (from the satellite gateway to the user terminals) is required. We assume many earth terminals (users) with each earth terminal having multiple links (carriers) and limited in maximum effective isotropic radiated power (EIRP) for all links on that terminal.

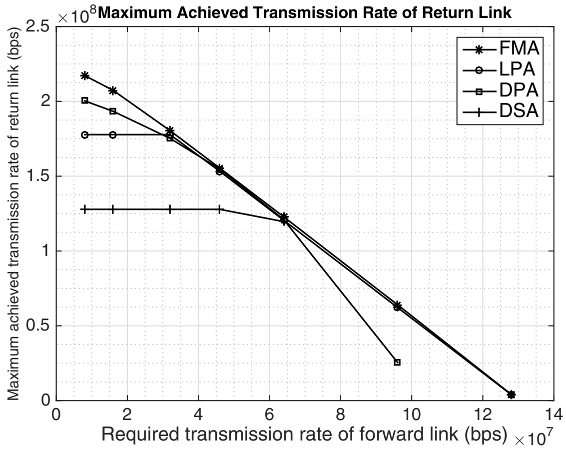


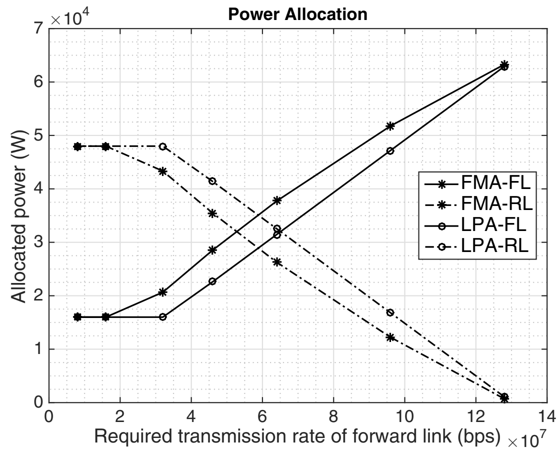
Figure 3. Maximum achieved transmission rate of return link.

The transponder has a total spectrum bandwidth of $B_0 = 32M$ bit and the maximum effective EIRP available is $P_{th} = 48dBW$ The channel gain in terms of path loss and rain attenuation of forward link is $h_{RL} = 3.7 \cdot 10^{-17}$ and of return link is $h_{RL} = 5.7 \cdot 10^{-16}$. The ground receive antenna gain for forward link is $G_{FL} = 45.46dBi$ and for return link is $G_{RL} = 61.32dBi$, with low-noise amplifier noise density N_{0FL} and N_{0RL}, respectively (Boltzmann's constant is $1.38 \times 10^{-23}W/(HzK)$). Minimum transmission power of downlink transmission is required for forward link and return link: $P_{FL,min} = 42dBW$ and $P_{RL,min} = 23dBW$, which guarantees the information signal detected from noise signal. The minimum required transmission rate of forward link varies from $16Mbps$ to $128Mbps$.

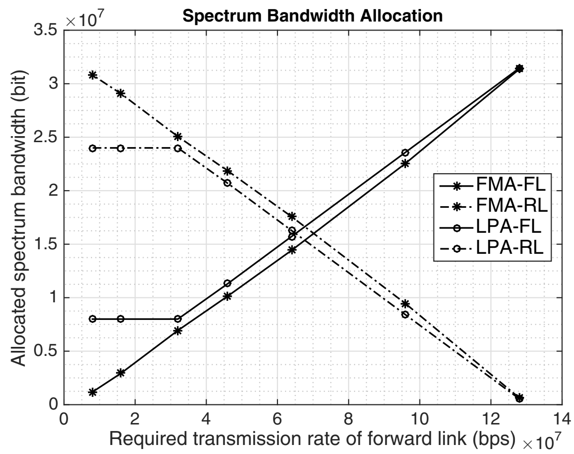
The proposed FMA is evaluated and compared with the following three resource allocation schemes:

- Linear proportional allocation algorithm (LPA) [9], which basically assume a linear operated transponder of bandwidth B_0 and with total linear power P_{th} to transmit all carriers (links) and all noise. The allocated spectrum and power will always follow the linear proportion, which makes the allocation easier and strait-forward. Typically, a linear operated transponder of bandwidth B_{th} and with total linear power P_{th} is assumed to transmit all carriers (links) and all noise.
- Dedicated power allocation scheme (DPA), which allocates the dedicated amount of power to different links and the allocation of spectrum bandwidth is flexible within the available constraint.
- Dedicated spectrum allocation scheme (DSA), which allocates the dedicated amount of spectrum bandwidth to different links according to pre-determined protocols, and the allocation of power is adjustable based on transmission requirement.

Figure 3 illustrates the maximum achievable transmission rate of return link with different minimum required transmission rate of forward link. With the increase of the required



(a) Power allocation



(b) Spectrum allocation

Figure 4. Power and spectrum allocation.

transmission rate of forward link, the achievable maximum transmission rate of return link decreases stably for all four schemes. This is attributed to the fact that the forward link and return link share the total available transponder resources (power and spectrum allocation). The proposed FMA achieves the highest maximum achievable transmission rate of return link, and this trend of superiority becomes even more remarkable as the required transmission rate decreases. FMA outperforms the other three schemes (LPA, DPA and DSA), The advantage of FMA allocation scheme is embodied in this two aspects: (i) FMA takes consideration of both power and spectrum bandwidth to make sure the most effective combination of resource allocation and make the best use of available resources. That is, even achieving the same utilization of resources, FMA receives the highest combination gain for link capacity. (ii) When it comes to the condition that the required transmission rate is too small that the accordingly required transmission power is lower than the signal-detective transmission power, the minimum transmission power will be allocated to achieve a lower transmission rate in all schemes.

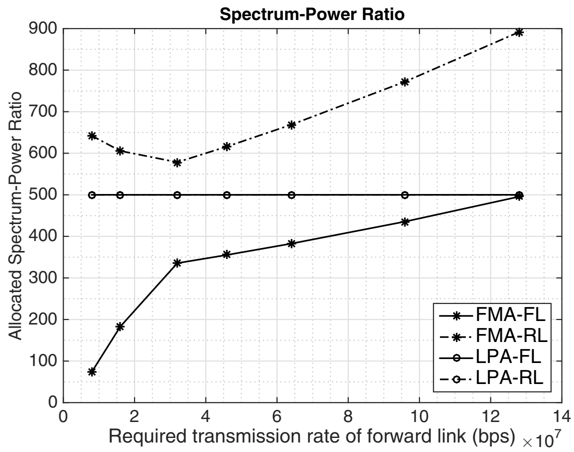


Figure 5. Allocated Spectrum-Power Ratio.

With regard to this minimum transmission power, FMA then allocate minimum required spectrum bandwidth to achieve the forward link requirement, and save the large remaining portion to return link. However, the traditional LPA will allocate proportional spectrum bandwidth for forward link, which causes profusion waste of spectrum resources. In this case, FMA achieves the highest utilization of resources and also combination gain of resource allocation.

Figure 4 shows allocation of both power and spectrum bandwidth. The results demonstrate stable performance trend of the resources allocation: the power and spectrum allocated to the forward link increase dramatically with the increase of minimum required transmission rate of forward link, and the remaining for return link drop accordingly. It is clear that as the forward link becomes the power stressing part, more and more power and spectrum bandwidth are allocated for the satisfaction of required forward transmission rate. As shown in Figure 4(a), the allocated power reaches the minimum transmission power requirement when required transmission rate drops. Figure 4(b) shows the differences of accordingly allocated spectrum bandwidth of the two schemes: LPA allocates the bandwidth proportional to allocated power instead of considering the actual required bandwidth; FMA allocates the spectrum bandwidth dynamically based on the actual demand for the required transmission rate - that is, the required spectrum bandwidth for forward link can be much less than that of return link. In general, Figure 4 show that FMA assign more spectrum bandwidth and much less power for return link than that of LPA.

Figure 5 depicts the ratio of allocated spectrum bandwidth and power. With traditional LPA, the forward link shares the same spectrum-power ratio with the return link, which trends to be stable with the increase of required forward transmission rate. To satisfy the transmission requirement, different spectrum-power ratio is achieved to obtain the maximum return link capacity in FMA. The spectrum-power ratio of return link aggregates faster than that of forward link. With the increase of minimum required transmission rate of forward link, the spectrum-power ratio of return link increases, with both power (Figure 4(a)) and spectrum bandwidth allocation (Figure 4(b)) decrease. That is, the power dropped more than that of spectrum decreases and it turns out the spectrum bandwidth contributes more aggressively to the link capacity. To conclude, achieving certain link capacity, less percent of bandwidth could be cost to release more power resource. As the required transmission rate rises too much (e.g. $128Mbps$ in this case), all the available resources need to be reserved for forward link, and the amount of allocated resources meet at the same points (Figure 4(a) and 4(b)), leading to the maximum transmission rate of return link reaches zero (Figure 3).

V. Conclusion

This paper proposes a dynamic resource allocation design at the smart transponder by jointly considering the power and spectrum bandwidth used for different links. The link capacity maximization problem is formulated and is solved by using the primal-dual method. Simulation results show that the proposed dynamic resource allocation design can obtain the performance gain, comparing to the linear proportional allocation and dedicated spectrum or power allocation schemes at the traditional transponder. Moreover, the proposed design at the smart transponder is more applicable to cope with the multiple-constrains satellite communication system in practice. The proposed scheme allocates limited transponder resources in a more flexible and adaptive way, obtaining the maximum resource utilization and achieving the maximum combination gain. The results are analyzed to explore the performance gain of different combined allocation of spectrum bandwidth and power resource, which may play a guiding role for the future design of satellite transponder.

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