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릴레이 주파수재사용을 위한 하향링크 전력 자원 할당

(Downlink Power Allocation for Relay Frequency Reuse)

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요 약

릴레이 간섭채널에서 하향링크 용량 극대화를 위한 전력할당 최적화 방안을 다룬다. 제 1 시간자원 영역에서 기지국은 단말과 릴레이 기지국에 직교채널을 통해서 전력전송을 한다. 제 2 시간자원 영역에서 기지국과 릴레이 기지국은 서로에게 간섭을 일으키면서 각각의 단말에게 전력을 전송한다. 본 논문에서 얻어진 전력 할당 최적화 방안은 제 2 시간자원 영역에서의 간섭 레벨이 낮을 경우, 기지국과 릴레이 기지국의 동시 전력전송을 허용하고, 반면에 간섭레벨이 높을 경우, 릴레이 기지국의 전력전송을 차단한다.

Abstract

We consider the optimum power allocation problem for downlink system throughput maximization in a 2 time slotted relay interference channel. Base station (BS) transmits power to Mobile Station (MS) and Relay Station (RS) in time slot 1 (orthogonal channel). In time slot 2, BS and RS transmit power to each MS, while causing cochannel interference to each other. The obtained optimum power allocation scheme allows simultaneous transmissions of BS and RS when the interference level in time slot 2 is low. However, when the interference level is high, RS shuts down its power. Numerical results are provided to support our analysis.

Keywords : Relay, Interference Channel, Power Allocation, Frequency Reuse

I. Introduction

Recently, research efforts have been focused on the issue of relay in cellular systems.^[1,3] Assuming half Duplex mode, relay operation requires additional resource. For example, IEEE Std 802.16j Relay Specification defined that the physical layer frame structure includes additional time zone for relay link^[2]. Due to additional resource expense, to get the true benefit from relay operation, resource reuse plays a role of throughput enhancement. This resource reuse includes simultaneous transmissions of

BS and RS on the same channel, while causing cochannel interference to each other.

In this contribution, we investigate the optimum power allocation problem for downlink throughput maximization. With the consideration of Relay frame structure defined in IEEE Std 802.16j Specification, we model 2-time slotted system. More specifically, in time slot 1, BS transmits power to MS1 and RS through the orthogonal channel. In time slot 2, through the interference channel, BS transmits power to MS1 and RS transmits power to MS2 in order to relay the data received from BS in time slot 1. By intuition, simultaneous transmission is preferred when the interference level is low. In this contribution, to validate th intuition, we propose the optimum

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transmission strategy to improve the throughput enhancement.

The obtained optimum power allocation scheme allows simultaneous transmissions when the interference level is below the specific level. On the other hand, when the interference level is beyond that level, the optimum strategy allows BS transmission only.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a single cell system with a BS and a RS as in Figure 1 where solid arrow and dotted arrow represent signal and interference, respectively. Figure 2 represent 2 time slot system with transmit power.

In time slot 1, BS with maximum power budget P_T allocates power to MS1(user 1) and RS(user 2), such that $p_1 + p_2 \leq P_T$ where p_m denotes the allocated power for user m . In time slot 2, BS and RS each with maximum power budget P_T allocates power to MS1(user 3) and MS2(user 4), respectively, such that $p_3 \leq P_T$ and $p_4 \leq P_T$.

The signal to interference ratio at the receiver side of user m is expressed as

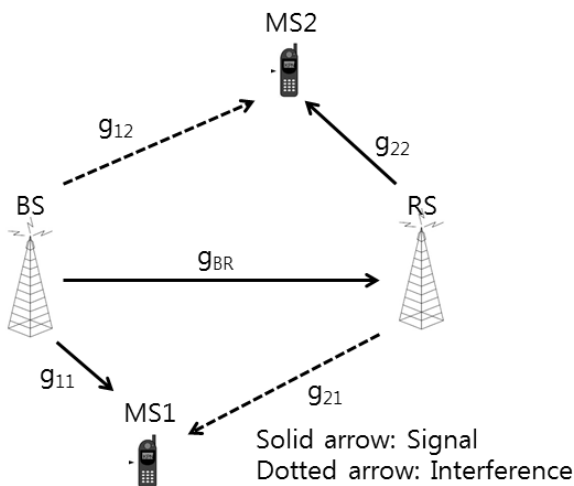


그림 1. 시스템 모델
Fig. 1. System Model with channel gain.

$$SIR_m = \frac{p_m g_{ii}}{p_n g_{ji} + I_m} \quad (1)$$

where g_{ii} denotes the channel gain from BS ($j = 1$) or RS ($j = 2$) to MS i .

We denote g_{BR} as channel gain from BS to RS.

I_m denotes the sum of the thermal noise and other interference for user m .

We define the utility of user m as follows:

$$U_m(p_m, p_n) = \log\left(1 + k \frac{p_m g_{ii}}{p_n g_{ji} + I_m}\right) \quad (2)$$

where \log denotes the natural logarithm.

Utility is the achievable rate. We denote the factor k , capturing the SNR gap, which is derived from the target bit error rate(BER), $k = \frac{-\ln(5BER)}{1.5}$ [4].

By the assumption of orthogonal channel in time slot 1, i.e.,

$$U_m(p_m, p_n = 0) = U_m(p_m) = \log\left(1 + k \frac{p_m g_{ii}}{I_m}\right),$$

sum of the individual utility for MS1 and RS is as follows:

$$\begin{aligned} J_1(p_1, p_2) &= U_1(p_1) + U_2(p_2) \\ &= \log\left(1 + k \frac{p_1 g_{11}}{I_1}\right) + \log\left(1 + k \frac{p_2 g_{BR}}{I_2}\right) \end{aligned} \quad (3)$$

In time slot 2, sum of the individual utility for MS1 and MS2, is as follows:

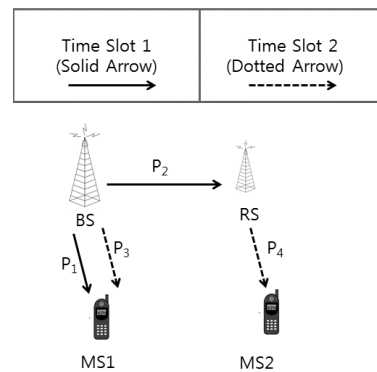


그림 2. 2 슬롯 시스템
Fig. 2. 2-time slot System.

$$\begin{aligned}
J_2(p_3, p_4) &= U_3(p_3, p_4) + U_4(p_4, p_3) \\
&= \log\left(1 + k \frac{p_3 g_{11}}{p_4 g_{21} + I_3}\right) + \log\left(1 + k \frac{p_4 g_{22}}{p_3 g_{12} + I_4}\right)
\end{aligned} \quad (4)$$

The system utility, i.e., sum of utilities for MS1 and MS2 in two time slot duration, is as follows:

$$\mathcal{J}(p_1, p_2, p_3, p_4) = U_1(p_1) + U_3(p_3, p_4) + U_4(p_4, p_3) \quad (5)$$

Note that $U_2(p_2)$ is not included in (5) because it is the utility to be relayed for the transmission in time slot 2.

Formally, the optimization problem is formulated as:

$$\max_{p_1, p_2, p_3, p_4} \mathcal{J}(p_1, p_2, p_3, p_4) \quad (6)$$

$$s.t. \quad U_2(p_2) \geq U_4(p_4, p_3) \quad (7)$$

$$s.t. \quad p_1 + p_2 \leq P_T, \quad p_1, p_2 \geq 0 \quad (8)$$

$$s.t. \quad 0 \leq p_3, p_4 \leq P_T \quad (9)$$

(7) implies that transmission rate of RS in time slot 2 can not exceed reception rate of RS in time slot 1.

In general, (6) is not convex, so it does not appear to be easy to solve.

III. OPTIMUM TRANSMIT STRATEGY AND POWER ALLOCATION

A. Time Slot Wide Approach

By examining the behavior of (3), (4) and (5) under constraints (7), (8) and (9), we observe that the followings hold.

Observation III.1.

Suppose $p^* = (p_1^*, p_2^*, p_3^*, p_4^*)$ is the optimum power allocation, then $p_1^* + p_2^* = P_T$ in time slot 1.

This is obvious. Because both $U_1(p_1)$ and $U_2(p_2)$ are increasing concave.

Proposition III.2

Suppose $p^* = (p_1^*, p_2^*, p_3^*, p_4^*)$ is the optimum power allocation, then $U_2(p_2^*) = U_4(p_4^*, p_3^*)$.

Proof:

Suppose $U_2(p_2^*) \geq U_4(p_4^*, p_3^*)$. Consider another power allocation in time slot 1, i.e., $(p_1^* + \delta, p_2^* - \delta)$ where $\delta > 0$, such that $U_2(p_2^* - \delta) = U_4(p_4^*, p_3^*)$.

By noting that $U_1(p_1^* + \delta) > U_1(p_1^*)$ $J(p_1^* + \delta, p_2^* - \delta, p_3^*, p_4^*) > J(p_1^*, p_2^*, p_3^*, p_4^*)$ which contradicts p^* is the optimum power allocation.

Proposition III.2 implies that RS should relay (or transmit) all the received data received from BS in the optimum transmission strategy.

Proposition III.3

Suppose $p^* = (p_1^*, p_2^*, p_3^*, p_4^*)$ is the optimum power allocation. Then, either $p_3^* = P_T$ or $p_4^* = P_T$ holds in time slot 2. More specifically,

$$p_3^* = P_T \quad \text{when } A < A_{mp} \quad (\text{i.e. } p_2^* < p_2^{mp}) \quad (10)$$

$$p_4^* = P_T \quad \text{when } A > A_{mp} \quad (\text{i.e. } p_2^* > p_2^{mp}) \quad (11)$$

where $A = \frac{p_2^* g_{BR}}{I_2}$ and $A_{mp} = \frac{P_T g_{22}}{I_4 + P_T g_{12}}$ are SIRs of $U_2(p_2^*)$ and $U_4(P_T, P_T)$, respectively, and $p_2^{mp} = \frac{I_2}{g_{BR}} A_{mp}$.

proof:

From the fact that $J_2(\alpha p_3, \alpha p_4) > J_2(p_3, p_4)$ for $\alpha > 1$, $J_2(p_3, p_4)$ can be increased until either $p_3 = P_T$ or $p_4 = P_T$ meets. More specifically, by

Proposition (III.2), $A = \frac{P_T g_{22}}{I_4 + p_3^* g_{12}}$ holds.

Case-I: Consider the case of $A < A_{mp}$, i.e.,

$$\frac{p_4^* g_{22}}{I_4 + p_3^* g_{12}} < A_{mp}.$$

Suppose the optimum solution is such that $p_4^* = P_T$.

$$\text{Then, } \frac{P_T g_{22}}{I_4 + p_3^* g_{12}} < \frac{P_T g_{22}}{I_4 + P_T g_{12}}.$$

This means $p_3^* > P_T$, i.e., p_3^* exceeds maximum power budget.

Hence, $p_4^* \neq P_T$. That is, $p_4^* = P_T$ for the case of $A < A_{mp}$.

Case-II: Similarly, consider the case of $A > A_{mp}$, i.e., $\frac{p_4^* g_{22}}{I_4 + p_3^* g_{12}} > A_{mp}$. Suppose the optimum solution

is such that $p_3^* = P_T$. Then,

$$\frac{p_4^* g_{22}}{I_4 + P_T g_{12}} > \frac{P_T g_{22}}{I_4 + P_T g_{12}}.$$

This means $p_4^* > P_T$, i.e., p_4^* exceeds maximum power budget.

Hence, $p_3^* \neq P_T$. That is $p_3^* = P_T$ for the case of $A > A_{mp}$.

By Proposition III.3, (6) can be factored by two in terms of p_2 , (i.e., $p_2 < p_2^{mp}$ and $p_2 > p_2^{mp}$) as described in the next section.

In Proposition III.3, A implies SIR at RS (where the BS's transmit power level is p_2^*) in time slot 1. A_{mp} means SIR at MS2 (where the BS's and RS's transmit power levels are P_T) in time slot 2. Proposition III.3 implies that the optimum transmit power level can be obtained by simply comparing A and A_{mp} .

B. System Wide Approach

Let us write the system utility, J , in terms of allocated power for user 2, i.e., p_2 after replacing $U_4(p_4, p_3)$ by $U_2(p_2)$ and taking log out as

following:

$$\max (1 + k \frac{(P_T - p_2) g_{11}}{I_1}) (1 + k \frac{p_2 g_{BR}}{I_2}) (1 + k \frac{P_T g_{11}}{I_3 + T p_2 g_{21}}) \quad (12)$$

$$s.t. \quad 0 \leq p_2 \leq \min(P_T, p_2^{mp}) \quad (13)$$

$$\max (1 + k \frac{(P_T - p_2) g_{11}}{I_1}) (1 + k \frac{p_2 g_{BR}}{I_2}) (1 + k \frac{(\frac{X}{I_3} - Y) g_{11}}{I_3 + P_T g_{21}}) \quad (14)$$

$$s.t. \quad \min(P_T, p_2^{mp}) \leq p_2 \leq P_T \quad (15)$$

where $T = \frac{g_{BR}}{I_2} \frac{I_4 + P_T g_{12}}{g_{22}}$, $X = \frac{P_T g_{22} I_2}{g_{12} g_{BR}}$, and

$Y = \frac{I_4}{g_{12}}$. (12) is derived from the case of $p_2^* < p_2^{mp}$ in

proposition (III.3). In this case,

$$U_3(p_3, p_4) = \log(1 + k \frac{P_T g_{11}}{I_3 + p_4 g_{21}}) = \log(1 + k \frac{P_T g_{11}}{I_3 + T p_2 g_{21}}).$$

Similarly, (14) is derived from the case of $p_2^* > p_2^{mp}$ in

proposition (III.3). In this case,

$$U_3(p_3, p_4) = \log(1 + k \frac{p_3 g_{11}}{I_3 + P_T g_{21}}) = \log(1 + k \frac{(\frac{X}{I_3} - Y) g_{11}}{I_3 + P_T g_{21}}).$$

When $\min(P_T, p_2^{mp}) = P_T$, the optimum power

allocation is obtained by solving only (12). Otherwise,

(14) also should be solved. In order to find the

optimum power allocation, we should search over all

possible boundary points ($p_2 = 0$, $p_2 = \min(P_T, p_2^{mp})$,

and $p_2 = P_T$) and extreme points $\frac{\partial J}{\partial p_2} = 0$ for each

case, i.e., (12) and (14). The derivative of J is

$$\frac{\partial J}{\partial p_2} = \frac{A p_2^3 + B p_2^2 + C p_2 + D}{E} \quad (16)$$

Since E is always positive, $\frac{\partial J}{\partial p_2} = 0$ is equivalent

to $A p_2^3 + B p_2^2 + C p_2 + D = 0$. Let p_2^{E1} be the

extreme point for $(0 \leq p_2 \leq \min(P_T, p_2^{mp}))$ and let p_2^{E1} be the extreme point for $\min(P_T, p_2^{mp}) \leq p_2 \leq P_T$.

By comparing the system utility of (12) and (14) for each extreme point and boundary point and selecting the largest, the optimum power allocation can be obtained.

More specifically, the optimum power allocation is as following:

$$\begin{aligned} p_1^* &= P_T - p_2^*, p_3^* = P_T, p_4^* = T p_2^* \quad \text{when } p_2^* < p_2^{mp} \\ p_1^* &= P_T - p_2^*, p_3^* = X p_2^* - Y, p_4^* = P_T \quad \text{when } p_2^* > p_2^{mp} \end{aligned} \quad (17)$$

IV. NUMERICAL RESULT

As Figure 3, distance between BS and RS is 700m and the distance between BS and MS1 is 200m. Channel gain is modeled as $g_{ij} = \frac{1}{d_{ij}^\alpha}$ where d_{ij} denotes the distance. $P_T = 10$ WATTS. $I_1 = I_2 = I_3 = I_4 = 10^{-13}$ WATTS. Factor k is 0.5. Figure 4 compares the system utility of different power allocation schemes i.e., Optimum scheme in (17), TDM scheme, and Fixed power scheme for a range of distance between RS and MS2. IN and OUT indicate that MS1 is on the righthand side and on the lefthand side from the BS, respectively. OPT, TDM, and FIX denote Optimum Scheme, TDM Scheme, Fixed Power Scheme, respectively. In TDM scheme, BS transmits full power, P_T in a round robin fashion to MS1 and MS2 through time slot 1 and time slot 2, i.e. no Relay. In Fixed power scheme, equal power is assigned to MS1 and RS in time slot 1. In time slot 2, each BS and RS transmits full power P_T to MS1 and MS2, respectively.

Two scenarios are investigated with the consideration of MS1's location. In other words, one scenario is the case when MS1 is located in the lefthand side of BS. In this case, MS1 receives weak cochannel from RS.

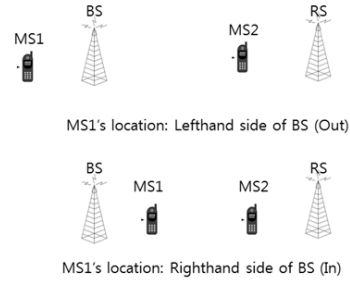


그림 3. 2 가지 시나리오

Fig. 3. 2 Scenarios.

Thus, the optimum power allocation of user 2, p_2^* is $[1.9, 10, 10, 10, 10, 10]$.

The other scenario is the case when MS1 is located in the righthand side of BS. In this case, MS1 receives relatively strong interference from RS. Thus, the optimum power allocation of user 2, i.e., p_2^* is $[0.3, 0, 0, 0, 0, 0]$ for a range of MS2's distance.

Optimum scheme shows significant gain in system utility, while sacrificing fairness. Note that when $p_2 = 0$, MS2 is not supported. For Optimum scheme and Fixed power scheme, the scenario of left hand side, thanks to low cochannel interference, shows higher system utility than that of righthand side. For TDM scheme, where no cochannel interference exists, both scenarios have identical system utility.

V. CONCLUSION

We have characterized the optimum power allocation policy for downlink throughput maximization on the relay enabled 2 time slotted system. More specifically, we took the approach of examining the system utility in terms of allocated power for RS.

The optimum policy shows that when the interference level is below the specific level in time slot 2, simultaneous transmissions from BS and RS are preferred. On the other hand, when the interference level is strong, single transmission is preferred. Conceptually, the philosophy of the obtained strategy is in line with Fractional Frequency

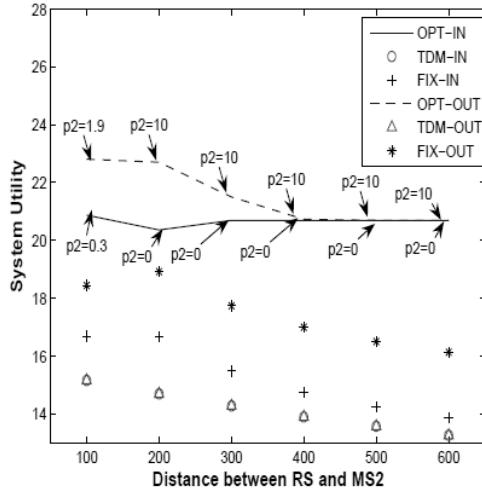


그림 4. 거리에 따른 시스템 유틸리티
Fig. 4. System Utility versus Distance

Reuse(FFR) in WiMAX and LTE.^[5-6]

Numerical results have verified the benefit of the optimum policy over fixed power scheme and TDM scheme.

VI. APPENDIX

The coefficients of $Ap_2^3 + Bp_2^2 + Cp_2 + D = 0$ for (12) are given as follows:

$$A = -2k^2 Tg_{11}g_{BR}g_{21} \quad (18)$$

$$B = Tg_{21}(-4k^2g_{11}g_{BR}I_3 - kTg_{11}g_{21}I_2 - k^3g_{11}^2g_{BR}P_T + kTg_{21}g_{BR}I_1 + k^2Tg_{21}g_{11}g_{BR}P_T)$$

$$C = I_3[-kg_{11}(I_2Tg_{21} + kg_{BR}(I_3 + kP_Tg_{11})) + kg_{BR}((I_1 + kP_Tg_{11})Tg_{21} - kg_{11}(I_3 + kP_Tg_{11})) + Tg_{21}((I_1 + kP_Tg_{11})kg_{BR} - kg_{11}I_2)]$$

$$D = [-kg_{11}I_2(I_3 + kP_Tg_{11}) + kg_{BR}(I_1 + kP_Tg_{11})(I_3 + kP_Tg_{11}) + kg_{21}(I_1 + kP_Tg_{11})I_2]I_3 - Tg_{21}(I_1 + kP_Tg_{11})I_2(I_3 + kP_Tg_{11})$$

$$E = I_1I_2(I_3 + Tp_2g_{21})^2$$

The coefficients of $Ap_2^3 + Bp_2^2 + Cp_2 + D = 0$ for (14) are given as follows:

$$A = -4(1-B)k^2g_{11}g_{BR}$$

$$B = -k^2g_{11}g_{BR}A + kg_{BR}(I_1 + kP_Tg_{11})(1-B) - (1-B)kg_{11}I_2$$

$$C = 0$$

$$D = -(I_1 + kP_Tg_{11})I_2A$$

$$E = I_1I_2p_2^2$$

$$\text{where } A = \frac{Xkg_{11}}{I_3 + P_Tg_{21}} \text{ and } B = \frac{Ykg_{11}}{I_3 + P_Tg_{21}}.$$

Regarding derivation of T , from the fact that $U_2(p_2) = U_4(p_4, p_3)$ and $p_3 = P_T$ by proposition

$$(III.2) \text{ and } (III.3), \frac{p_2g_{BR}}{I_2} = \frac{p_4g_{22}}{I_4 + P_Tg_{12}} \text{ holds.}$$

$$\text{This leads to } p_4 = \frac{g_{BR}}{I_2} \frac{I_4 + P_Tg_{12}}{g_{22}} p_2 = Tp_2.$$

Regarding derivation of X and Y , from the fact that $U_2(p_2) = U_4(p_4, p_3)$ and $p_4 = P_T$ by Proposition

$$(III.2) \text{ and } (III.3), \frac{p_2g_{BR}}{I_2} = \frac{P_Tg_{22}}{I_4 + p_3g_{12}} \text{ holds. This}$$

$$\text{leads to } p_3 = \frac{P_Tg_{22}I_2}{g_{12}g_{BR}p_2} - \frac{I_4}{g_{12}} = \frac{X}{p_2} - Y.$$

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