

Impact of Concurrent Transmissions on Downstream Throughput in Multi-hop Cellular Networks

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Abstract—In this paper, we investigate the impacts of transmission concurrency on the throughput of the downstream channel in multi-hop cellular networks. In particular, this paper focuses on the tradeoff between the improvement of resource reuse and the increase in radio interference. We evaluate and compare the throughput for various concurrency types of multi-hop relaying. We also propose a hybrid control strategy, in which we advocate the use of both, the concurrent and the non-concurrent transmissions. Our results show that the throughput can be increased by allowing transmission concurrency, but the concurrency does not always result in higher throughput, relative to the non-concurrency case, because of the interference between concurrently transmitting links. In the random topology with shadowing, depending on the particular circumstances, either the concurrent or the non-concurrent case can be the optimal transmission strategy. Thus, in order to achieve a significant improvement, a hybrid scheme should be employed. Additionally, if concurrency is applied, it should be used among the different downstream paths, rather than between the hops on the same downstream path.

I. INTRODUCTION

Multi-hop cellular networks have been proposed as an extension to the conventional single-hop cellular network by combining the fixed cellular infrastructure with the multi-hop relaying technology, usually used in ad-hoc networks. Through the use of the multi-hop relaying, more favorable path than a direct single-hop link can be utilized between a base station (BS) and a mobile station (MS), so that the system capacity can be considerably enhanced [1].

One way to increase the capacity of the multi-hop systems is to allow concurrency among the multi-hop transmissions. Such concurrency can improve the channel reuse efficiency, but also leads to an increase in the interference. Toumpis and Goldsmith [2] showed that the concurrent transmission can enhance the system capacity in multi-hop cellular networks. However, their results were obtained for a single cell system and also for just two cases of network topology, i.e. a linear topology and a single realization of a random topology. Hence, those results are insufficient to demonstrate, in general,

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the concurrency tradeoff between the interference and the channel reuse efficiency. Moreover, several studies reported that it is not easy to enhance the capacity of code division multiple access (CDMA) systems by the use of the multi-hop relaying [3]–[7]. This is mainly due to the interference increase resulting from by the concurrent transmissions. Since such interference might be the most significant factor limiting the network capacity, the concurrent transmission should be comprehensively studied and cautiously applied.

In this paper, we investigate the impact of concurrent transmissions on the throughput in the multi-hop cellular networks. The concurrency of interest in this work is classified into two types: The concurrency among the different hops along the path to one target MS, which is referred to as *type A concurrency*; the other type is the concurrency among the hops on the different downstream paths for multiple target MSs, which is referred to as *type B concurrency*. Our previous work [1] showed that the *type A concurrency* can increase the throughput, but such an increase is rather small. In this paper, we extend our investigation to the *type B concurrency*, and compare the performance of these two concurrency types. We also propose a hybrid control scheme in which both, the concurrent and the non-concurrent transmissions, can be used, depending on the particular circumstances.

This paper focuses on the best-effort (delay-tolerant) type of service in the downstream direction, from a BS to a target MS. Since the nature of data traffic for most services on the Internet is asymmetric, efficient utilization of resource on the downlink is becoming more and more important. For this reason, recently standardized systems, which is evolved from the third-generation (3G) mobile communication systems, aim at supporting high data rate packet services on the downlink, e.g., the 1xEV-DO system [8] and the HSDPA system [9]. In the next section, we describe our system model. The *throughput gain* for each concurrency type is derived in Section III, while the numerical results are presented and compared in Section IV. In Section V, we discuss the impact of the concurrency on the capacity of the conventional power-controlled CDMA systems. Finally, we draw some conclusions in Section VI.

II. SYSTEM MODEL

Let us consider a cellular system where a number of BSs are placed according to a hexagonal grid pattern. Every MS in

the system is assumed to be capable of multi-hop relaying. We also assume a fully loaded system and an infinite buffers at the network nodes. The upstream and the downstream channels are assumed to work independently. The downstream transmission may involve multiple relaying MS-s, in which case packets are relayed between neighboring MS-s on the same downstream path through the use of time division duplex (TDD), as in [10]. The channels assigned to each cell share the same frequency spectrum by CDMA. Time division multiplexing (TDM) is selected for multiplexing downstream channels at the BS; i.e., each BS provides one downstream channel to one target MS at a time.¹

In our system, rate control is utilized based on the channel condition, as in the 1xEV-DO system and the HSDPA systems.² The transmission power P is fixed, and the data rate assigned to each link R is determined by the signal to interference and noise ratio (SINR). *Shannon* capacity formula is then used in the rate control model to evaluate the network capacity [2]:

$$R = W \log_2 (1 + \text{SINR}) , \quad (1)$$

where W is the channel bandwidth and SINR at the receiver of the transmission from node i is given by:

$$\text{SINR} = \frac{L_i P_i}{\sum_{j \in \mathcal{J}, j \neq i} L_j P_j} , \quad (2)$$

where the subscript j denotes the a transmitting node (BS or MS) and \mathcal{J} is the set of transmitting nodes at a given time. In this paper, the interference limited scenario is considered, and so the contribution of the thermal noise to the SINR is neglected. In (2), L_i denotes the link gain, so that at distance d_i from the node i , it can be represented as:

$$L_i = A \cdot d_i^{-\gamma} \cdot 10^{\zeta_i/10} , \quad (3)$$

where A is a constant, γ is the path loss exponent, and ζ_i is the shadowing random variable.

III. THROUGHPUT GAIN

The downstream throughput can be calculated as the *effective data rate* on the direct link or on the multi-hop path between BS and the target MS. We define the *decision parameter* and the *throughput gain* based on this effective data rate.

A. Simple Relaying without Concurrency

We first consider the case of *simple relaying*, in which only one downstream channel for a target MS is provided in each cell at any time. Let us assume that a time period for data transmission T is assigned to the target MS. In the conventional system, the effective data rate is identical to the

¹In multi-rate CDMA systems, packet traffic channels can be assigned in a code division multiplexing (CDM) or TDM fashion; e.g., TDM is used in the 1xEV-DO system, and TDM and/or CDM in HSDPA system.

²For the best effort type data services, the rate control is preferable to the power control, because in the rate control scheme high SINR available over a large portion of the cell area can be exploited to provide higher data rate by the rate control.

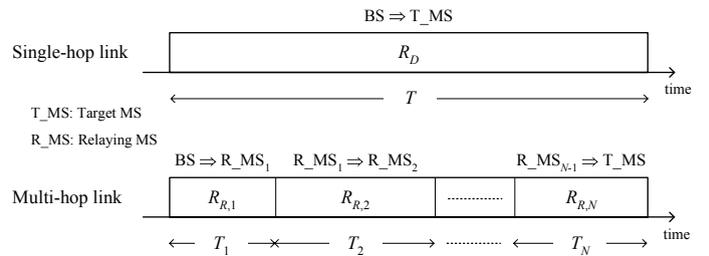


Fig. 1. Transmission data rates in single-hop and multi-hop transmission

data rate of the direct single-hop link, R_D . Let U_R be the effective data rate of the relaying path comprised of multi-hop links. Each hop is assigned the downstream channel for a short time duration, as shown in Fig. 1. We assume that the relaying MS-s act as forwarders only during T . Hence the transmitted amount of data for each time slot should be identical for all the nodes on the relaying path³; i.e.,

$$T_1 R_{R,1} = T_2 R_{R,2} = \dots = T_N R_{R,N} , \quad (4)$$

where $R_{R,n}$ denotes the data rate on the n -th hop of the relaying path ($n = 1, \dots, N$), and N is the number of hops. Then U_R can be given by the number of effective transmitted bits per T , and the *decision parameter* D can be defined as the ratio of the two effective data rates, the effective data rate in the multi-hop system to the effective data rate in the conventional system [1]:

$$D \equiv \frac{U_R}{R_D} = \frac{T_N R_{R,N}}{T} \cdot \frac{1}{R_D} = \frac{1}{\sum_{n=1}^N R_D / R_{R,n}} . \quad (5)$$

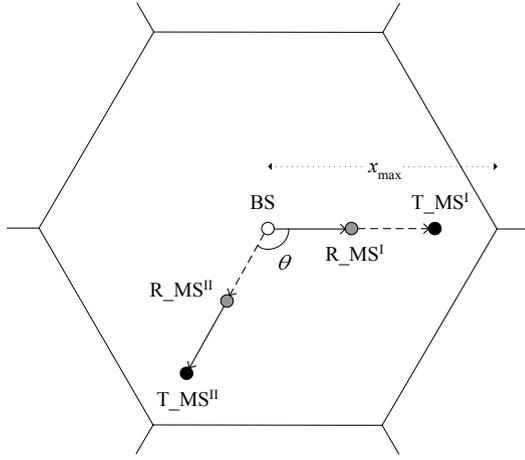
Note that in our network model, either the direct link or the multi-hop path can be selected, whichever case provides higher throughput. That is, the multi-hop path is selected if $D > 1$; otherwise, the direct link is selected. Then the *throughput gain*, G , in a network that uses such a hybrid scheme can be defined as the ratio of throughput of the most favorable case (the direct link or the multi-hop path) to that of the direct link. Therefore,

$$G \equiv \begin{cases} D & \text{if } D > 1 \\ 1 & \text{otherwise} \end{cases} . \quad (6)$$

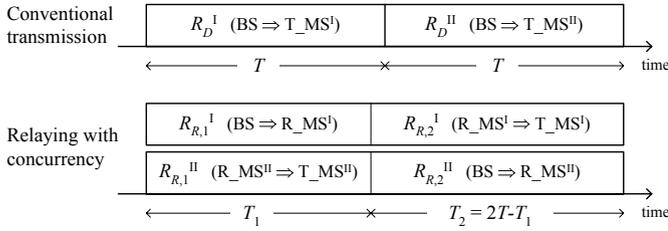
B. Type A Concurrency

In the case of the *type A concurrency*, while only one target MS is provided with a downstream channel at a time, the concurrent transmissions on this channel are allowed on the different hops of the path. Each concurrent transmission uses the distinct spreading code. Note that even though the concurrency occurs, all the transmitted data during T is for one target mobile MS. Hence, the transmitted amount of data in each time slot is limited by the hop whose data rate is the minimum among the multiple concurrent hops. It also should

³In this paper the time slot means a *logical time slot* which has a variable length.



(a) Topology



(b) Transmission timing

Fig. 2. Illustration of the *type B concurrency*.

be equal to the transmitted amount of data in the other time slots. So, as in (4),

$$T_1 \cdot \min_{n \in \mathcal{T}_1} \{R_{R,n}\} = \dots = T_M \cdot \min_{n \in \mathcal{T}_M} \{R_{R,n}\}, \quad (7)$$

where \mathcal{T}_m is the set of the hops sharing the m -th time slot, and M ($2 \leq M \leq N$) is the number of time slots during T . Then U_R can be represented by:

$$U_R = \frac{1}{1/\min_{n \in \mathcal{T}_1} \{R_{R,n}\} + \dots + 1/\min_{n \in \mathcal{T}_M} \{R_{R,n}\}}. \quad (8)$$

We use the same selection criterion for the multi-hop path as applied in the case of the *simple relaying* and the same definition for of the metrics; i.e., $D \equiv U_R/R_D$ and $G \equiv \max\{D, 1\}$.

C. Type B Concurrency

With the *type B concurrency*, the different downstream paths for multiple target MS-s can share time slots. For simplicity, we consider two downstream paths (for two target MS-s) with 2-hop paths.

The multi-hop relaying with the *type B concurrency* is illustrated in Fig. 2, where the superscript I and II denote each target MS. Since the relaying MS-s act as forwarders only during $2T$, the transmitted amounts during T_1 and T_2 should

be the same, i.e., $T_1 R_{R,1}^I = T_2 R_{R,2}^I$ and $T_1 R_{R,1}^{II} = T_2 R_{R,2}^{II}$. However, $R_{R,1}^I/R_{R,2}^I$ is generally not equal to $R_{R,1}^{II}/R_{R,2}^{II}$. Thus the two equations cannot be satisfied simultaneously with the same time division of the two paths. Rather, we should assign different time division to each one of the two paths, so that for both channels the transmitted amounts on the first hop is equal to that on the second hop.

We illustrate the transmission timing with the different time division of each path, in Fig. 3. According to the length of T^I and T^{II} , the applied time division is divided into 2 cases. We first consider the case of $T^I \leq T^{II}$. From Fig. 3 (a), we can formulate the following set of equations:

$$R_{R,1}^I T^I = (T^{II} - T^I) R_{R,2}^I + (2T - T^{II}) R_{R,3}^I, \quad (9)$$

$$R_{R,1}^{II} T^I + (T^{II} - T^I) R_{R,2}^{II} = (2T - T^{II}) R_{R,3}^{II}. \quad (10)$$

Solving the these two equations for T^I and T^{II} , and we obtain:

$$T^I = \frac{(R_{R,2}^{II} R_{R,3}^I + R_{R,2}^I R_{R,3}^{II}) 2T}{C_a}, \quad (11)$$

$$T^{II} = \frac{[(R_{R,2}^{II} - R_{R,1}^{II}) R_{R,3}^I + (R_{R,2}^I - R_{R,1}^I) R_{R,3}^{II}] 2T}{C_a}, \quad (12)$$

where

$$C_a \equiv (R_{R,1}^I + R_{R,2}^I)(R_{R,2}^{II} + R_{R,3}^{II}) - (R_{R,3}^I - R_{R,2}^I)(R_{R,1}^{II} - R_{R,2}^{II}). \quad (13)$$

Hence, the effective data rates during $2T$ for the two multi-hop paths are given by:

$$U_R^I = \frac{T^I R_{R,1}^I}{2T} = \frac{(R_{R,3}^I R_{R,2}^{II} + R_{R,2}^I R_{R,3}^{II}) R_{R,1}^I}{C_a}, \quad (14)$$

$$U_R^{II} = \frac{(2T - T^{II}) R_{R,3}^{II}}{2T} = \frac{(R_{R,1}^I R_{R,2}^{II} + R_{R,1}^I R_{R,2}^{II}) R_{R,3}^{II}}{C_a}. \quad (15)$$

Now let us proceed with the case of $T^I > T^{II}$, which is illustrated in Fig. 3 (b). As in (9) and (10), by formulating a set of equations, we obtain the following solution:

$$T^I = \frac{[(R_{R,1}^{II} + R_{R,2}^{II}) R_{R,3}^I - (R_{R,1}^I - R_{R,2}^I) R_{R,3}^{II}] 2T}{C_b}, \quad (16)$$

$$T^{II} = \frac{(R_{R,3}^I R_{R,2}^{II} + R_{R,3}^I R_{R,2}^I) 2T}{C_b}, \quad (17)$$

where

$$C_b \equiv (R_{R,1}^{II} + R_{R,3}^{II}) R_{R,2}^I + (R_{R,1}^I + R_{R,3}^I) R_{R,2}^{II} + 2(R_{R,3}^I R_{R,2}^{II} - R_{R,3}^I R_{R,2}^I). \quad (18)$$

Hence the effective data rates are:

$$U_R^I = \frac{(2T - 2T^I + T^{II}) R_{R,3}^I}{2T} = \frac{(R_{R,1}^I R_{R,2}^{II} + R_{R,1}^I R_{R,2}^{II}) R_{R,3}^I}{C_b}, \quad (19)$$

$$U_R^{II} = \frac{T^{II} R_{R,1}^{II}}{2T} = \frac{(R_{R,3}^I R_{R,2}^{II} + R_{R,1}^I R_{R,2}^{II}) R_{R,1}^{II}}{C_b}. \quad (20)$$

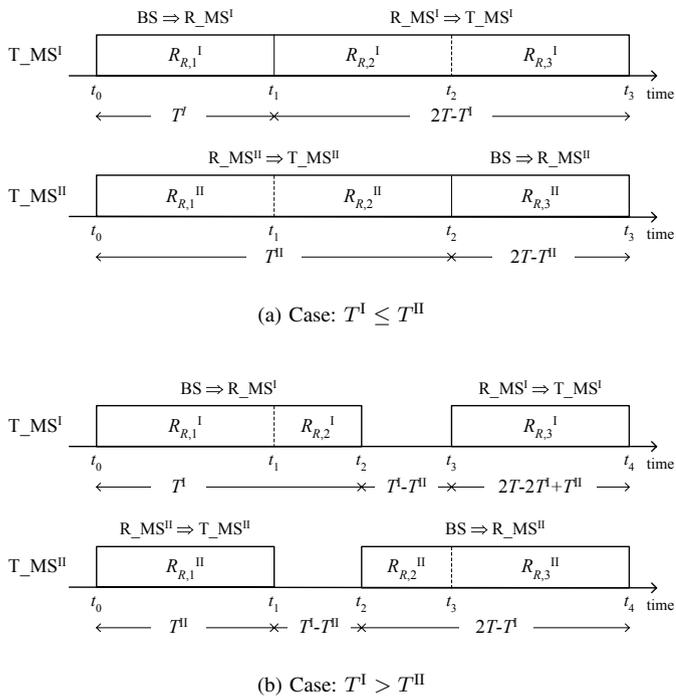


Fig. 3. Transmission timing for the *type B* concurrency.

The effective data rates for the direct link are given by $U_D^I \equiv R_D^I/2$ and $U_D^{II} \equiv R_D^{II}/2$. Unlike in the case of the *simple relaying* and in the case of the *type A* concurrency, the effective data rate now should be calculated as half of the data rate of the link. This is because for a fair comparison with the *type B* concurrency, the period assigned to the direct link should be regarded as $2T$.⁴

For the case of *type B* concurrency, we apply two different criteria for the selection of the multi-hop path. If the condition specified below is met, the multi-hop paths are selected for both target MS-s. Otherwise, the direct transmission is used.

- *Criterion 1*: If $U_R^I + U_R^{II} > U_D^I + U_D^{II}$, select the multi-hop paths.
- *Criterion 2*: If $U_R^I > U_D^I$ and $U_R^{II} > U_D^{II}$, select the multi-hop paths.

For both criteria, *throughput gain* can be represented by:

$$G \equiv \begin{cases} (D^I + D^{II})/2 & \text{if the multi-hop paths are selected} \\ 1 & \text{otherwise} \end{cases}. \quad (21)$$

where $D^I \equiv U_R^I/U_D^I$ and $D^{II} \equiv U_R^{II}/U_D^{II}$.

IV. PERFORMANCE ANALYSIS

We investigate here the impact of the *type B* concurrency on the downstream throughput. The system model for the performance evaluation is comprised of 19 cells. The hexagonal cell

⁴Recall that in the case of the *type B* concurrency both downstream channels share the whole period of $2T$, but in the case of the direct transmission each downstream channel exploits relatively only half duration of $2T$, i.e. T .

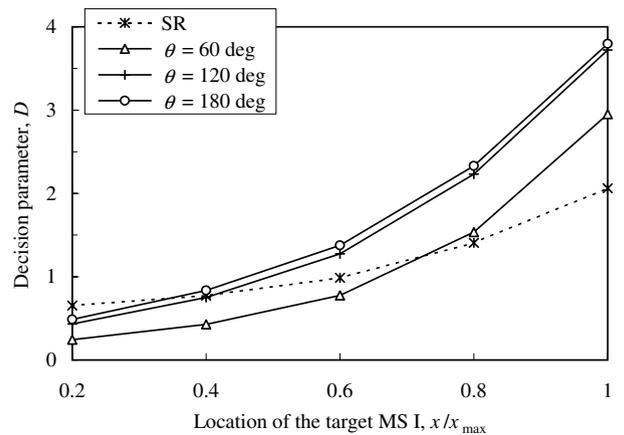


Fig. 4. the *decision parameter* for linear topology and no shadowing.

radius x_{max} is 500 m. The ratio of the transmission powers of a BS and a MS is set to 4, and the path loss exponent γ is assumed to be 4. The shadowing in dB, ζ , follows the *Gaussian* distribution with zero mean and standard deviation $\sigma = 10$ dB. Both auto-correlation and cross-correlation are applied to the shadowing variables of links between a BS and an MS [1]. We also assume that the shadowing between MS-to-MS links or between an MS-to-MS and a BS-to-MS links are all independent one from another.

A *Monte Carlo* computer simulation has been developed to evaluate the performance of the relaying schemes. For simplicity, the multi-hop relaying is employed only in the center cell. In the other cells, the direct transmission mode is assumed. The simulation collects statistical data from the center cell.

A. Performance for Linear Topology

In this section, we study the impact of the spatial separation of concurrent links, while varying the location of the two target MS-s. We place the target MS I at the given position $(x, y = 0)$ in *Cartesian* coordinates with respect to the center cell site, as shown in Fig. 2 (a). The target MS II is placed at $(x \cdot \cos \theta, -x \cdot \sin \theta)$, so that the two MS-s are separated by the angle θ . Each relaying MS is placed at the midway point between the BS and the target MS.

We first consider this case without shadowing. Fig. 4 shows the value of D for *type B* concurrency for various locations of the target MS-s. The result for the *simple relaying* with 2-hop path is also shown in the figure and is denoted by *SR*. Note that by symmetry, $U_R^I = U_R^{II}$ and $U_D^I = U_D^{II}$, and so the *criterion 1* and *2* result in the same decision. The results show that D increases with the separation θ , as expected. However, we can see that, in some cases, the concurrency may not provide a gain over *simple relaying*. In particular, when $\theta = 60$ deg, the *simple relaying* outperforms the concurrency except at the cell boundary. Hence, the results in this figure confirm that if the concurrent links are closed to each other, the concurrency should not be used.

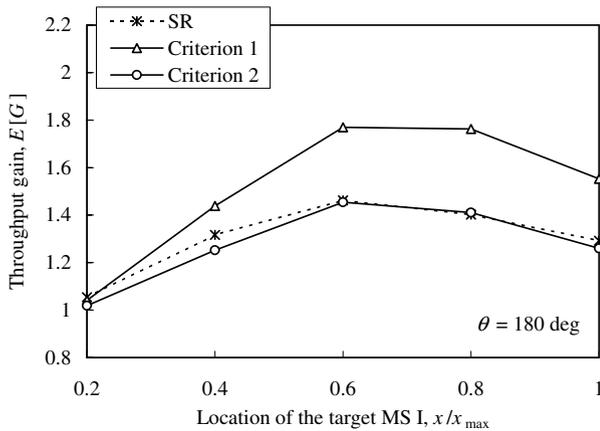


Fig. 5. The *throughput gain* for linear topology with shadowing.

We now continue our evaluation by incorporating shadowing into our system. Fig. 5 shows the results of G for the shadowed environment. Note that G is now a random variable due to the stochastic nature of the shadowing process, so we consider the expected value of G , $E[G]$. These results were calculated for $\theta = 180$ deg. We can see here that $E[G]$ can be increased by concurrency with the *criterion 1*. However, since this criterion is based on the calculation of the total throughput, the throughput of one of the two target MS's throughputs may be lower than that with the conventional direct transmission, while the sum of the two throughputs is higher. In order to avoid the throughput decrease for any of the two target MS-s, the *criterion 1* should be replaced by the *criterion 2*. However, we note that, since the *criterion 2* is more stringent in selecting the multi-hop path case, the performance of the *criterion 2* is worse than that of the *criterion 1*, as shown in the figure. Nevertheless, the *criterion 2* should be employed in order to ensure the superiority of the relaying system over the conventional system at any time.

The fact that the $E[G]$ with the *criterion 2* is not higher than that with the *simple relaying*, as shown in Fig. 5, is due to the flexibility in the path selection in the case of the *simple relaying*. The *type B concurrency* provides only two options such that, whether the multi-hop path or direct link is chosen, this choice is assigned to both target MS-s. On the other hand, with *simple relaying*, we can select and utilize the multi-hop path for *each* target MS individually. Such freedom of the path selection can lead to higher *throughput gain* than the concurrency.

From the the results above, one can expect that a hybrid scheme of the *criterion 2* and the *simple relaying* will exploit both the concurrency and the flexible path selection. Besides, since the throughput improvement by concurrency is highly dependent on the separation of the concurrent links, the concurrency cannot always ensure a higher throughput gain than in the non-concurrent case. For a severe interference environment, the *simple relaying* would be a better choice. Therefore, we conclude that a hybrid scheme would provide better overall performance.

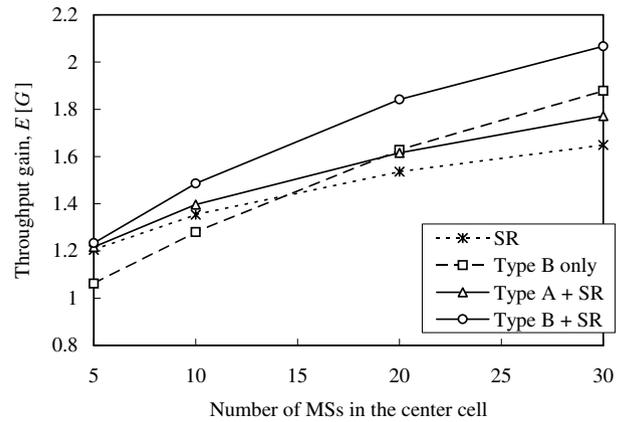


Fig. 6. Performance comparison of the concurrency in random topology.

Unlike the results in Fig. 4, in Fig. 5, we can see that $E[G]$ decreases at the cell boundary. This is due to the effect of the *best BS selection*. For detailed explanation of such this effect, the reader is referred to our previous work [1].

B. Performance Comparison in Random Topology

We present and compare the performances of various relaying schemes in random topology with shadowing. A number of MS-s which are capable of relaying and the target MS-s are assumed to be uniformly distributed over the cell area. We find the best path for each target MS, one with the maximum throughput.

In the hybrid control of the *type B concurrency* and the *simple relaying*, we compare the three effective data rates for each target MS: of the direct single-hop link, of the multi-hop path with the *simple relaying*, and of the multi-hop path with the *type B concurrency*. Then we select the best scheme, the one with the maximum sum of the effective data rates for the two target MS-s. Considered the *criterion 2* case, if any of the two effective data rates of the multi-hop paths with the *type B concurrency* is smaller than that of the direct single-hop link, then *type B concurrency* is eliminated from the selection. Note that in this hybrid control scheme, the effective data rate with *simple relaying* should be considered for $2T$, and then it is given by $1/(2 \cdot (1/R_{R,1} + 1/R_{R,2}))$.

Fig. 6 shows $E[G]$ while varying the number of total MS-s in the center cell. The throughput for all the schemes increases with the number of MS-s, as expected. Compared to the *simple relaying* case, the stand-alone *type B concurrency* does not provide a significant gain, similar to the results in the previous subsection. In particular, for the small number of MS-s, the performance of the *type B concurrency* is even worse than the *simple relaying* case. However, we observe that the throughput is considerably increased by the use of the proposed hybrid control scheme. The best scheme depends on the topology and may be either *type B concurrency* or the *simple relaying*, according to the MS locations and the shadowing. This comparison results support our claim that a hybrid scheme should be used in the general case.

We also present the results for the hybrid control of the *type A concurrency* and *simple relaying* in Fig. 6. The results were calculated for the case where the maximum number of allowable hops is 5. Note that except for this hybrid control, for three other cases in the figure the number of hops is limited to 2. The results in the figure show that the amount of increase offered by the *type A concurrency* is much smaller than that by the *type B concurrency*. Since the concurrent transmissions in the *type B concurrency* can be farther away from each other than in the *type A concurrency*, the increase in interference power can be smaller in the *type B concurrency* case. From the results, we conclude that in order to achieve the best improvement, the concurrency should be applied between different downstream paths, rather than within the same downstream path.

V. IMPACT ON THE CAPACITY OF THE CONVENTIONAL POWER-CONTROLLED SYSTEM

We now discuss the impact of the multi-hop relaying on the capacity of the conventional CDMA system, where the power control is employed for providing a constant bit rate with the required quality, and the channel multiplexing within a cell is based on CDM (for downlink) or CDMA (for uplink).

Previous works showed that coverage of those systems can be increased by the multi-hop relaying, but it is not easy to enhance the capacity under the interference-limited conditions, such as the case in the high-loaded systems with small cells [3]–[7].⁵ This is mainly due to the interference increase from the concurrent relaying transmission. Recall that in the conventional systems, the near-far problem can be avoided by power control. However, in the multi-hop system, it is possible that the interfering transmitter, rather than the intended transmitter, is closer to the receiver. In such a case, any power control would be ineffective and would, in fact, result in very high interference level, possibly leading to total outage.⁷ Although such interfering transmission may be avoided by the use of a sophisticated algorithm for routing and time slot assignment, optimization of both selections of relaying MS and time slot seems to be difficult, because of the a large number of transmissions that would normally occur concurrently within the same cell.

In this work, we have realized the concurrency gain by allowing only two downstream paths at any time and also by utilizing both concurrent and the non-concurrent transmissions. Since the downstream paths are implemented in the

⁵Although Rouse *et al.* [7] evaluated the capacity improvement achieved through multi-hop relaying over the conventional system, such an improvement does not occur for all non-local traffic cases in which the source and the target are in different cells, or only one of the two resides in the wireless network. Note that in our paper the non-local traffic is assumed to be much more dominant than the local-traffic whose source and target are in the same cells.

⁶Zadeh *et al.* [10] demonstrated the capacity improvement achievable by multi-hop relaying, unlike in their previous work [4]. However, interference cancellation scheme such as multi-user detection (MUD) was employed in [10]. Note that in our work, we do not apply any scheme for the interference cancellation.

⁷Such near-far problem may also arise in mobile ad-hoc networks (MANETs) [11].

TDM fashion, in such a way that any period $2T$ is dedicated to pair of MS-s, the path selection of the two MS-s does not affect the signal quality of the other MS-s in the same cell. So we have only to consider the interference between the two paths for these two MS-s. If this mutual interference is too high, it can be avoided by choosing the direct paths or the non-concurrent relaying paths. Clearly, such control will be easier in a TDM system than in a CDM system where the path selection for each MS affects one another. More comprehensive comparison of TDM and CDM in multi-hop system is left as a future study. Though, we can claim at least that the capacity gain by multi-hop relaying can be easier implemented in the rate-controlled CDMA system with TDM for multiplexing the same cell channels, than in the conventional power-controlled CDMA systems.

VI. CONCLUSIONS

We have shown in this work that the downstream throughput can be increased by allowing concurrently relayed transmissions in the multi-hop cellular networks. However, the concurrency cannot always ensure a higher throughput gain than the non-concurrent system, because of the mutual interference between concurrently relaying links. In order to achieve a significant improvement, we should employ a hybrid control scheme utilizing both concurrency and non-concurrency. In addition, the concurrency should be applied among different downstream paths rather than between the hops on the same downstream path.

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