

On the Uplink Capacity and Coverage of Relay-Assisted UMTS Cellular Network with Multiuser Detection

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Abstract—Capacity and Coverage are the two major concerns for the wireless operators to deploy cellular networks. This paper investigates the uplink capacity and coverage of relay-assisted UMTS network when multiuser detection techniques are employed at both macrocell base station (BS) and relay station (RS). A hierarchical geometric system model is used where the fixed relay stations are deployed within the macrocell. We are particularly interested in the cases where macro BSs and RSs have different capabilities in mitigating intracell and intercell interferences. Simulation results show that the capacity can be tripled and the cell range can be extended when MUD can be employed at base stations and relay stations. Furthermore, we studied the practical scenario where the users in the relay region are partially served by the relay station. This case is meaningful when there are not enough relay resources or users are restricted due to limited handover capability. We then proposed a partial relay system to enhance the cell range while maintaining a reasonable cell load.

I. INTRODUCTION

The primary challenge of the network planning is to achieve extended coverage with maximal users it can support with targeted quality of services. Cellular system based on code division multiple access (CDMA) air-interface features flexible access of the users and high spectral efficiency. Third generation (3G) and beyond 3G cellular networks have employed CDMA in the physical layer standardization. Wireless operators have already deployed Wideband-CDMA (WCDMA) and high speed downlink packet access (HSDPA) networks world wide.

However, extensive studies have shown that the cell coverage and capacity are uplink limited. One way to improve the cellular system capacity is to deploy more macrocell base stations (BSs). However, deploying additional macrocell BSs are expensive for wireless operators as the infrastructure is the main show stopper. Recent progress in relay communications [1]–[3] has shown that the deployment of fixed relay station (RS) in WCDMA cellular systems can significantly improve the cell coverage and capacity. In relay-assisted cellular network, the macrocell BSs connects to the RSs such that the multihop paths are formed to redirect the transmission. RS has the benefits of low cost and flexible design. It also reduces the transmission power in both uplink and downlink for the

macrocell BSs and User Equipments (UEs), which is more critical for the battery life of hand held devices.

Another effective solution to enhance the capacity of cellular system is to employ multiuser detection (MUD) techniques [4], [5] to remove the severe intracell as well as the intercell interferences. Hence, a natural extension for further capacity and coverage enhancement is to apply MUD to relay-assisted cellular networks [6]–[9].

In this paper, we further investigate the coverage and capacity of relay-based networks proposed in [2], [6]. In particular, we are interested in the cases where BSs and RSs have different capabilities in mitigating intracell and intercell interference. In [6], multiuser detection is simplified by an empirical interference suppression factor λ , which lies in a wide range ($\lambda \in (0.1, 0.7)$) [10]. In addition, the results are in terms of the total transmit power. As a consequence, it can not be used directly as a guideline in determining system design parameters for cell coverage improvement. We apply the results in large-scale CDMA system to study the consequences of specific multiuser detection techniques, e.g., minimum mean square error (MMSE) detector and iterative multiuser detector, etc., on the cell coverage and capacity. This facilitates the study on the tradeoff between the performance and cost when operators decide on adopting advanced technology in the deployed UMTS networks. Moreover, we consider the cases where users in the conventional “relay region” are partially served by relay stations. The study of this scenario is meaningful when there are not enough RSs available in the cell or some users entering the relay region are not successfully transferred from BS to RS due to the limited handover capacity of the latter.

The rest of the paper is organized as follows. In Section II, a general relay-assisted cellular network model is introduced. In Section III, we discuss the interference and signal to interference ratio (SIR) analysis for fixed relay network. In Section IV, we present the relay systems with different interference mitigation capabilities to achieve further capacity and coverage enhancement. In Section V, we incorporate the cases for partial relay and study its effect on cell coverage. The numerical results on capacity and coverage are present in

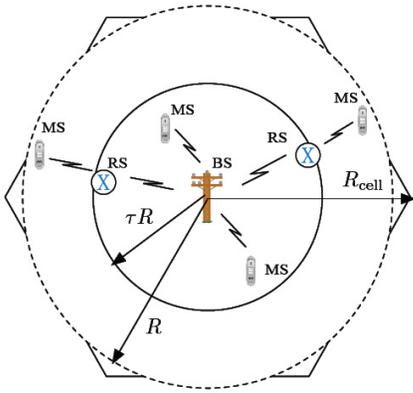


Fig. 1. Relay-assisted cellular cell

Section VI. Section VII concludes the paper.

II. SYSTEM MODEL

In [2], a practical fixed relay multihop based cellular network design is proposed. Fig. 1 shows the structure of the hexagonal-shaped cell of such a system. R_{cell} is the radius for the hexagonal cell and R is the radius of an approximated circle-shaped cell, with the two related by:

$$R = \left(\frac{3\sqrt{3}}{2\pi} \right)^{1/2} R_{cell}. \quad (1)$$

Macrocell BS is installed in the geometrical center of the cell, while mobile subscribers (MS) are uniformly distributed in the cell. RS are uniformly deployed on a circle that is τR ($\tau \leq 1$) away from the BS, while it is assumed in this study that each RS only serve one MS. The density of MSs, the radiuses of one-hop and two-hop regions, and the numbers of one-hop and two-hop users are then given by:

$$\rho = \frac{K}{\pi R^2}, \quad (2)$$

$$R_{BS} = \tau R, \quad (3)$$

$$R_{RS} = (1 - \tau)R, \quad (4)$$

$$K_d = \tau^2 K, \quad (5)$$

$$K_r = (1 - \tau^2)K, \quad (6)$$

where K is the total number of mobile subscribers in a macrocell.

We assume that the direct transmission from MS to BS and the relay transmission between MS and RS take on two different carrier frequencies. Table I summarized the outdoor pathloss model [11] and cellular network system parameters.

TABLE I
SYSTEM PARAMETERS FOR RELAY-ASSISTED CELLULAR NETWORK

	MS to RS link	MS to BS link
Chip Rate	3.84Mcps	3.84Mcps
Spreading factor (SF)	64	64
Target SIR	3.2dB	3.2dB
Maximum Tx power	0.125W	0.125W
Tx antenna gain	0dBi	0dBi
Tx antenna loss	0dB	0dB
Rx antenna gain	0dBi	10dBi
Rx antenna loss	0dB	2dB
Rx noise figure (NF)	7dB	5dB
Body loss	4dB	2dB
Pathloss model	$138 + 35.2 \log_{10}(r)$ dB	$137 + 35.2 \log_{10}(r)$ dB

III. INTERFERENCE AND SIR ANALYSIS FOR RELAY-ASSISTED CELLULAR NETWORK

In the WCDMA based UMTS cellular system, the SIR of the k^{th} user at BS is given by:

$$SIR_{BS,k} = \frac{SF \times P_{BS,k}}{\sigma_{BS}^2 + I_{BS,ite} + I_{BS,itrr}}, \quad (7)$$

where SF is the spreading factor, $P_{BS,k}$ is the received power for the k^{th} user at BS, σ_{BS}^2 is the variance of the chip-level Additive White Gaussian Noise (AWGN), $I_{BS,ite}$ and $I_{BS,itrr}$ are the co-channel intercell and intracell interferences, respectively. In a large-scale UMTS cellular network, the co-channel interferences are on average the same for all users. As a consequence, we drop the user index in the interference notations. Furthermore, we assume perfect power control at BS, i.e. $P_{BS,k} \equiv P_{BS}$.

Given the hexagonal cell structure, the cell of interested by T tiers of neighboring cells, with the t^{th} tier consists of $6t$ cells. The intercell interference from neighboring macrocell i ($i = 0, 1, \dots, 6t - 1$) at tier t is given by [2] by

$$P^{t,i} = \int_0^{\tau R} \int_{-\pi}^{\pi} \rho P_{BS} \left(\frac{r_d}{x_d(r_d, \theta_d)} \right)^{\mu} r_d dr_d d\theta_d + \int_{-\pi}^{\pi} \frac{K_r}{2\pi} P_{BS} \left(\frac{\tau R}{x_d(\tau R, \theta_d)} \right)^{\mu} d\theta_d. \quad (8)$$

In equation (8), the double integral on the top is the interference from one-hop users, and the integral at the bottom is the interference from the two hop relay-assisted users. μ is the pathloss exponent, r_d is the distance between a MS in cell- (t, i) and its serving BS, θ_d denotes the azimuth w.r.t. the line connecting BS_0 and $BS_{t,i}$, and $x_d(r_d, \theta_d)$ is the distance between the coordinate (r_d, θ_d) and BS_0 , which is given by

$$x_d(r_d, \theta_d) = \sqrt{(d_{t,i}^{BS})^2 + r_d^2 + 2d_{t,i}^{BS} r_d \cos \theta_d}, \quad (9)$$

where $d_{t,i}^{BS}$ is the distance between BS_0 and $BS_{t,i}$. The intercell interference can be calculated as

$$I_{BS,ite} = 6 \sum_{t=1}^T \sum_{i=0}^{6t-1} P^{t,i}, \quad (10)$$

and the intercell interference ratio can be defined as interfering power over the total intracell received power at BS_0 :

$$\alpha_{BS} = \frac{I_{BS,ite}}{KP_{BS}}. \quad (11)$$

The intracell interference can be modeled as weighted summation of the intracell received power except the user of interest as follows:

$$I_{BS,itr} = \lambda \sum_{l \neq k} P_{BS,l} = \lambda(K-1)P_{BS}, \quad (12)$$

where $\lambda(\leq 1)$ is the interference mitigation factor.

Similar to the BS, the SIR at the RS for a MS user k is given by:

$$SIR_{RS,k} = \frac{SF \times P_{RS,k}}{\sigma_{RS}^2 + I_{RS,ite} + I_{RS,itr}}, \quad (13)$$

where $P_{RS,k}$ is the received power for user k at the serving RS, $I_{RS,ite}$ and $I_{RS,itr}$ are the intercell and intracell interference, respectively. σ_{RS}^2 is the noise variance at RS.

At relay station, the intracell interference is given by [2] as follows:

$$I_{RS,itr} = \int_{\tau R}^R \int_{-\pi}^{\pi} \rho P_{RS} \left(\frac{r - \tau R}{x(r, \theta)} \right)^{\mu} r dr d\theta, \quad (14)$$

where $x(r, \theta) = \sqrt{r^2 + (\tau R)^2 - 2r\tau R \cos \theta}$ is the distance between the coordinate (r, θ) and the target RS. Furthermore, the intercell interference from cell- (t, i) to one RS in the serving region of BS_0 is calculated as:

$$P^{t,i} = \int_{\tau R}^R \int_{-\pi}^{\pi} \rho P_{RS} \left(\frac{r - \tau R}{x_r(r, \theta)} \right)^{\mu} r dr d\theta, \quad (15)$$

where the distance $x_r(r, \theta)$ between the MS at the coordinate (r, θ) and the target RS is $\sqrt{(d_{t,i}^{RS})^2 + r^2 + 2d_{t,i}^{RS}r \cos \theta}$. Hence, the total intercell interference at RS is given by:

$$I_{RS,ite} = \sum_{t=1}^T \sum_{i=0}^{6t-1} P^{t,i}. \quad (16)$$

In practical UMTS system, P_{BS} and P_{RS} can be power controlled to achieve target SIR for certain designed block error rate operating point, the cell range can be obtained through link budget calculation. Furthermore, the pole capacity of the cellular network can be obtained from SIR equation (7) and (13).

IV. RELAY WITH MUD

In this section, we present the SIR analysis for the relay-assisted multihop cellular networks when multiuser detection capabilities are employed at BSs and RSs.

A. Baseline System

We first introduce the system in [2] as the baseline system for further comparison. The baseline system employs single-user detection (SUD) at both BS and RS. Therefore, the intercell interference for BS is shown in equation (8) and (10). The mitigation factor for intracell interference is set to be unity, i.e., $\lambda = 1$.

B. Parallel Interference Cancellation (PIC)-Assisted BS and RS

Multiuser detection method has been shown to effectively mitigate the multiple-access interference discussed in the previous sections. In particular, PIC method was proposed to reduce the intracell interference due to its low complexity. According to [10], the ballpark figure of interference mitigation factor λ is approximately 0.7.

C. Minimum Mean Square Error (MMSE)-Assisted BS and RS

MMSE detection is another advanced multiuser detection method known for its supreme performance [4]. For a large-scale CDMA based cellular system, the effective interference from l^{th} user to k^{th} user is given in [5] as follows:

$$I_{l,k} = \frac{P_{BS,l}P_{BS,k}}{P_{BS,k} + SIR_{BS,k}P_{BS,l}}. \quad (17)$$

If MMSE detection is deployed at BS to combat the intracell interference, the corresponding mitigation factor for the k^{th} user is given by:

$$\begin{aligned} \lambda_k &= \frac{\sum_{l \neq k} I_{l,k}}{\sum_{l \neq k} P_{BS,l}} \\ &= \frac{P_{BS,k}}{\sum_{l \neq k} P_{BS,l}} \left(\sum_{l \neq k} \frac{P_{BS,l}}{P_{BS,k} + SIR_{BS,k}P_{BS,l}} \right). \end{aligned} \quad (18)$$

As perfect power control is assumed at BS, i.e., $P_{BS,k} \equiv P_{BS} \forall k$, it can be deduced that in this case the received SIR is constant for all users, i.e., $SIR_{BS,k} \equiv SIR_{BS}$, where SIR_{BS} is the target SIR at BS. As a result, the equation (18) can be simplified to $\lambda = \frac{1}{1+SIR_{BS}}$.

We further adopt the MMSE filter to RS to mitigate the intracell interference in the MS-RS uplink. The effective interference from MS at the coordinate (r, θ) to the target RS is formulated as

$$\begin{aligned} I(r, \theta) &= \frac{P_{RS}P(r, \theta)}{P_{RS} + SIR_{RS}P(r, \theta)} \\ &= \frac{P_{RS} \left(\frac{r - \tau R}{x(r, \theta)} \right)^{\mu}}{1 + SIR_{RS} \left(\frac{r - \tau R}{x(r, \theta)} \right)^{\mu}}, \end{aligned} \quad (19)$$

and the residual intracell interference is given by

$$I_{RS,itr} = \int_{\tau R}^R \int_{-\pi}^{\pi} \rho \frac{P_{RS} \left(\frac{r - \tau R}{x(r, \theta)} \right)^{\mu}}{1 + SIR_{RS} \left(\frac{r - \tau R}{x(r, \theta)} \right)^{\mu}} r dr d\theta. \quad (20)$$

V. PARTIAL RELAY WITH MUD

It should be noted that the ratio τ of the radius of one-hop and that of the cell varies to achieve maximum capacity for different cell ranges. We work out the optimal τ for different relay schemes at various cell coverage in Table II. It can be seen that the use of multiuser detection only affects τ marginally and the number of relayed users is above 50% of all

TABLE II
PERCENTAGE OF TWO-HOP USERS IN RELAY CELLULAR NETWORKS WITH OPTIMAL τ

Cell Radius	SUD τ	SUD K_r/K	PIC τ	PIC K_r/K	MMSE τ	MMSE K_r/K
0.8km	0.244	94.0%	0.283	92.0%	0.377	85.8%
1.5km	0.530	71.4%	0.535	71.4%	0.550	70.0%
2.2km	0.671	55.0%	0.671	55.0%	0.673	54.7%

MSs in the cell to achieve the enhanced coverage and capacity. This incurs a substantial cost on relay station installation.

In realistic situation, a constraint may be set on the number of relay stations in a cell and regulate that they are only deployed close to the boundary of the cell. However, this will result in a drastic performance degradation. In this case, each BS serves a tremendous number of one-hop users, which leads to a significant performance loss.

To address this problem, we propose to reduce the ratio τ to generate a larger region in the cell, where users may request multihop service. To maintain the number of RSs the same, we suggest that only a fraction of the users in the outer region be served by RSs, while the rest still communicate with the BS. This scheme greatly alleviates the burden on RS when there are not enough number of RSs or the handover from BS to RS is not successful as MSs travel from the inner part to the outer part of the cell. Denote by β the ratio of two-hop users in the outer region, the number of one-hop and two-hop users are given by:

$$K_d = (1 - \beta(1 - \tau^2))K, \quad (21)$$

$$K_r = (1 - \tau^2)\beta K. \quad (22)$$

VI. SIMULATION RESULTS

In this section, we conduct the numerical analysis on coverage and capacity for relay networks described in previous sections. Channel parameters specified in Table I are used for evaluation. For a given cellular network topology, the required received power P_{BS} and P_{RS} at BS and RS can be calculated from equation (7) and (13) if the target SIR is defined. Hence, the maximum range of the relay-assisted multihop cellular system under investigation can be determined by the radius of two regions for direct and relay transmission. Considering all the attenuation factors in the wireless link, the maximum range for both regions can be obtained as follows:

$$R_{BS,max} = \sqrt[\mu]{\frac{\min\{P_{TRS}, P_{TMS}\}G_{tx}L_{tx}G_{rx}^{BS}L_{rx}^{BS}}{\kappa P_{BS}}}, \quad (23)$$

$$R_{RS,max} = \sqrt[\mu]{\frac{P_{TMS}G_{tx}L_{tx}G_{rx}^{RS}L_{rx}^{RS}}{\kappa P_{RS}}}, \quad (24)$$

where μ and κ are the path loss exponent and constant, P_{TRS} and P_{TMS} are the maximum allowed transmission powers of RS and MS, G_{tx} and G_{rx} are the gains at transmitter and receiver antennas, and L_{tx} and L_{rx} are the antenna losses, including the body loss.

Fig. 2 shows coverage-capacity results for relay systems with multiuser detection capability, compared with the generic

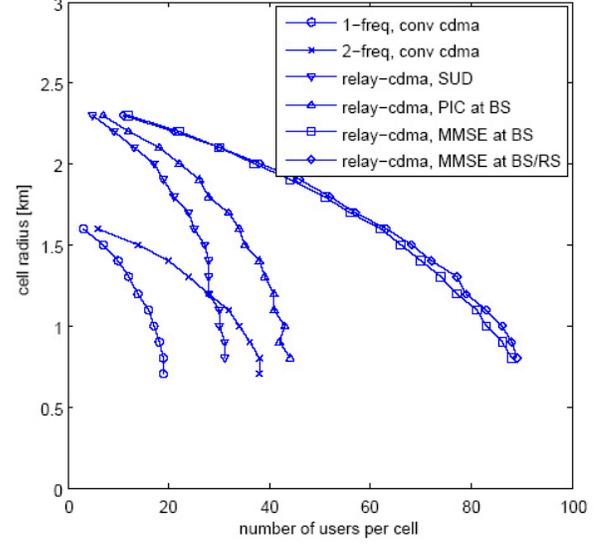


Fig. 2. Coverage-capacity for relay-assisted cellular network with MUD capability

system in [2]. It can be seen that adoption of PIC at base station can substantially improve the system capacity, which increases by about 30% for $R \leq 1$ km. Employment of the more advanced MMSE filter can further enhance the coverage and capacity. On the other hand, additional MMSE capability at relay station is not necessary as the resultant improvement is marginal. It is also shown that all relay schemes significantly extend the cell range compared to the traditional CDMA cellular network. Meanwhile, as the cell range becomes large, the performance of relay systems converge as the intercell interference becomes dominant and MUDs deployed to tackle intracell interference fail to address this performance limiting factor.

To further illustrate the intercell/intracell interference in different relay schemes, the intracell/intercell interference ratios are defined for relay station, in addition to α_{BS} for BS in equation (11):

$$\alpha_{RS} = \frac{I_{RS,ite}}{K_r P_{RS}}, \quad (25)$$

$$\alpha_{RS0} = \frac{I_{RS,itr}}{K_r P_{RS}}. \quad (26)$$

Fig. 3 shows the interference ratios for both BS and RS at different cell ranges. Although the multiuser detection is used to resolve the intracell interference, it also affects the intercell interference by requiring less transmit power from MS in neighboring cells, evidenced by the improvement in

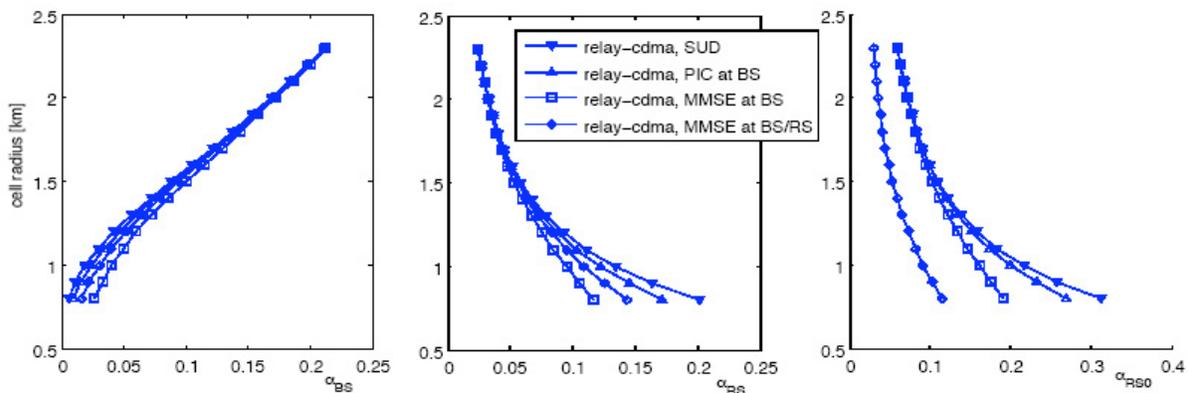


Fig. 3. Intracell and intercell interference ratio for relay-assisted cellular systems.

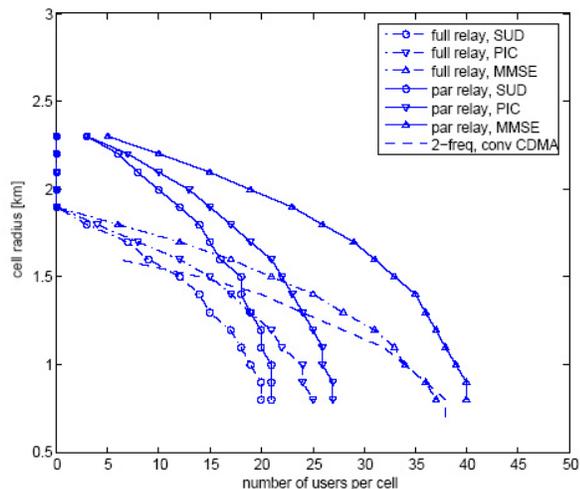


Fig. 4. Coverage-capacity for partial relay-assisted cellular network with MUD capability

α_{BS} and α_{RS} . It is also observed that α_{BS} increases, while α_{RS} and α_{RS0} decreases as the cell range becomes larger. This indicates that the intercell interference at BS is severe in large scale networks.

Finally, we show the performance of the proposed partial relay-assisted networks. We define two types of relay systems that serve one fifth of the users in a cellular system. The first type, named full relay system, is the same as that in [2] with $\tau_1 = 0.894$. The other, named partial relay system, only relays $\beta = 40\%$ of the users in the outer region and has a corresponding $\tau_2 = 0.707$. The coverage and capacity results of these two alternative schemes are shown in Fig. 4 with different MUDs adopted at BS. It can be seen that for a certain relay ratio, the full relay system only slightly improves the cell range when the cell load is low to medium. On the other hand, the proposed partial relay system can significantly enhance the cell range while maintaining a reasonable cell load.

VII. CONCLUSION

In this paper, we studied the uplink capacity and coverage of relay-assisted UMTS network when MUD techniques are

employed at both macrocell BS and RS. We show through analysis and simulations that network capacity can be tripled and the cell range can be extended when MUD can be employed. We further proposed partial relay-assisted scheme to address practical scenario that limited RS is deployed in the network. This partial relay scheme provides good tradeoff between cell range and load.

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