On the Uplink Performance and Optimization of a Relay-assisted Cellular Network

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***Abstract*—Using relay stations (RSs) has been known as a promising technology to improve the system performance of a traditional cellular network. This paper aims to investigate the uplink performance of a relay-assisted cellular network with optimal system parameters. Two performance measures, average power consumption of mobile stations and uplink system spectral efficiency, are optimized by jointly considering the system parameters of RSs' locations, reuse patterns, path selections and resource allocation. A genetic algorithm along with a method of MAI (multiple access interference) estimation is proposed to solve the optimization problem. Numerical results show that significant improvement on system performance can be achieved from both power consumption and system spectral efficiency aspects if RSs are deployed and used in the optimal way.**

I. Introduction

Using fixed relay stations (RSs) in the traditional cellular network is an emerging technology to improve system performance and has recently drawn research interest in both academia and industry [1]-[11]. By reducing the propagation loss between the base station (BS) and a mobile station (MS), RSs can significantly improve the cell coverage, increase the user throughput, and save the MS's transmit power [2]-[10]. In addition, the system capacity can also be largely enhanced if RSs are deployed and used in an optimal way [7]. The performance of the relay-assisted cellular network has been investigated extensively from both theoretical and practical points of view [5]-[10]. These studies, however, have been done for very limited system scenarios: fixed number of RSs and locations, fixed reuse pattern, or seeking optimal RSs' positions with a simplified one-dimensional model, except the one by the authors in [7], where the downlink performance was optimized for a general relay-assisted cellular network. In this work, we investigate the uplink performance and optimization.

There have been few studies on the uplink performance of the relay-assisted cellular systems [8]-[10]. In [8], the issues of capacity, cell coverage, and MS transmit power were considered in a relay-assisted CDMA network with six RSs under different frequency allocation methods. In [9], the uplink capacity of an 802.16j system was discussed, where a simplified one-dimensional model is analyzed for the maximal capacity gains, and fixed number of RSs with uniform placement is also simulated. In [10], the issues of RS positioning and spectrum partitioning were studied by searching optimal RSs locations along the lines connecting BS and the six vertices of a hexagonal cell to maximize the mean user data rate.

In this work, the uplink performance is evaluated for a general relay-assisted cellular system. Two performance measures, average MS's power consumption and uplink system spectral efficiency, are optimized by jointly considering RSs' locations, reuse patterns, path selections and resource allocation. The optimization is done based on a genetic algorithm (GA) and a method for MAI (multiple access interference) estimation. MAI estimation is important when applying intra-cell frequency reuse among MS to RS links, where locations of interferer are usually unknown to MSs. Numerical results show that the average MS's transmit power is significantly reduced and the uplink system spectral efficiency is largely enhanced.

The rest of the paper is organized as follows. Section II describes the system setups. Section III formulates the objective functions under different criteria. The optimization algorithm is described in Section IV. Section V provides the numerical results, and finally, Section VI concludes this paper.

II. System Setups

A. Cell Architecture

Fig. 1(a) depicts a hexagon cell structure with radius D and coverage Ω investigated in this paper. The BS is located at the cell center. N RSs are deployed into the cell with the position vector $\vec{r_j}$ of R_j, the j^{th} RS, and $\Upsilon \doteq \{\vec{r_j}\}$ denotes the set of N RSs' positions. In addition, MSs are uniformly distributed over Ω with position vector $\vec{m}$. MS can communicate with BS either through a direct path (the MS-BS link) or a 2-hop path (the MS-RS link and the RS-BS link). All stations are equipped with an omni-directional antenna and one RF transceiver.

B. Relaying Technique

We consider RSs which operate in the in-band decode-and-forward mode, where the received signal is fully decoded and forwarded to the destination using the same frequency band as BS. Besides, the orthogonal radio resources are allocated for direct paths and 2-hop paths respectively. A practical scheme is shown in Fig. 1(b), where resource for 2-hop links is

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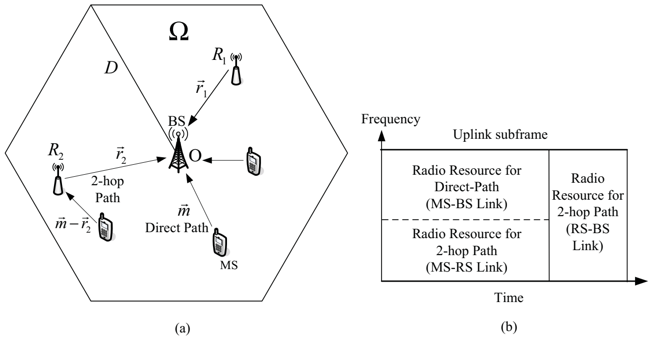


Fig. 1. (a) Cell architecture, (b) radio resource allocation.

further divided into one for MS-RS and the other for RS-BS transmissions. With this allocation, RSs do not need to transmit and receive at the same time (half-duplex relaying).

C. Propagation Models

The line-of-sight (LOS) and non-line-of-sight (NLOS) path-loss models for suburban macro-cell environment in [11] are adopted, which are given in (1) and (2), respectively.

$$L_{\mathrm{LOS}}(d) = 23.8\log_{10}(d) + 41.9 \text{ dB}, \tag{1}$$

$$L_{\mathrm{NLOS}}(d) = 40.2\log_{10}(d) + 27.7 \text{ dB}, \tag{2}$$

where d is the separation (in meters) between the transmitter and the receiver. The LOS model is used for RS-BS links because RSs are usually installed in the relatively high position, e.g. on the rooftop, while the NLOS one is for MS-BS links and MS-RS links.

D. Power Setup for RSs

The transmit power of each RS is set to achieve a pre-specified spectral efficiency, S_t, for users at the cell boundary in the downlink. We assume RSs use the same power level to communicate with BS in the uplink. In this work, the AWGN channel is taken as an example to demonstrate the uplink theoretic performance. Hence, S_t can be expressed as

$$S_t = \log_2(1 + \frac{p_{R_j} \cdot L_{NLOS}^{-1}(D - \|\vec{r}_j\|)}{N_0 + I_0}), \tag{3}$$

where p_{R_j} is the transmit power spectral density (PSD) for R_j, $L(d)$ is propagation loss in linear scale, $\|\vec{r}_j\|$ denotes the Euclidean distance of the position vector $\vec{r}_j$, and N_0 and I_0 are the PSDs of AWGN and MAI, respectively. Accordingly, p_{R_j} is setup by

$$p_{R_j} = \frac{(2^{S_t} - 1) \cdot (N_0 + I_0)}{L_{NLOS}^{-1}(D - \|\vec{r}_j\|)} \text{ watts/Hz}. \tag{4}$$

The transmit power P_{R_j} is then equal to $p_{R_j} \cdot W$, where W is the link bandwidth.

E. Frequency Reuse over MS-RS Links

In Fig. 1(a), the radio resource can be further reused over the MS-RS links to increase the spectral efficiency because of the spatial separation between RSs. To exploit this advantage, let RSs be divided into L groups, where $L \le N$, and each group shares the same radio resource. The reuse pattern then can be specified by the set $\mathrm{G} \doteq \{\mathrm{G}_l\}_{l=1}^{L}$, where $\mathrm{G}_l = \{R_{j_l}\}$ is the set of RSs in the l^{th} group. It is clear that $\sum_{l=1}^{L} |\mathrm{G}_l| = N$, where $|\mathrm{G}_l|$ is the cardinality of the set G_l.

III. Problem Formulation

In the uplink, in addition to the system spectral efficiency, MS's power consumption is also an important performance measure due to the limited battery life. In this section, given a fixed amount of bandwidth for each MS, two system performance measures are investigated: 1. minimization of average MS's transmit power for a specified throughput; 2. maximization the uplink spectral efficiency by given a fixed MS's transmit power, by jointly searching optimal RSs' positions, reuse patterns, path selections and bandwidth allocation.

Let w_t (Hz per unit area) be the bandwidth allocated to MS at any location $\vec{m}$. Then, $w_t = w_{M\to B}(\vec{m}) = w_{M\to R_j}(\vec{m}) + w_{R_j\to B}(\vec{m})$. Let $S_{M\to B}(\vec{m})$, $S_{M\to R_j}(\vec{m})$, and $S_{R_j\to B}(\vec{m})$ denote the spectral efficiency for the MS-BS link, the MS-RS link, and the RS-BS link, respectively. In the AWGN channel,

$$S_{M\to B}(\vec{m}) = \log_2\left(1 + \frac{P_{M\to B}(\vec{m}) \cdot L_{NLOS}^{-1}(\|\vec{m}\|)}{(N_0 + I_{M\to B}) \cdot w_t}\right), \tag{5}$$

$$S_{M\to R_j}(\vec{m}) = \log_2\left(1 + \frac{P_{M\to R_j}(\vec{m}) \cdot L_{NLOS}^{-1}(\|\vec{r}_j - \vec{m}\|)}{(N_0 + I_{M\to R_j}) \cdot w_{M\to R_j}(\vec{m})}\right), \tag{6}$$

and

$$S_{R_j\to B}(\vec{m}) = \log_2\left(1 + \frac{P_{R_j\to B}(\vec{m}) \cdot L_{LOS}^{-1}(\|\vec{r}_j\|)}{(N_0 + I_{R_j\to B}) \cdot w_{R_j\to B}(\vec{m})}\right), \tag{7}$$

where $P_{M\to B}(\vec{m})$ and $P_{M\to R_j}(\vec{m})$ are MS's transmit power of the MS-BS link, and the MS-RS link, respectively, $P_{R_j\to B}(\vec{m})$ is the RS's transmit power of the RS-BS link, and $I_{M\to B}$, $I_{M\to R_j}$ and $I_{R_j\to B}$ are the PSDs of average MAI appearing over the MS-BS link, the MS-RS link, and the RS-BS link, respectively. The throughput for each link is then expressed, respectively, by

$$t_{M\to B}(\vec{m}) = w_t \cdot S_{M\to B}(\vec{m}), \tag{8}$$

$$t_{M\to R_j}(\vec{m}) = w_{M\to R_j}(\vec{m}) \cdot S_{M\to R_j}(\vec{m}), \tag{9}$$

and

$$t_{R_j\to B}(\vec{m}) = w_{R_j\to B}(\vec{m}) \cdot S_{R_j\to B}(\vec{m}). \tag{10}$$

A. Measure 1-Minimization of Average MS's Transmit Power

In this section, the average MS's transmit power will be minimized to achieve a targeted throughput T_t. From (5) and (8), the MS's transmit power for direct path is given by

$$P_{M\to B}(\vec{m}) = \frac{(2^{\frac{T_t}{w_t}} - 1) \cdot (N_0 + I_{M\to B})}{L_{NLOS}^{-1}(\|\vec{m}\|)} \cdot w_t. \tag{11}$$

For a 2-hop path, since $t_{M\to R_j\to B}(\vec{m}) = \min\{t_{M\to R_j}(\vec{m}), t_{R_j\to B}(\vec{m})\}$, where $t_{M\to R_j\to B}(\vec{m})$ is the effective throughput of a 2-hop link, the most efficient way is to make $t_{M\to R_j}(\vec{m}) = t_{R_j\to B}(\vec{m}) = T_t$. As a result, the bandwidth allocation for each hop is given by

$$w_{R_j\to B}(\vec{m}) = \frac{T_t}{S_{R_j\to B}(\vec{m})}, \tag{12}$$

and

$$w_{M\to R_j}(\vec{m}) = w_t - w_{R_j\to B}(\vec{m}). \tag{13}$$

Then, the MS's transmit power to R_j can be expressed as

$$P_{M\to R_j}(\vec{m}) = \frac{(2^{\frac{T_t}{w_{M\to R_j}(\vec{m})}}-1)\cdot(N_0+I_{M\to R_j})}{L_{NLOS}^{-1}(\|\vec{r}_j-\vec{m}\|)}\cdot w_{M\to R_j}(\vec{m}). \quad (14)$$

The optimal path selection is to select direct path if $P_{M\to B}(\vec{m}) \leq P_{M\to R_j}(\vec{m})$, where $P_{M\to R_j}(\vec{m}) = \min_{R_i}\{P_{M\to R_i}(\vec{m})\}$; otherwise the 2-hop path via R_j is selected, where $R_j = \arg\min_{R_i}\{P_{M\to R_i}(\vec{m})\}$. Finally, the objective function is given by

$$\min_{\Upsilon,\mathrm{G}} P_{M_{avg}}, \quad (15)$$

with

$$P_{M_{avg}} = \int_{\vec{m}\in\Omega_B} \frac{1}{\Omega_B}P_{M\to B}(\vec{m})dA + \sum_{j=1}^{N}\int_{\vec{m}\in\Omega_{R_j}} \frac{1}{\Omega_{R_j}}P_{M\to R_j}(\vec{m})dA, \quad (16)$$

where Ω_B and Ω_{R_j} are the service area of BS and R_j.

B. Measure 2-Maximization of Uplink System Spectral Efficiency

In this section, given w_t and a fixed MS's transmit power P_M, the uplink system spectral efficiency will be maximized. For direct path, by substituting P_M into (5), the throughput can be obtained by (8). For a 2-hop path, again, $t_{M\to R_j}(\vec{m}) = t_{R_j\to B}(\vec{m})$ gives the highest spectral efficiency. Hence, when

$$w_{R_j\to B}(\vec{m}) = \frac{S_{M\to R_j}(\vec{m})}{S_{M\to R_j}(\vec{m}) + S_{R_j\to B}(\vec{m})}\cdot w_t, \quad (17)$$

and

$$w_{M\to R_j}(\vec{m}) = \frac{S_{R_j\to B}(\vec{m})}{S_{M\to R_j}(\vec{m}) + S_{R_j\to B}(\vec{m})}\cdot w_t, \quad (18)$$

the maximum attainable throughput is

$$t_{M\to R_j\to B}(\vec{m}) = \frac{S_{M\to R_j}(\vec{m})\cdot S_{R_j\to B}(\vec{m})}{S_{M\to R_j}(\vec{m}) + S_{R_j\to B}(\vec{m})}\cdot w_t. \quad (19)$$

Notice that from (6) and (18), we need to solve the following nonlinear equation for the optimal $S_{M\to R_j}(\vec{m})$,

$$S_{M\to R_j}(\vec{m}) = \log_2\left(aS_{M\to R_j}(\vec{m}) + b\right), \quad (20)$$

where

$$a = \frac{P_M\cdot L_{NLOS}^{-1}(\|\vec{r}_j-\vec{m}\|)}{(N_0+I_{M\to R_j})\cdot S_{R_j\to B}(\vec{m})\cdot w_t}, \quad (21)$$

and

$$b = \frac{P_M\cdot L_{NLOS}^{-1}(\|\vec{r}_j-\vec{m}\|)}{(N_0+I_{M\to R_j})\cdot w_t} + 1. \quad (22)$$

The optimal path selection is to select direct path if $t_{M\to B}(\vec{m}) \geq t_{M\to R_j\to B}(\vec{m})$, where $t_{M\to R_j\to B}(\vec{m}) = \max_{R_i}\{t_{M\to R_i\to B}(\vec{m})\}$; otherwise, the 2-hop path via R_j is selected, where $R_j = \arg\max_{R_i}\{t_{M\to R_i\to B}(\vec{m})\}$. Let S_Ω, T_Ω, and W_Ω denote the uplink system spectral efficiency, system throughput, and system bandwidth consumption, respectively. The objective function is then expressed by

$$\max_{\Upsilon,\mathrm{G}} S_\Omega \doteq \frac{T_\Omega}{W_\Omega}\ \text{(bps/Hz)}, \quad (23)$$

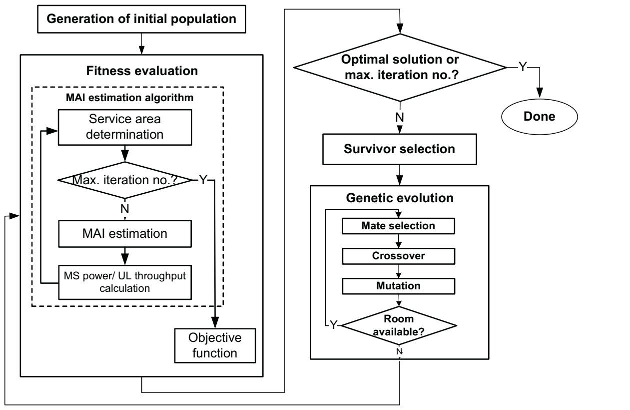


Fig. 2. The GA operation flowchart.

with

$$T_\Omega = \int_{\vec{m}\in\Omega_B} t_{M\to B}(\vec{m})dA + \int_{\vec{m}\in\Omega_{R_j}} t_{M\to R_j\to B}(\vec{m})dA, \quad (24)$$

and

$$\begin{aligned} W_\Omega &= \int_{\vec{m}\in\Omega_B} w_t dA + \sum_{j=1}^{N}\int_{\vec{m}\in\Omega_{R_j}} w_{R_j\to B}(\vec{m})dA \\ &+ \sum_{l=1}^{L}\max_{R_j\in G_l}\{\int_{\vec{m}\in\Omega_{R_j}} w_{M\to R_j}(\vec{m})dA\}. \end{aligned} \quad (25)$$

IV. Optimization Algorithm

It is observed that both (15) and (23) are highly nonlinear functions for RSs' positions Υ and the reuse pattern G, and the analytic solutions are not available in general. To resolve these issues, a particular design of GA based optimization together with an MAI estimation method for uplink are proposed. Fig. 2 illustrates the GA operation flowchart.

A. GA Operation

The Cartesian coordinate and the reuse group of a RS, $(\vec{r}_j, \mathrm{G}_l)$, is encoded as a gene, and the set of N RSs' positions and the corresponding reuse pattern, (Υ, G), denotes a chromosome. As shown in Fig. 2, in the beginning N_{pop} chromosomes are randomly generated and used as the *initial population* involved in the evolution. Each chromosome is evaluated against the objective function, called *fitness evaluation*. Then, *survivor selection* selects the best $N_{sur} = \beta\cdot N_{pop}$ chromosomes and the rest is discarded to make room for the new offspring, where β is the survival rate.

In the genetic evolution, *Roulette wheel selection* [13] is adopted to select two mates from the survival chromosomes to produce two new offspring. *Uniform crossover* [13] is then applied to produce two offspring from two selected mates. In a real-valued encoding scheme, a small zero-mean random perturbation is suggested to add to each gene of the offspring to prevent the evolutions being dominated by few genes [14]. A mutation probability P_{mut} is set to determine whether a gene is mutated or not. Once a mutation is performed, the coordinate of the corresponding RS will be regenerated. Sufficient offspring are produced until the total number of the survivors and the offspring equals N_{pop}.

The GA operation iterates until the optimal solution is found or the maximum iteration number is reached.

B. MAI Estimation Algorithm

An MAI estimation algorithm, also shown in Fig. 2, is proposed to determine the MAI level when the frequency is reused over MS-RS links. Initially, MS chooses the nearest BS or RS as its serving station, hence the Ω_B and Ω_{R_j} are pre-determined. Given a MS served by the k^{th} RS in the reuse group l, i.e., $\vec{m} \in \Omega_{R_{k_l}}$, the MAI for this MS is caused by the co-channel user in G_l. We calculate the MAI level for the MS by averaging over the potential location of the interferer, which is expressed by

$$I_{M\rightarrow R_k} = \sum_{\substack{R_i \in G_l \\ i\neq k}} \int_{\vec{m}_I \in \Omega_{R_i}} \frac{1}{\Omega_{R_i}} \cdot p_{M_I\rightarrow R_i}(\vec{m}_I) \cdot L^{-1}_{NLOS}(\|\vec{m}_I - \vec{r}_k\|) dA, \tag{26}$$

where $\vec{m}_I$ is the location of interferer and R_i is the serving station of $\vec{m}_I$.

In Measure 1, assume $I_0 = N_0$ for the PSD setup of the interferer, which is

$$p_{M_I\rightarrow R_i}(\vec{m}_I) = \frac{(2^{\overline{w_{M_I\rightarrow R_i}(\vec{m}_I)}^{T_t}} - 1)\cdot 2N_0}{L^{-1}_{NLOS}(\|\vec{r}_i - \vec{m}_I\|)}. \tag{27}$$

By substituting (27) into (26), the average MAI for the MS can be obtained. Then, the transmit power of $\vec{m}$ for the 2-hop path can be determined by

$$P_{M\rightarrow R_k}(\vec{m}) = \frac{(2^{\overline{w_{M\rightarrow R_k}(\vec{m})}^{T_t}} - 1)\cdot (N_0 + I_{M\rightarrow R_k})}{L^{-1}_{NLOS}(\|\vec{r}_k - \vec{m}\|)} \cdot w_{M\rightarrow R_k}(\vec{m}). \tag{28}$$

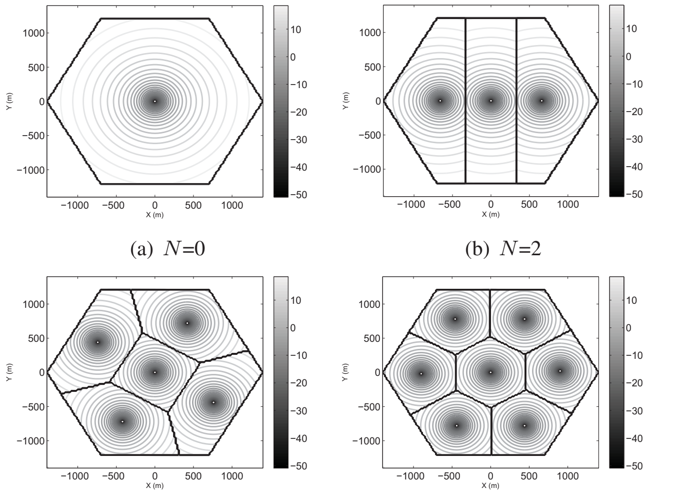
Each MS can decide its new serving station by choosing minimal transmit power among the direct path and 2-hop paths. Then, Ω_B and Ω_{R_j} can be re-determined.

In Measure 2, since $P_{M_I\rightarrow R_i}(\vec{m}_I) = P_M$, the throughput for the 2-hop path can be determined according to Section III-B. Again, each MS can decide its new serving station by choosing maximal throughput among the direct path and 2-hop paths, and Ω_B and Ω_{R_j} can be re-decided.

The process is repeated until the service area is converged or the maximum iteration number is reached.

V. Numerical Results

In our numerical results, the cell radius is set as 1400 meters, the cell region is divided into grids with each side equal to 20 meters, and the locations of all stations are rounded into the nearest grid vertices. Let S_t be set as 0.5 for PSD setup of RSs. In GA, N_{pop} = 200, β = 0.5 and P_{mut} = 0.05 are adopted. The Gaussian variable with variance equal to a grid length is used as the perturbation when performing crossover operations. Through the work, $w_t = 28.5$ KHz per unit area is allocated to MS. Newton's method is adopted to solve the nonlinear equation mentioned in (20) to (22). Besides, the inter-cell interference is assumed to be constant and embedded into the thermal noise, while the effect of intra-cell interference caused by frequency reuse over MS-RS links is considered. Note that more generations (iterations) are needed in GA for a larger number of RSs.



(a) N=0 (b) N=2 (c) N=4 (d) N=6

Fig. 3. Optimal RSs' positions and MS's transmit power distribution (dBm).

A. Measure 1-Minimization of Average MS's Transmit Power

The targeted throughput, $T_t = 14.25$ (Kbps per unit area) is set in this section. No frequency reuse is adopted among MS-RS links. Fig. 3 shows the optimal RSs' placement and the distribution of MS's transmit power (in dBm). Fig. 3(a) is the case for no RS ($N = 0$). Clearly, more transmit power is needed for a more distant MS. The average transmit power, $P_{M_{avg}}$, is 14.54 dBm, shown in Table I(a). Fig. 3(b) is the case of $N = 2$. The optimal RSs positions are in $(\pm 660, 0)$. The service area of BS and RSs is indicated by the black lines, where $\Omega_B = 31\%$ and $\Omega_R = 69\%$ with $\Omega_R = \cup_j \Omega_{R_j}$. Besides, $P_{M_{avg}} = 10.75$ dBm in this case. Fig. 3(c) shows the case of $N = 4$, where $\Omega_R = 86\%$ and $P_{M_{avg}} = 3.18$ dBm. Fig. 3(d) is the case of 6 RSs. As can be seen, the optimal RSs' positions are on the lines connecting the cell center and six vertices of the hexagonal cell with distance 900m from BS, and the whole area is almost evenly partitioned by BS and 6 RSs, where each station serves about 14% of total area. In this case, $P_{M_{avg}} = -2.05$ dBm, which is reduced 16.59 dB compared to $N = 0$. Table I(a) summarizes the service area ratio of BS and RSs, bandwidth allocation ratio for each link, and the average uplink transmit power for $N = 0$ to $N = 10$.

To explore frequency reuse over MS-RS links, the case of $N = 6$ is taken as an example with reuse patterns $\mathrm{G} = \{\mathrm{G}_1, \mathrm{G}_2, \mathrm{G}_3, \mathrm{G}_4, \mathrm{G}_5, \mathrm{G}_6\}$, $\mathrm{G} = \{\mathrm{G}_1, \mathrm{G}_2, \mathrm{G}_3\}$, $\mathrm{G} = \{\mathrm{G}_1, \mathrm{G}_2\}$, and $\mathrm{G} = \{\mathrm{G}_1\}$, where each group has equal number of RSs. The optimal RSs are symmetrically placed on the line connecting the cell center to six vertices of the cell with RSs in the same reuse group being pulled as far apart as possible. Table II(a) provides more detailed results of all cases. The uplink system spectral efficiency is getting better when the frequency is more aggressively reused (i.e., $\mathrm{G} = \{\mathrm{G}_1\}$); however, it costs more transmit power to achieve the same targeted throughput due to larger MAI.

B. Measure 2-Maximization of Uplink System Spectral Efficiency

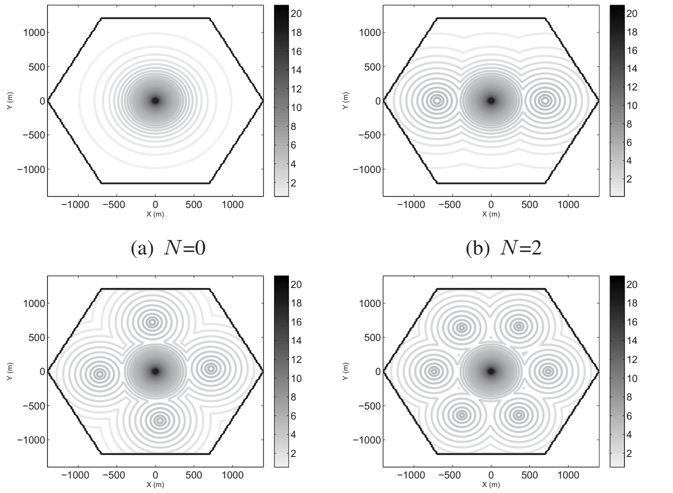
In this section, P_M is set as 15 dBm and no frequency reuse is adopted among MS-RS links. Fig. 4 describes the optimal RSs' positions and the distribution of link spectral efficiency

TABLE I
IMPORTANT SYSTEM PARAMETERS FOR $N=0$ TO $N=10$.

	N	0	2	4	6	8	10
(a). Measure 1	Ω_B:Ω_R (%)	100:0	31:69	14:86	14:86	14:86	11:89
	$w_{M\to B}$: $w_{M\to R}$:$w_{R\to B}$ (%)	100:0:0	31:65:4	14:80:6	14:80:6	14:79:7	11:82:7
	$P_{M_{avg}}(dBm)$	14.54	10.75	3.18	-2.05	-3.75	-5.07
(b). Measure 2	Ω_B:Ω_R (%)	100:0	36:64	14:86	13:87	12:88	11:89
	$w_{M\to B}$: $w_{M\to R}$:$w_{R\to B}$(%)	100:0:0	36:49:15	14:59:27	13:53:34	12:51:37	11:50:39
	S_Ω (bps/Hz)	1.58	2.54	3.37	3.83	4.02	4.16

TABLE II
IMPORTANT PARAMETERS FOR FREQUENCY-REUSE PATTERNS, N=6.

	G	$\{G_1, G_2, G_3, G_4, G_5, G_6\}$	$\{G_1, G_2, G_3\}$	$\{G_1, G_2\}$	$\{G_1\}$
(a). Measure 1	Ω_B:Ω_R (%)	14:86	14:86	14:86	15:85
	$w_{M\to B}$: $w_{M\to R}$:$w_{R\to B}$ (%)	14:80:6	23:66:11	29:57:14	42:39:19
	$P_{M_{avg}}$ (dBm)	-2.05	-2.03	-2.02	-1.57
	S_Ω (bps/Hz)	0.5	0.83	1.07	1.46
(b). Measure 2	Ω_B:Ω_R (%)	13:87	10:90	9:91	13:87
	$w_{M\to B}$: $w_{M\to R}$:$w_{R\to B}$(%)	13:53:34	14:44:42	16:39:45	31:27:42
	S_Ω (bps/Hz)	3.83	5.31	6.08	6.23



(a) N=0 (b) N=2 (c) N=4 (d) N=6

Fig. 4. Optimal RSs' positions and distribution of uplink spectral efficiency (bps/Hz), $P_M = 15$ dBm.

(in bps/Hz). Fig. 4(a) is for $N=0$, where $S_\Omega = 1.58$ bps/Hz given in Table I(b). Fig. 4(b) is the case of $N=2$. The optimal RS positions are at $(\pm 700, 0)$ and $S_\Omega = 2.54$ bps/Hz. Fig. 4(c) shows the case of $N=4$, where $\Omega_R = 86\%$ and $S_\Omega = 3.37$ bps/Hz. Fig. 4(d) is for $N=6$, where the optimal RSs' positions are on the line connecting the cell center to the six vertices of the cell with distance 740m from BS. Note that since the RS-BS link is not perfect, the maximum throughput for a 2-hop link is limited by the RS-BS link no matter how close the MS and the RS is. Obviously, more uniform data rate to MS can be provided with RSs' assistance. Important system parameters are summarized in Table I(b).

Table II(b) shows the results of different reuse patterns for $N=6$ with equal number of RSs in each reuse group. The system spectral efficiency is getting better if the frequency is more aggressively reused (i.e., $G = \{G_1\}$). With respect to the service area ratio, Ω_R becomes larger in $G = \{G_1, G_2, G_3\}$ and $G = \{G_1, G_2\}$ cases. However, in $G = \{G_1\}$, Ω_R is shrunk due to large MAI.

VI. CONCLUSIONS

In this work, the uplink performance of relay-assisted cellular networks is investigated with optimized system parameters. The optimal RSs' positions, reuse patterns, path selections and bandwidth allocation are jointly considered under two criteria: one is to minimize the average MS's transmit power for a specified throughput, and the other is to maximize the uplink system spectral efficiency by given a fixed MS's transmit power. Genetic algorithm approach along with a multiple access interference estimation method designed for the uplink performance evaluation are adopted. Numerical results conclude that given a fixed allocated bandwidth, the average uplink transmit power is significantly reduced for a targeted throughput, and the user throughput as well as the system spectral efficiency are largely enhanced for a fixed uplink transmit power with the assistance of RSs compared to the conventional cellular system.

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