Optimal Relay Station Placement in Broadband Wireless Access Networks

Bin Lin, Pin-Han Ho, *Member*, *IEEE*, Liang-Liang Xie, *Senior Member*, *IEEE*, Xuemin (Sherman) Shen, *Fellow*, *IEEE*, and János Tapolcai, *Member*, *IEEE*

Abstract—To satisfy the stringent requirement of capacity enhancement in wireless networks, cooperative relaying is envisioned as one of the most effective solutions. In this paper, we study the capacity enhancement problem by way of Relay Stations (RSs) placement to achieve an efficient and scalable design in broadband wireless access networks. To fully exploit the performance benefits of cooperative relaying, we develop an optimization framework to maximize the capacity as well as to meet the minimal traffic demand by each Subscriber Station (SS). In specific, the problem of joint RS placement and bandwidth allocation is formulated into a mixed-integer nonlinear program. We reformulate it into an integer linear program which is solvable by CPLEX. To avoid exponential computation time, a heuristic algorithm is proposed to efficiently solve the formulated problem. Numerical analysis is conducted through case studies to demonstrate the performance gain of cooperative relaying and the comparison between the proposed heuristic algorithm against the optimal solutions.

Index Terms—Cooperative relaying, decode-and-forward, placement problem.

1 INTRODUCTION

Enhancing the capacity has become a stringent requirement for the emerging fourth-generation telecommunication systems in order to satisfy the explosively growing demands in Wireless Metropolitan Area Networks (WMAN). The scalability of a wireless network is usually limited by the system radio bandwidth and channel interference. Studies on radio resource management which target at addressing capacity enhancement have been extensively reported in the past, and most of the research efforts center at maximizing resource utilization [1], [2]. However, these approaches are still subject to the constraints of limited resources. Alternatively, deploying Relay Stations (RSs) in the existing wireless Point-to-Multi-Point (PMP) networks has provided a competitive solution to capacity/throughput enhancement.

With the RSs, the quality of wireless channels can be significantly improved not only by replacing one long-distance low-rate link with multiple short-distance high-rate links, but also due to the ability of circumventing any obstacles between Subscriber Stations (SSs) and Base Station (BS) that may impair the channel quality. Therefore, deploying RSs can solve a number of legacy problems in an existing wireless network. In practice, a new round of RS placement work may be triggered due to the following deployment demands: 1) The need of boosting wireless network capacity and/or extending mobile service coverage. For instance, low signal-to-noise ratio (SNR) at cell edge is expected to be improved to achieve the ubiquitous mobile broadband access, and subscribers in densely populated area may have higher traffic demand and different Quality-of-Service (QoS) requirements. 2) The change of wireless network environments. Typically, new shopping centers and communities may lead to new hot spots or new (micro-) cell sites; newly constructed buildings may change the multipath environments of the existing telecommunication systems, possibly resulting in "black holes" in the coverage area due to the shadowing effect. 3) Stringent traffic demands. For instance, spontaneous events, such as large conferences, sports meetings, fairs, disasters, and wireless system hardware failure, may launch significant traffic demands during the period of the events. Moreover, with the advantages of less complexity, lower installation and maintenance cost of RSs compared against those of BSs, the deployment of RSs has drawn extensive attention from both industry and academia. As a typical example, IEEE 802.16j Mobile Multihop Relay (MMR) has been recognized as an economic and scalable network architecture [3].

Recent advances in cooperative relaying technology at the physical layer, such as Decode-and-Forward (D-F), can further improve the data rate by virtue of the inherent spatial diversity. The capacity improvement by cooperative relaying is due to the exploitation of all received signals that were originally taken as noise and interference, where the quality of wireless transmission can be substantially improved [4].

To fully exploit the advantages of adopting RSs as well as cooperative relaying in a cell, a foremost critical task is the location planning for RSs, namely, RS placement, which is one of the most important issues of network

- *B. Lin is with the Department of Electrical and Computer Engineering, University of Waterloo, 200 University Avenue West, Waterloo, ON N2L 3G1, Canada, and the Department of Information Engineering, Dalian Maritime University, 1 Linghai Road, Dalian, Liaoning 116026, China. E-mail: b2lin@bbcr.uwaterloo.ca.*
- *P.-H. Ho, L.-L. Xie, and X. (Sherman) Shen are with the Department of Electrical and Computer Engineering, University of Waterloo, 200 University Avenue West, Waterloo, ON N2L 3G1, Canada. E-mail: {pinhan, xshen}@bbcr.uwaterloo.ca, llxie@ece.uwaterloo.ca.*
- *J. Tapolcai is with the Department of Telecommunication and Media Informatics, Budapest University of Technology and Economics, Magyar tud. krt. 2, Budapest H-1117, Hungary. E-mail: tapolcai@tmit.bme.hu.*

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planning and deployment for a wireless network. The quality of RS placement no doubt has a predominant influence on the subsequent service provisioning and the operator's long-term profitability and competitiveness. Poor RS placement may lead to the diminishment of expected benefits of adopting RSs as well as a waste of the invested capital expenditures.

Two types of RSs, namely, Fixed RSs (FRSs) and Nomadic RSs (NRSs), have been studied in this paper for relaying data transmission between the BS and SSs. Since RSs cannot be placed anywhere, certain physical locations in the cell are taken as candidate positions (CPs) for placing RSs permanently (for FRSs) or for a period of time (for NRSs). NRSs are used to mitigate capacity/coverage problems and improve adaptability to traffic demands growth due to special events, emergency response, or newly emerging hot spots that generate large traffic demands. Thus, an efficient RS placement computation method which allows timely adaptation to the traffic demand change is required for the network deployment.

In this paper, we investigate the problem of capacity enhancement by jointly optimizing RS placement and bandwidth allocation in wireless cooperative networks. Our task aims at maximizing a cell capacity by properly placing the RSs such that an efficient and scalable network can be achieved. The cell capacity is defined as the total achievable rate at each SS in this study. While most previous studies related to relay placement only consider data forwarding through traditional multihop relaying [5], [6], [7], we focus on exploiting the utmost performance benefits of cooperative relaying by placing the RSs. Bandwidth allocation is taken as another closely related design dimension which has been jointly solved for achieving better performance.

The contributions of the paper are summarized as follows: 1) We identify a new design paradigm of location planning of RSs for the BWA networks, where the cooperative relaying technology is incorporated in the network design. 2) We provide a complete optimization framework for the **C**apacity **M**aximization **R**S **P**lacement (CMRP) problem, where RS placement and bandwidth allocation are jointly considered, unlike conventional approaches that decouple the placement and bandwidth allocation into two phases. The optimization framework provides a mathematical model with a fine consideration on the affecting factors in the communication environment, such as the wireless propagation environment, the cell bandwidth, and the cell layout, i.e., the geographical distribution of traffic demands of a set of fixed SSs, and a set of CPs for deploying the RSs. The outcomes of interest include the optimal (or near-optimal) locations of RSs, the association between RSs and SSs, the bandwidth allocation, and the corresponding cell capacity.

Due to the intractability caused by mixed-integer and nonlinear characteristics of decision variables in the developed mathematic formulation, finding an optimal (near-optimal) solution is challenging. We transform the developed formulation into a Mixed-Integer Linear Program (MILP) such that the resultant optimization problem can be solved by CPLEX—a well recognized optimization package for solving MILP. To avoid the exponential computation time of solving the MILP, an efficient heuristic approach is developed that can obtain the solution in polynomial time. It also enables a timely response by deploying RSs to cope with traffic demands growth. A series of case studies are conducted to verify the optimization framework and demonstrate the significant performance benefits of the cooperative relay-based network model.

The remainder of the paper is organized as follows: We review the related work in Section 2. In Section 3, the system model is presented. In Section 4, the CMRP problem along with its equivalent MILP model and the cell capacity upper bound are given. In Section 5, a heuristic approach is proposed aiming to improve the computation efficiency, followed by numerical experiments in Section 6. Section 7 concludes this paper.

2 Related Work

The node placement problem in the context of telecommunications, rooted in the fundamental study of *facility location* and *k-median* problem in operations research, is one of the most important issues in network planning and deployment. The placement problem has been widely formulated to determine the locations of communication network equipments, such as BSs, RSs, access point (APs), and gateways. It becomes an even more complicated task when the QoS, the cost incurred by the network providers, and environmental effects such as radio smog [8], are jointly taken into consideration.

Early research on relay-enabled wireless networks was mainly conducted in mobile ad hoc networks, where mobile nodes relay data to the peer neighbor nodes. The first relay-based cellular radio network was proposed in [9], which was a consequence of merging ad hoc networks and cellular networks. Relay nodes (RNs) were introduced to forward data traffic from a congested cell to a less congested neighboring cell in the Integrated Cellular and Ad Hoc Relay architecture [10]. In wireless sensor networks, subject to power constraint and requirement of network connectivity, RNs were employed for data aggregation and fusion to better balance the energy depletion and achieve prolonged lifetime of the sensor nodes (SNs) [5], [6]. In Wireless Local Area Networks (WLANs), extension points and Tetherless relay points were deployed to improve the network throughput of a rectilinear network [11] and an IEEE 802.11g-like WLAN environment under Rayleigh fading [7], respectively. Dynamic load balancing and/or scheduling schemes were reported in relay-based wireless networks [10], [12].

The placement problems have been extensively tackled by formulating into various mathematical models either in a *discrete* [11], [13] or *continuous* [14] space. In the discrete model, the design space is usually divided into rectangles (grids), and only the centers of the rectangles can be placed with an RS. The size of the grid must be sufficiently small so as to obtain satisfactory results. The TRP placement problem was formulated in a discrete space, and was solved by a Lagrangian relaxation iterative algorithm [7]. To reduce access latency in multihop wireless networks,

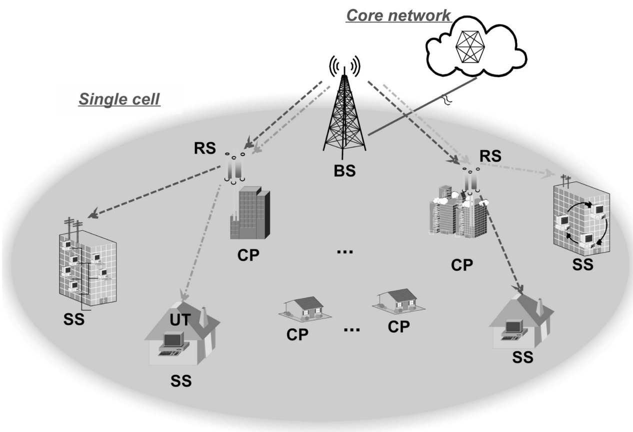


Fig. 1. A relay-based broadband wireless access network architecture.

Nuggehalli et al. [13] adopted an effective strategy with caching the server information at some distributed nodes, and proposed a polynomial-time algorithm, which can apply to any arbitrary network topology and can be implemented in a distributed and asynchronous manner. In the continuous case, since no restriction is on the position of placement, the traditional optimization algorithm (e.g., quasi-Newton method [15] and direct search methods [16]) can be employed to solve the placement problem. In [14], to determine the coverage, connectivity, cost, and lifetime of a Wireless Sensor Network, Wang et al. formulated the sensor placement into a minimum set covering problem and proposed a two-phase heuristic algorithm to solve it in energy limited scenario.

In the field of information theory, numerous studies have focused on the design of cooperative communication/relaying protocols, outage probability analysis, and symbol error rate analysis. Cover and El Gamal derived the achievable rate for the Gaussian relay channel [17]. The achievable rate formula and a coding scheme for the multiple-level relay channel were reported in [18]. The multihop relaying, along with even more complex multisource multidestination structure, was shown to significantly increase the total network throughput [4]. These researches have provided the basis for our study of RS placement. To the best of our knowledge, this is the first study on RS location planning, which incorporates the cooperative relaying technology as well as bandwidth allocation to achieve better performance.

3 System Model

3.1 A Relay-Based Wireless Access Network Architecture

A three-tier network architecture is considered in the study as shown in Fig. 1, which consists of three network entities: the BS, the RSs, and the fixed SSs. The BS serves as a central controller/coordinator and handles all the routing and signaling issues in the cell. The RSs are responsible for relaying data between the BS and the associated SSs based on the given cooperative relaying strategy. The RSs have no direct connections to the core network and are eligible to be deployed at certain outdoor CPs where uninterrupted power supply can be provided. The SS may stand for a hot spot or a building at which a large amount of traffic load generated by user terminals (UTs) are aggregated at the corresponding SS. To a certain degree, the network design and deployment depends on the geographical distribution of traffic demands. Based on the statistical analysis data of traffic measurement and monitoring as well as the anticipation of traffic load growth [19], the mean and peak traffic load demand of each SS can be estimated for the network planning. For the sake of long-term network deployment, upgrading, and extensions, we take the geographical distribution of peak traffic load demands at SSs as a known input in this study.

The BS can be multiple accessed simultaneously by different SSs at their assigned frequency band with the Orthogonal Frequency-Division Multiple Access (OFDMA) technique. In other words, each transmission between the BS and an SS is inherently an instance of the basic "BS-RS-SS" three-node relay model, where the three wireless links, BS-SS, BS-RS, and RS-SS links, are assigned a common frequency spectrum. In addition, due to the consideration regarding transmission delay, only two-hop cooperative relaying is assumed in this study. The COST231-Hata model is adopted as the radio propagation model which is applicable to the transmissions inside an urban environment [20]. Small scale fading is not explicitly included in the system model since a long-term planning and design is targeted.

3.2 Cooperative Relaying Strategy

A cooperative relay with the D-F technology is adopted in the wireless networks. The relay cooperates with the source by demodulating and decoding the received data packets, and forwarding them to the destination possibly using a different code. With D-F cooperative relaying, an alternative connection between the source and the destination is established through two shorter ranged links with better reliability and larger data rates. D-F allows an interference-free transmission when all transmissions share a common frequency band [18]. Because the relay decodes the received packet, reencodes it using a different channel code, and (re)transmits the reencoded packet to the destination. The channels used by the source and by the relay are orthogonal such that no interference exists. In contrast, conventional noncooperative relaying uses same channel code at both source and relay. The relay simply forwards the received data to the destination. The destination will receive the signals from both the source and the relay within a same frequency band, so their signals will interfere with each other. The simplest relay channel model is a class of three node communication networks [17], as shown in Fig. 2. With D-F cooperative relaying, the achievable rate for the destination node is

$$r = \min\left\{r^{(1)}(\theta), r^{(2)}(\theta)\right\}, \tag{1}$$

where

$$r^{(1)}(\theta) = C\left(\theta \frac{P_s}{N_0 d_{sr}^{\alpha}}\right),$$

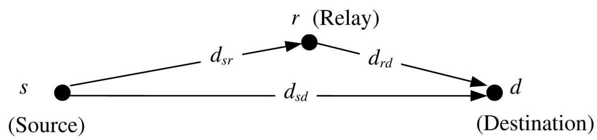


Fig. 2. The three-node relay channel model.

and

$$r^{(2)}(\theta) = C\left(\frac{P_s}{N_0 d_{sd}^{\alpha}} + \frac{P_r}{N_0 d_{rd}^{\alpha}} + \frac{2}{N_0}\sqrt{(1-\theta)\frac{P_s P_r}{(d_{sd} d_{rd})^{\alpha}}}\right).$$

$C(.)$ is a Shannon function defined as $C(x) = \frac{1}{2}\log(1+x)$ for $x \geq 0$. α is the path loss exponent, P_s and P_r are the transmit power of the source and the relay, respectively. d_{sr}, d_{sd}, and d_{rd} are the distances illustrated in Fig. 2. N_r and N_d are the noise power at the relay and destination node, respectively. Parameter θ $(0 < \theta < 1)$ is the transmit power allocation ratio at the source node between the "source-relay" path and "source-destination" path, which is an important parameter in (1) that affects the achievable rate dramatically.

To facilitate the CMRP formulation in a wireless network with multiple RSs and multiple SSs, so called *multi-RS-multi-SS* (*MRMS*) relay model, we need to derive the close form expression of optimal transmit power allocation ratio of the source node, denoted as θ^*, in the fundamental three-node relay model such that the achievable rate r can be maximized given the locations of the source, relay, and destination. For simplicity, we assume $N_r = N_d$ and is normalized to one. The optimal source power allocation ratio θ^* is expressed as

$$\theta^* = \arg\max_{\theta}\left[\min\left(r^{(1)}(\theta), r^{(2)}(\theta)\right)\right]. \quad (2)$$

Since $r^{(1)}(\theta)$ is a monotonously increasing function of θ, and $r^{(2)}(\theta)$ is a monotonously decreasing function of θ, the optimal value of θ must be the value when $r^{(1)}(\theta) = r^{(2)}(\theta)$. Therefore, θ^* is given by

$$\theta^* = \begin{cases} \frac{d_{sr}^{\alpha}}{P_s}\left(\frac{2(-d_{rd}^{\alpha}P_r + \sqrt{u})}{d_{sd}^{\alpha}d_{rd}^{\alpha}} + \frac{P_s}{d_{sd}^{\alpha}} + \frac{P_r}{d_{rd}^{\alpha}}\right), & \text{for } u \geq 0, \\ 1, & \text{for } u < 0, \end{cases} \quad (3)$$

where $u = P_r(d_{sd}^{\alpha} - d_{sr}^{\alpha})(P_s d_{rd}^{\alpha} - P_r d_{sr}^{\alpha})$.

We had investigated the performance gains of single RS placement with D-F and Compress-and-Forward mode in [21]. The benefits of cooperative relaying are mainly due to the potential spatial diversity of the virtually formed antenna arrays at the source and the RS. Performance gain can be obtained and demonstrated via either a higher data rate or an increase in cell coverage at the same power level, or a reduced transmit power at the same data rate.

4 RS Placement in MRMS Relay Model

The RS placement problem with multiple RSs and multiple SSs (or referred to as the MRMS model) is studied in this section, where the full-duplex D-F cooperative relaying strategy is adopted. Note that the other cooperative relaying strategy (e.g., the C-F scheme) can be adopted, and the RS placement problem can be formulated in a similar manner.

TABLE 1
Definitions of Symbols

Symbol	Definition
K	The number of RSs to be deployed within the cell.
$\mathbb{N}_{\mathbb{SS}}$	The set of SSs, $\lvert\mathbb{N}_{\mathbb{SS}}\rvert = N$.
$\mathbb{N}_{\mathbb{CP}}$	The set of CPs, $\lvert\mathbb{N}_{\mathbb{CP}}\rvert = M$.
$\mathbb{N}_{\mathbb{RS}}$	The set of RSs, $\lvert\mathbb{N}_{\mathbb{RS}}\rvert = K$.
ρ_n	The minimum traffic demand for SS$_n$.
$\mathbb{P}$	The set of minimum traffic demand for SSs, $\mathbb{P} = \{\rho_n, \forall n \in \mathbb{N}_{\mathbb{SS}}\}$.
d_{ij}	The distance between node i and node j.
d_m	The distance between the BS and CP$_m$.
d_n	The distance between the BS and SS$_n$.
α	Attenuation factor.
θ	The power allocation ratio of BS between the relay path and direct transmission path.
P_{BS}	The transmit power of BS.
P_{RS}	The transmit power of RS.
BW	The upper bound of radio bandwidth allocated to the cell.
$\mathcal{C}$	The cell capacity.
$\mathbb{A}$	The RS-SS incidence matrix (decision variable), $\mathbb{A} = (a_{mn})_{M\times N}$.
$\mathbb{W}$	The bandwidth-allocation vector (decision variable), $\mathbb{W} = (\omega_n)_{1\times N}$.
$\mathbb{Z}$	The RS location incidence vector (decision variable), $\mathbb{Z} = (z_m)_{1\times M}$.

4.1 Problem (CMRP) Formulation

Problem (CMRP) is defined as follows:

Given the locations and the traffic load demands of N SSs, the finite locations of M CPs for deploying RSs, total bandwidth allocated to the cell, and transmit power of the BS and RSs, the CMRP problem is to maximize the cell capacity, denoted as $\mathcal{C}$, by deploying a set of fixed number of $K (K < M)$ RSs and allocating bandwidth to each SS.

The decision variables of Problem (CMRP) are $\mathbb{Z}$, $\mathbb{A}$, and $\mathbb{W}$. $\mathbb{Z} = (z_m)_{1\times M}$ is an *RS location incidence vector*, such that

$$z_m = \begin{cases} 1, & \text{if an RS is placed at CP}_m, m \in \mathcal{N}_{CP}; \\ 0, & \text{otherwise.} \end{cases}$$

$\mathbb{A} = (a_{mn})_{M\times N}$ is an SS-CP incidence matrix, or the *location-allocation matrix*, such that

$$a_{mn} = \begin{cases} 1, & \text{if SS}_n \in \mathcal{N}_{SS} \text{ is relayed via an RS at CP}_m \in \mathcal{N}_{CP}; \\ 0, & \text{otherwise.} \end{cases}$$

$\mathbb{W} = (\omega_n)_{1\times N}$ is the *bandwidth allocation vector*, where ω_n is the amount of bandwidth assigned to SS_n. The notations taken in Problem (CMRP) are listed in Table 1.

The formulation of Problem (CMRP) can be expressed as

$$(\text{CMRP})\ \underset{\mathbb{Z},\mathbb{A},\mathbb{W}}{maximize} \quad \mathcal{C} = \sum_{n=1}^{N}\omega_n\sum_{m=1}^{M}a_{mn}r_{mn}, \quad (4)$$

subject to

$$\omega_n \sum_{m=1}^{M} a_{mn} r_{mn} \geq \rho_n, \quad \text{for} \quad \forall n \in \mathbb{N}_{\mathbb{SS}}, \tag{5}$$

$$\sum_{m=1}^{M} a_{mn} = 1, \quad \text{for} \quad \forall n \in \mathbb{N}_{\mathbb{SS}}, \tag{6}$$

$$a_{mn} \leq z_m, \quad \text{for} \quad \forall n \in \mathbb{N}_{\mathbb{SS}}, \forall m \in \mathbb{N}_{\mathbb{CP}}, \tag{7}$$

$$\sum_{m=1}^{M} z_m = K, \tag{8}$$

$$\sum_{n=1}^{N} w_n \leq BW, \tag{9}$$

$$a_{mn} \in \{0,1\}, \quad \text{for} \quad \forall n \in \mathbb{N}_{\mathbb{SS}}, \forall m \in \mathbb{N}_{\mathbb{CP}}, \tag{10}$$

$$z_m \in \{0,1\}, \quad \text{for} \quad \forall m \in \mathbb{N}_{\mathbb{CP}}, \tag{11}$$

where $r_{mn} = \min[C(\theta^* \frac{P_{BS}}{d_m^\alpha}), C(\frac{P_{BS}}{d_n^\alpha} + \frac{P_{RS}}{d_{mn}^\alpha} + 2\sqrt{\theta^* \frac{P_{BS}P_{RS}}{(d_n d_{mn})^\alpha}})]$, d_m (d_n) represents the distance between the BS and CP_m (SS_n), and θ^* is the optimal power allocation ratio which is given by (3).

The objective function (4) maximizes the cell capacity in the MRMS relay model. Constraint (5) ensures that the throughput of each SS is no less than its minimal traffic load demand. Constraint (6) ensures that each SS is exclusively associated with a single RS. Constraint (7) ensures that if SS_n is associated with CP_m, an RS must first be placed at CP_m. Constraint (8) stipulates that K RSs are allocated among the M CPs. Constraint (9) is the bandwidth constraint of the cell. Constraints (10) and (11) state that each entry in the decision variables of $\mathbb{A}$ and $\mathbb{Z}$ is binary.

The mixed-integer and nonlinear characteristics of the formulation will result in computational intractability. To facilitate a more systematic and efficient computation, we reformulate Problem (CMRP) from an MINLP into an MILP, such that the optimal solution can be obtained by using a well recognized high performance optimization solver CPLEX for MILP problems [22].

4.2 MILP Model of Problem (CMRP)

The reformulated problem is denoted as Problem (CMRP-MILP). In order to realize the model transformation and eliminate the nonlinearity in the original CMRP model, a new set of decision variables is introduced and defined as follows: $\mathbb{B} = (b_{mn})_{M\times N}$ such that $b_{mn} = \omega_n$ if SS_n is relayed via CP_m and allocated ω_n bandwidth; otherwise, $b_{mn} = 0$.

$$\text{(CMRP-MILP)} \quad \text{maximize} \quad \mathcal{C} = \sum_{m=1}^{M}\sum_{n=1}^{N} b_{mn} r_{mn}, \tag{12}$$

subject to

$$\sum_{m=1}^{M} b_{mn} r_{mn} \geq \rho_n, \quad \text{for } \forall n \in \mathbb{N}_{\mathbb{SS}}, \tag{13}$$

$$b_{mn} \geq 0, \quad \text{for } \forall m \in \mathbb{N}_{\mathbb{CP}}, \forall n \in \mathbb{N}_{\mathbb{SS}}, \tag{14}$$

$$b_{mn} \leq B a_{mn}, \quad \text{for } \forall m \in \mathbb{N}_{\mathbb{CP}}, \forall n \in \mathbb{N}_{\mathbb{SS}}, \tag{15}$$

$$b_{mn} \leq BW(1 - a_{mn}) + \omega_n, \quad \text{for } \forall m \in \mathbb{N}_{\mathbb{CP}}, \forall n \in \mathbb{N}_{\mathbb{SS}}, \tag{16}$$

$$\sum_{m=1}^{M} z_m = K, \tag{17}$$

$$a_{mn} \leq z_m, \quad \text{for } \forall m \in \mathbb{N}_{\mathbb{CP}}, \forall n \in \mathbb{N}_{\mathbb{SS}}, \tag{18}$$

$$\sum_{m=1}^{M} a_{mn} = 1, \quad \text{for } \forall n \in \mathbb{N}_{\mathbb{SS}}, \tag{19}$$

$$\sum_{n=1}^{N} w_n \leq BW, \tag{20}$$

$$a_{mn} \in \{0,1\}, \quad \text{for } \forall m \in \mathbb{N}_{\mathbb{CP}}, \forall n \in \mathbb{N}_{\mathbb{SS}}, \tag{21}$$

$$z_m \in \{0,1\}, \quad \text{for } \forall m \in \mathbb{N}_{\mathbb{CP}}. \tag{22}$$

Proposition 1. *The optimal solution of Problem (CMRP) is identical with that of Problem (CMRP-MILP).*

Proof. To prove the proposition, we will show that the objective functions and the constraints of the two problems are equivalent.

Clearly, the objective function of (12) and constraint (13) in Problem (CMRP-MILP) are equivalent to those of (4) and (5) in Problem (CMRP), respectively. In addition, the constraints (19)-(22), in Problem (CMRP-MILP) are the same as the constraints (6) and (9)-(11) in Problem (CMRP). To show that the decision variable $(b_{mn})_{M\times N}$ is defined validly in the domain, the constraints (14)-(16) function as follows: If $a_{mn} = 0$, then $b_{mn} \leq 0$ by (15) and $b_{mn} \leq BW + \omega_n$ by (16), with (14), thus $b_{mn} = 0$. If $a_{mn} = 1$, then $b_{mn} \leq BW$ by (15), $b_{mn} \leq \omega_n$ by (16), and with (14), thus, $0 \leq b_{mn} \leq \omega_n$. Such a relaxation of b_{mn} does not change the solution of the problem. Therefore, the formulations of the two problems are equivalent, and there is no nonlinear constraints and objective function in the Problem (CMRP-MILP). In other words, the optimal solution of Problem (CMRP) equals that of Problem (CMRP-MILP). □

4.3 Upper Bound of the Cell Capacity Given a Network Configuration

We derive an upper bound of the cell capacity $\mathcal{C}^{\mathcal{UB}}$. This analytical bound can be used to assist the fast estimation of cell capacity performance given a specific *network configuration*. The *network configuration* here refers to the cell bandwidth and network layout information which consists of the locations of a set of CPs for deploying RSs and a set of SSs. Note that this analytical bound is independent of the number of deployed RSs.

Let $\omega_n = \omega_n^0 + \Delta_n$, where ω_n^0 denotes the minimum bandwidth allocated to SS_n to achieve the rate requirement

ρ_n given the associated RS's location information. To minimize the ω_n^0 that is allocated to SS_n while ρ_n is achieved, the rate of SS_n needs to be maximized. Namely, $\omega_n^0 = \min_{\forall m} \frac{\rho_n}{r_{mn}} = \frac{\rho_n}{\max_{\forall m} r_{mn}}$. For $SS_n (\forall n \in \mathbb{N}_{SS})$, $a_{mn} = 1$ when $m = \arg\max_{\forall m} r_{mn}$; otherwise, $a_{mn} = 0$. Then, we can derive the upper bound of the cell capacity as follows:

$$\begin{aligned}
\mathcal{C} &= \sum_{m=1}^{M} \sum_{n=1}^{N} a_{mn} \omega_n r_{mn} = \sum_{m=1}^{M} \sum_{n=1}^{N} a_{mn} \left(\omega_n^0 + \Delta_n\right) r_{mn} \\
&= \sum_{m=1}^{M} \sum_{n=1}^{N} a_{mn} \omega_n^0 r_{mn} + \sum_{m=1}^{M} \sum_{n=1}^{N} a_{mn} \Delta_n r_{mn} \\
&= \sum_{n=1}^{N} \rho_n + \sum_{n=1}^{N} \Delta_n \sum_{m=1}^{M} a_{mn} r_{mn} \\
&\leq \sum_{n=1}^{N} \rho_n + \max\left(\sum_{n=1}^{N} \Delta_n \left(\sum_{m=1}^{M} a_{mn} r_{mn} \right) \right) \\
&\leq \sum_{n=1}^{N} \rho_n + \left(BW - \sum_{n=1}^{N} \omega_n^0 \right) \max_{\forall n, \forall m} (r_{mn}).
\end{aligned} \tag{23}$$

Therefore, the upper bound of the cell capacity is expressed as

$$\mathcal{C}^{\mathcal{UB}} = \sum_{n=1}^{N} \rho_n + \left(BW - \sum_{n=1}^{N} \frac{\rho_n}{\max_{\forall m} r_{mn}} \right) \max_{\forall n, \forall m} (r_{mn}). \tag{24}$$

Remark 1. Equation (24) can be employed to evaluate if the capacity requirement can be satisfied with current network configuration. If not, it indicates that the sum total of the minimum traffic demands at SSs exceed the capacity that the current network configuration can provide; in other words, upgrading current network configuration with more cell bandwidth and/or more CPs are needed to achieve the design requirement.

Remark 2. Another constraint,

$$\mathcal{C} \leq \mathcal{C}^{\mathcal{UB}}, \tag{25}$$

can be added in the formulation of problem (CMRP) and problem (CMRP-MILP). Constraint (25) is capable of speeding up the calculation of solutions due to the reduction of search space.

5 An Efficient Heuristic to Solve Problem (CMRP)

To avoid the exponential computation time of solving Problem (CMRP-MILP), we propose an efficient heuristic approach to solve Problem (CMRP) in this section. The pseudocode is shown in Algorithm 1, which is described as follows.

Algorithm 1: A Proposed Heuristic Algorithm for Problem (CMRP)

Input: $M, N, K, \mathbb{N}_{CP}, \mathbb{N}_{SS}, \mathbb{P}, P_{BS}, P_{RS}, BW, \alpha$;
Output: $\mathcal{C}, \mathbb{N}_{RS}, \mathbb{A}, \mathbb{W}$;
1 **begin**
2 $\mathbb{N}_{RS} = \Phi; \mathbb{A} = zeros([M, N]); n = 1;$ // *Initialization.*
3 $\mathcal{C}^{UB} \leftarrow$ **Capacity_Estimation**; // *Estimate upperbound of cell capacity given current network configuration.*
4 **if** $\mathcal{C}^{UB} < \sum(\mathbb{P})$ **then**
5 **return** Display ("No solutions exist for current network configuration!");
6 **end**
7 **else**
8 Sort($\mathbb{P}$, *'desc'*); Reorder ($\mathbb{N}_{SS}$);
9 **while** $|\mathbb{N}_{RS}| < K$ **do**
10 $Q_n \leftarrow$ **BestCP4SS**$(n, \mathbb{N}_{CP})$;
11 //*Find the best CP for* SS_n *among* $\mathbb{N}_{CP}$ *such that* $Q_n = \arg \max_{\forall m \in \mathbb{N}_{CP}} r_{mn}$;
12 $\mathbb{N}_{RS} \leftarrow Q_n$;
13 $\mathbb{A} \leftarrow$ **QMapA** (Q_n);
14 //Q_n *is mapped to* $\mathbb{A}$ *such that* $a_{Q_n,n} = 1$;
15 $n = n + 1$;
16 **end**
17 **for** $j = n$ *to* N **do**
18 $Q_j \leftarrow$ **BestCP4SS**$(j, \mathbb{N}_{RS})$;
19 //*Find the best CP for* SS_j *among* $\mathbb{N}_{RS}$ *such that* $Q_j = \arg \max_{\forall m \in \mathbb{N}_{RS}} r_{mj}$;
20 $\mathbb{A} \leftarrow$ **QMapA** (Q_j);
21 //Q_j *is mapped to* $\mathbb{A}$ *such that* $a_{Q_j,j} = 1$;
22 **end**
23 $[\mathcal{C}, (\omega_n)_{1 \times N}] \leftarrow$ **SolveLP_BWA**$((a_{mn})_{M \times N})$; // *Allocate bandwidth to each SS given* $\mathbb{A}$ *by solving an LP*;
24 **return** $\mathcal{C}$, $\mathbb{N}_{RS}$, $\mathbb{A} = (a_{mn})_{M \times N}$, $\mathbb{W} = (\omega_n)_{1 \times N}$
25 **end**
26 **end**

In essence, the process of determining the location of RS for each SS is to select an element from the set of CPs ($\mathbb{N}_{CP}$). After initialization (Line 2), the upperbound of the cell capacity is calculated using (24) and stored in $\mathcal{C}^{\mathcal{UB}}$. If $\mathcal{C}^{\mathcal{UB}}$ is less than the summation of minimum traffic demands of all the SSs (i.e., $\sum(\mathbb{P})$), it indicates that no solution exists with current network configuration. If $\mathcal{C}^{\mathcal{UB}} \geq \sum(\mathbb{P})$, then the SSs are sorted in a decreasing order in terms of their traffic demands and indexed in $\mathbb{N}_{SS}$ (Line 8). In Lines 9-16, beginning from SS_1- which denotes the SS with the largest traffic demand, all the CPs are enumerated by the function **BestCP4SS** to find the one that can provide the maximized achievable rate (denoted as Q_1), for SS_1. Namely, $Q_1 = \arg\max_{\forall m \in \mathbb{N}_{CP}} r_{m1}$, which is stored in the set of RSs (i.e., the set of selected CPs) $\mathbb{N}_{RS}$. Then Q_1 is mapped to the RS-SS association decision variable by the function **QMapA** such that $a_{Q_1,1} = 1$. The same operation repeats for the next SS. The iteration stops when the number of elements in $\mathbb{N}_{RS}$ equals K. For the remaining SSs $\in \mathbb{N}_{SS}$, in Lines 17-22, we still use function **BestCP4SS** to select the best CP in $\mathbb{N}_{RS}$ that offers the maximized achievable rate for the corresponding SS. Similarly, the index of the selected CP is then mapped to the RS-SS association decision variable. The constraints (6), (8), (10), and (11) in the CMRP formulation are guaranteed to be valid in these steps. Till now, the heuristic has obtained the solution of $\mathbb{N}_{RS}$ and $\mathbb{A}$. Next, in Line 23, the function **SolveLP_BWA** to calculate the optimal values of $\mathbb{W}$ provided $\mathbb{N}_{RS}$ and $\mathbb{A}$ by solving a linear program (BW-A) such that the cell capacity is maximized. (BW-A) is as follows:

$$\text{(BW-A)} \quad \text{maximize} \quad \mathcal{C} = \sum_{m=1}^{M} \sum_{n=1}^{N} a_{mn} \omega_n r_{mn}, \tag{26}$$

subject to

$$\sum_{m=1}^{M} a_{mn} \omega_n r_{mn} \geq \rho_n, \quad \text{for } \forall n, \tag{27}$$

$$\sum_{n=1}^{N} w_n \leq B. \tag{28}$$

Due to the maturity of current technique of solving linear programs, we can efficiently get the results of bandwidth allocation $(\omega_n)_{1\times N}$ and the objective value of cell capacity $\mathcal{C}$ immediately (Line 26), the constraints (5) and (9) are also ensured.

The analysis of the computational complexity of the above heuristic algorithm is as follows: The computation time for Lines 2-8 is $O(N \log N)$. The process of determining $\mathbb{N}_{SS}$ (Lines 9-16) yields a computation complexity $O(KM)$, and the process of allocating CPs in $\mathbb{N}_{RS}$ to the remaining SSs with smaller traffic demands (Lines 17-22) yields a worst case computation complexity $O(N(K+M))$. Line 23 yields the time complexity to solve an LP. Typically, a primal-dual interior point algorithm ensures the $O(\sqrt{N}L)$ iteration polynomial-time computation complexity, where L is the length of the binary representation of all the numbers involved [23]. Therefore, the overall computation complexity is $O(N \log N + KM + NM + \sqrt{N}L)$.

6 Numerical Results

Case studies are conducted to evaluate the solution to Problem (CMRP-MILP) and the proposed heuristic algorithm in terms of the optimality and the computational efficiency against the optimal solution. We also demonstrate the performance benefits of cooperative relaying against that without relaying and traditional multihop noncooperative relaying.

6.1 Performance of Three-Node Relay Model

Before getting into the scenarios with multiple RSs and multiple SSs, the performance gain in a simplest three-node relay model is investigated, aiming to show the impact of the relay's relative location to the destination's achievable rate as well as the significant insights to optimal RS placement in practical multi-RS-multi-SS deployment scenarios. The 1D location to the rate performance was investigated and shown in [21].

Fig. 3 shows the achievable rate gain versus the 2D location of relay. Without loss of generality, the distance

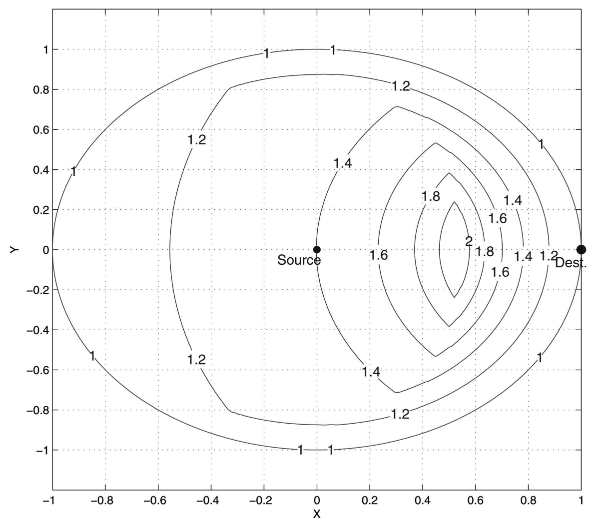


Fig. 3. 2D contour of relative rate gain.

between the source and destination is normalized as 1. The coordinates in x-axis and y-axis represent the normalized location of relay. The number shown in each contour line is the corresponding rate gain when the relay is placed at the point on the contour line. Here, rate gain is defined as $G_r = \frac{R_{relay}}{R_0}$, where R_0 is the direct transmission rate without relaying. This figure provides insights regarding the impact of the location of relay on the rate of the destination.

6.2 Performance of Multi-RS-Multi-SS Relay Model

To simulate practical CMRP problem, three cases are investigated, where an IEEE 802.16j cell with an OFDM interface is assumed in the case studies. The transmit power of the BS and RS are set to 1w and 0.5w, respectively. The attenuation factor α is set to 3. The bandwidth allocated to the cell is 20 MHz. In addition, the thermal noise is assumed to be a constant within the cell. We assume by using some frequency reuse scheme, the external interference from neighboring cells can be ignored. To simulate the presence of buildings, trees and, other obstructions in practical network environments, the shadowing effects typically result in 5-10 dB losses [24] are also taken into account in the simulations. Figs. 4a, 4b, and 4c illustrate the network layout of scenarios (I), (II), and (III), respectively. The coordinate of each SS in the cell is normalized, and the amount of traffic demand is proportional to the radius of the circle representing the SS.

The CMRP-MILP formulation is solved by CPLEX 11.0 [22] using a workstation with an Intel Zeon 3 GH CPU and 4 GB RAM. The results obtained by CPLEX are taken as a benchmark to evaluate the optimality gap by our proposed heuristic counterpart. The problem size, the number of constraints, variables, and nonzero elements of the constraint matrix, the average computation time, memory consumption, and optimality gap of the three scenarios are shown in Table 2. The computation time is averaged over different numbers of K. It can be seen that the complexity of solving the CMRP-MILP grows dramatically as the network size increases. In contrast, our proposed heuristic algorithm can solve the problem at a very fast speed which demonstrates its computation efficiency and scalability especially in practical large-scale network planning tasks.

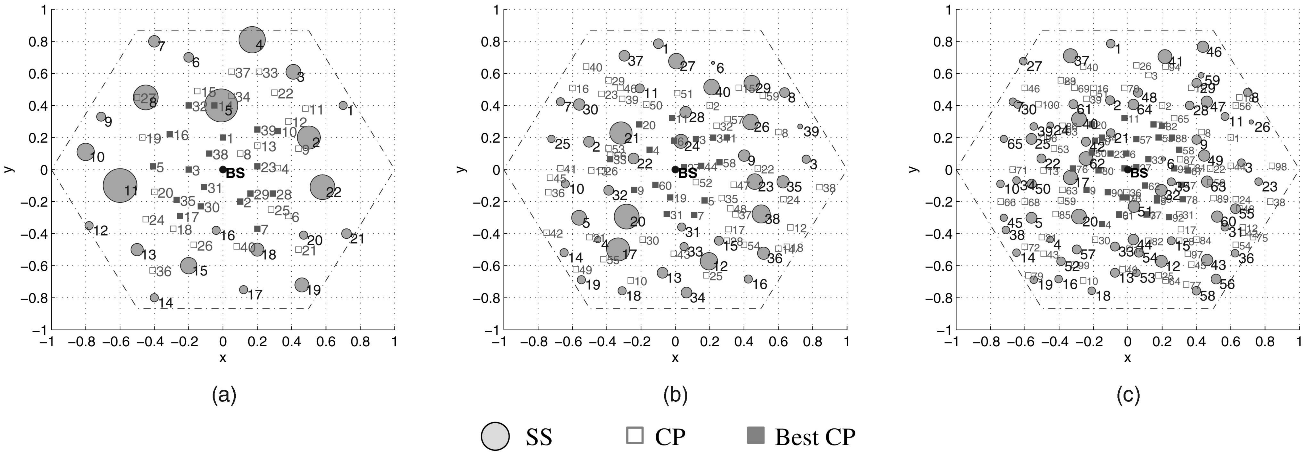


Fig. 4. Illustration of cell layout, geographical distribution of traffic demand, and best CPs for SSs in Scenario (I). (a) Scenario (I). (b) Scenario (II). (c) Scenario (III).

TABLE 2
Problem Size, Computation Time for CPLEX Solving the CMRP-MILP Formulation and Computation Time for Proposed Heuristic

Scenario	Num. of Nodes		Constraints	Variables	Nonzeros	Ave. Memory
	SS	CP				
(I)	22	40	2687	1822	7982	58.01 MB
(II)	40	60	7283	4900	21700	565.88 MB
(III)	65	100	19633	13165	58665	7372.23 MB

Scenario	Ave. Opt. Gap for CPLEX	Ave. computation time	
		CPLEX	Proposed heuristic
(I)	3.57%	631.62 Sec	1.197 Sec
(II)	4.14%	10831.74 Sec	3.422 Sec
(III)	6.20%	155174.25 Sec	9.418 Sec

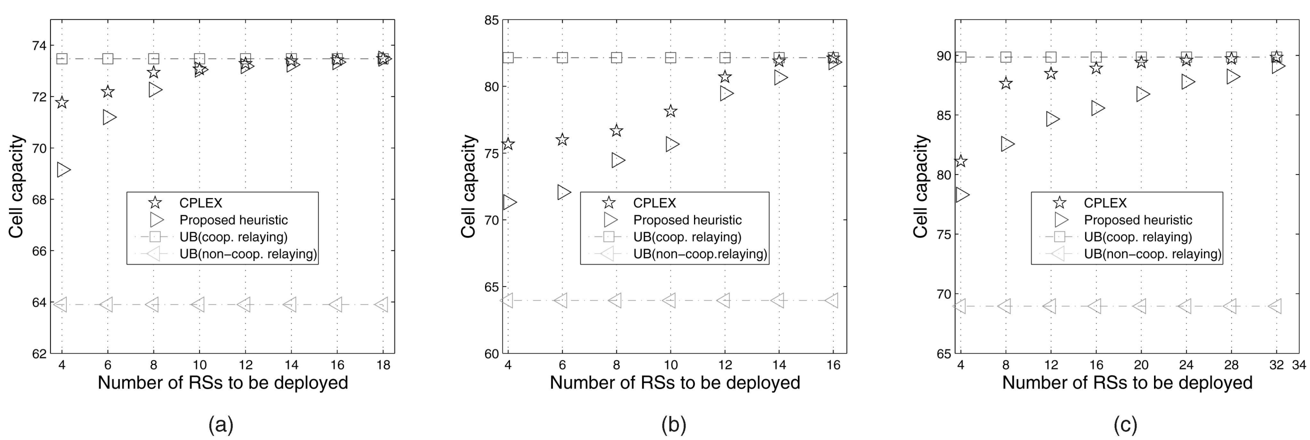
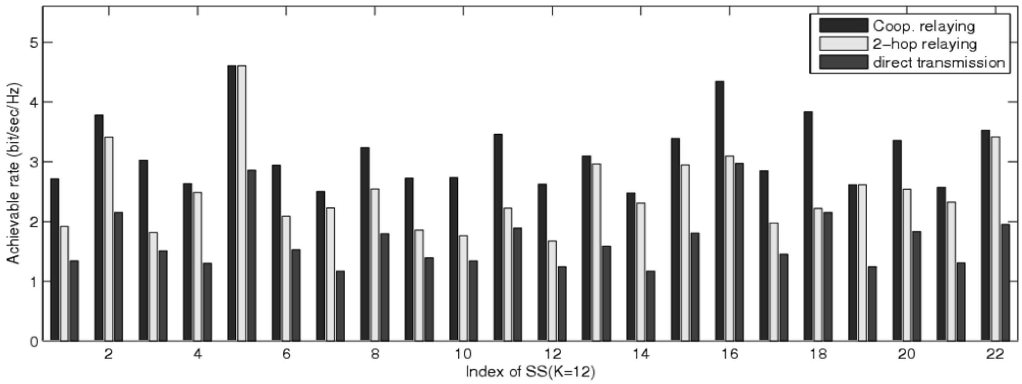


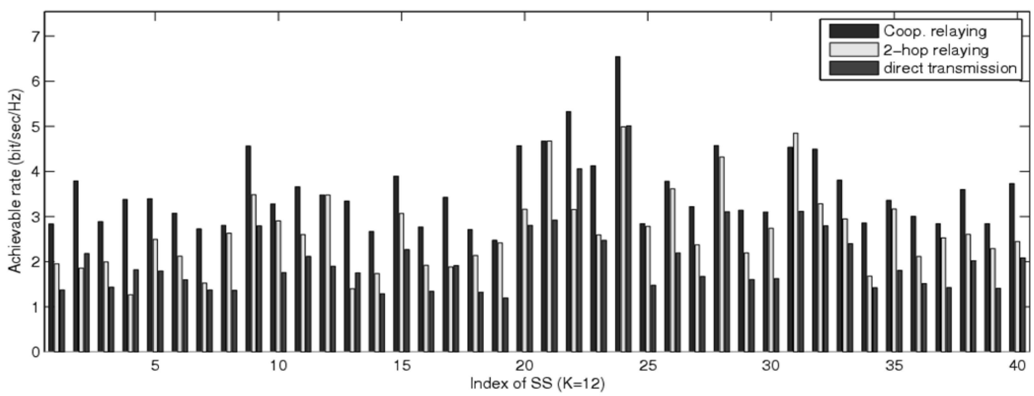
Fig. 5. Cell capacity versus number of RSs. (a) Scenario (I). (b) Scenario (II). (c) Scenario (III).

Fig. 5 shows the cell capacity with different number of RSs for the deployment in the three Scenarios. The results of proposed heuristic algorithm are compared against the optimal solution obtained with CPLEX. The upper bounds of cooperative relaying and traditional noncooperative relaying are also shown here. It can be seen that the proposed heuristic can provide a good solution with only slight degradation on the capacity performance, but it is much more computationally efficient than CPLEX. The maximum optimality gap between the heuristic solutions and optimal results in Scenario (I), (II), and (III) are 3.64, 5.74, and 5.79 percent, respectively. And cooperative relaying mode obviously outperforms noncooperative relaying mode in terms of capacity with the same deployment cost (numbers) of RSs.

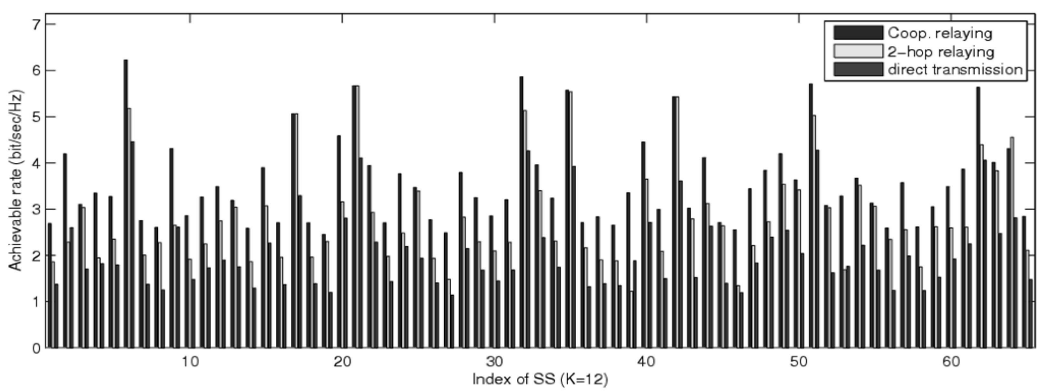
Fig. 6 compares each SS's achievable rate with 1) direct transmission, 2) cooperative relaying with $K = 12$ RSs, 3) noncooperative relaying in Scenario (I), (II), and (III),



(a)



(b)



(c)

Fig. 6. Achievable rate for each SS where 12 RSs are deployed. (a) Scenario (I). (b) Scenario (II). (c) Scenario (III).

respectively. It is clear that the data rate of each SS with relaying has a significant increase compared with that of without relaying. For instance, in Scenario (I), with cooperative relaying, the achievable rate for each SS increases from 46.27 to 113.87 percent over than that of the direct transmission case; while with noncooperative relaying, the achievable rate for each SS increases from 3.02 to 101.37 percent. Fig. 6 further demonstrates that cooperative relaying mode can achieve better rate than noncooperative relaying mode. And the transmission rate enhancement with optimal RS placement contributes substantially to the overall system performance gain in terms of the end-user throughput and the cell capacity enhancement.

7 CONCLUSIONS

In this paper, we have investigated the location planning of RS in broadband wireless access networks. The problem of joint optimal RS location and bandwidth allocation has been formulated by incorporating the cooperative relay strategy, which aims at enhancing the overall cell capacity as well as meeting the minimal traffic load demand of each SS. The proposed RS placement framework should play an important role in the future relay-based broadband wireless access network design and deployment by providing a guideline for the infrastructure providers in the effort of practical RS placement and capacity planning.

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Bin Lin received the BSc degree in computer communications in 1999, the MSc degree in computer science in 2003 from Dalian Maritime University (China), and joined the Department of Information Engineering, Dalian Maritime University, as a faculty member in the same year. She started her PhD study in 2005 and received the PhD degree in electrical and computer engineering from the University of Waterloo (Canada) in 2009. She held a postdoctoral position in the Department of Electrical and Computer Engineering, University of Waterloo, in 2009. Her research interests include wireless communications, wireless/optical network integration, network dimensioning and optimization, location problem, resource allocation, artificial intelligence, pattern recognition, neural networks, and marine remote sensing.

Pin-Han Ho received the BSc and MSc degrees from the Electrical Engineering Department at the National Taiwan University in 1993 and 1995, respectively, and the PhD degree from the Queen's University at Kingston in 2002. He is now an associate professor in the Department of Electrical and Computer Engineering, University of Waterloo, Canada. He is the author/coauthor of more than 150 refereed technical papers, several book chapters, and the coauthor of a book on optical networking and survivability. His current research interests cover a wide range of topics in broadband wired and wireless communication networks, including survivable network design, wireless Metropolitan Area Networks such as IEEE 802.16 networks, and network security. He is the recipient of the Distinguished Research Excellent Award in the Electrical and Computer Engineering Department at the University of Waterloo, the Early Researcher Award (Premier Research Excellence Award) in 2005, the Best Paper Award in SPECTS 2002, ICC 2005 Optical Networking Symposium, and ICC 2007 Security and Wireless Communications Symposium, and the Outstanding Paper Award in HPSR 2002. He is a member of the IEEE.

Liang-Liang Xie received the BS degree in mathematics from Shandong University, Jinan, China, and the PhD degree in control theory from the Chinese Academy of Sciences, Beijing, in 1995 and 1999, respectively. He held postdoctoral positions at the Automatic Control Group, Linkoping University, Sweden, during 1999-2000, and at the Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, during 2000-2002. He was a faculty member of the Institute of Systems Science, Chinese Academy of Sciences before joining the Department of Electrical and Computer Engineering, University of Waterloo, Canada, in 2005, where he is currently an associate professor. His research interests include network information theory, wireless networks, adaptive control, and system identification. He is a senior member of the IEEE.

Xuemin (Sherman) Shen received the BSc (1982) degree from Dalian Maritime University (China) and the MSc (1987) and PhD degrees (1990) from Rutgers University, New Jersey, in electrical engineering. He is a professor and a university research chair in the Department of Electrical and Computer Engineering, University of Waterloo, Canada. His research focuses on mobility and resource management in interconnected wireless/wired networks, UWB wireless communications networks, wireless network security, wireless body area networks, and vehicular ad hoc and sensor networks. He is a coauthor of three books and has published more than 400 papers and book chapters in wireless communications and networks, control, and filtering. He served as a tutorial chair for IEEE ICC 2008, a technical program committee chair for IEEE Globecom 2007, a general cochair for Chinacom 2007 and QShine 2006, and a founding chair for the IEEE Communications Society Technical Committee on P2P Communications and Networking. He also serves as a founding area editor for the *IEEE Transactions on Wireless Communications*, editor-in-chief for *Peer-to-Peer Networking and Application*, and associate editor for the *IEEE Transactions on Vehicular Technology*, the *KICS/IEEE Journal of Communications and Networks*, *Computer Networks*, *ACM/Wireless Networks*, *Wireless Communications and Mobile Computing* (Wiley), and more. He has also served as a guest editor for *IEEE JSAC*, *IEEE Wireless Communications*, the *IEEE Communications Magazine*, *ACM Mobile Networks and Applications*, and more. He received the Excellent Graduate Supervision Award in 2006 and the Outstanding Performance Award in 2004 and 2008 from the University of Waterloo, the Premier's Research Excellence Award (PREA) in 2003 from the Province of Ontario, Canada, and the Distinguished Performance Award in 2002 and 2007 from the Faculty of Engineering, University of Waterloo. He is a registered professional engineer of Ontario, Canada, a fellow of the IEEE, and a distinguished lecturer of the IEEE Communications Society.

János Tapolcai received the MSc (2000, in technical informatics) and PhD (2005, in computer science) degrees from the Budapest University of Technology and Economics (BME), Hungary. Currently, he is an associate professor in the High-Speed Networks Laboratory in the Department of Telecommunications and Media Informatics at BME. His research interests include applied mathematics, combinatorial optimization, linear programming, communication networks, routing and addressing, availability analysis, and distributed computing. He has been involved in several related European and Canadian projects. He is an author of more than 40 scientific publications and was the recipient of the Best Paper Award at ICC 2006. He is a member of the IEEE.