Relay-Centric Radio Resource Management and Network Planning in IEEE 802.16j Mobile Multihop Relay Networks

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***Abstract*—Mobile mulihop relay (MMR) networks based on the IEEE 802.16j standard are able to extend the service area as well as improve the performance of mobile WiMAX networks. In this paper, we present a relay-centric hierarchical optimization model for jointly optimizing the radio resource management (RRM) and network planning for the relay stations in MMR networks. We consider an in-band relaying system. For a relay station, the RRM problem deals with optimizing the amount of bandwidth reserved from the base station and admission control for the mobile subscriber stations (MSSs) using relay-based transmissions so that the utility of a relay station is maximized. A Markov decision process (MDP) model is formulated to obtain the short-term optimal action of a relay station. Based on the optimal action of each relay station, the network planning problem is solved for a group of relay stations by optimizing the relay placement and base station selection over a longer period of time considering uncertainties in user mobility and traffic load in the network. A chance-constrained assignment problem (CCAP) is formulated to obtain the optimal decisions to maximize the total utility of relay stations under the probabilistic constraint on the total bandwidth usage of the base stations. Numerical results show that the proposed scheme outperforms a static scheme. The proposed radio resource management and network planning framework will be useful for design and optimization of multihop cellular wireless networks in general.**

***Index Terms*—WiMAX, IEEE 802.16j, mobile multihop relay networks, relay placement, Markov decision process (MDP), bandwidth reservation, admission control.**

I. INTRODUCTION

BROADBAND wireless access (BWA) technology based on the IEEE 802.16e/Mobile WiMAX has been developed to provide high-speed wireless connectivity to mobile users. While IEEE 802.16e provides single-hop wireless connectivity, IEEE 802.16j [1] proposed for mobile multihop relay (MMR) networks provides multihop wireless connectivity where traffic between a base station (BS) and a mobile subscriber station (MSS) can be relayed through a relay station. This MMR technology extends the service area of mobile WiMAX networks and also improves the transmission quality for users experiencing poor channel conditions. While the standard defines the physical and the MAC layer specifications for MMR networks, the issues related to the radio resource management and network planning are kept open for innovations by the network service providers and device manufacturers.

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We consider the problem of radio resource management (RRM) and network planning in IEEE 802.16j MMR networks considering in-band relaying. A relay-centric hierarchical optimization framework is proposed to optimize the utility of the relay stations under uncertainty in network conditions. The RRM problem at a relay station (RS) deals with bandwidth reservation from the BS and admission control for MSSs using relay-based transmissions. An optimization problem based on Markov decision process (MDP) is formulated and the optimal actions for an RS are obtained on a short-term basis (e.g., when an MSS joins or leaves the extended service area). This MDP formulation considers the mobility as well as the bounded rationality and independence behavior of the MSSs in choosing direct or relay-based transmission according to the received utility. The network planning problem deals with placement of the relays and selection of BSs by the relays with an objective to maximizing the transmission rate and minimizing the amount of reserved bandwidth over a long-term. The decisions on RS placement and BS selection are made jointly to maximize the long-term utility of the relay stations. A chance-constrained assignment problem (CCAP) is formulated considering the uncertainty in system parameters (e.g., traffic load from MSSs) and the optimal decisions are obtained. The objective is to minimize the cost of MMR network operation in both short and long terms.

The rest of this paper is organized as follows. Section II provides a survey on the related work. The system model and assumptions are described in Section III. The optimization formulation for bandwidth reservation and admission control at a relay station is presented in Section IV. Section V presents the optimization formulation for network planning. Numerical results are presented in Section VI. Section VII states the conclusion.

II. RELATED WORK

In [2], performance of a MAC protocol for IEEE 802.16j networks was evaluated. A scheduling scheme for the relay stations in IEEE 802.16j MMR networks was presented in [3]. In [4], a new frame structure was proposed to optimize relay-based transmissions in IEEE 802.16e networks. Methods to reduce the overhead of traffic relaying in IEEE 802.16j network were proposed in [5]. In [6], a threshold-based adaptive transmit power control (or coverage control) scheme was proposed for relay stations. In [7], extension of multicast and broadcast services (MBS) mechanism in IEEE 802.16j standard was proposed which allows a relay station to opportunistically access the idle period in the transmission frame. A similar work considering the coexistence of unicast and multicast traffic in relay networks was presented in [8]. In [9], a signaling protocol for centralized scheduling was proposed for multihop polling service (mPS) in MMR networks. In [10], a bandwidth allocation scheme was proposed for MMR networks in order to satisfy traffic demand from different user groups.

Different from the above works on medium access control (MAC) and radio resource management problems [11] in MMR networks, [12] addressed the path-selection and routing problem in IEEE 802.16j networks considering metrics such as number of hops and maximum end-to-end throughput. A similar problem was also addressed in [13], [14]. The problem of joint routing and link scheduling in IEEE 802.16j MMR networks was addressed in [15] and suboptimal algorithms based on linear programming formulation were developed.

In [16], the problem of network deployment and radio resource reuse in IEEE 802.16j MMR networks was studied and a heuristic-based placement of relay stations was introduced. In [17], the base station and relay station placement problem was formulated as an integer programming problem with an objective to minimizing the cost of their installations under the constraint on traffic demand from the users. A clustering approach was applied to the same problem in [18]. In [19], a heuristic algorithm was proposed to obtain the minimum number of relay stations in an MMR network. The capacity of an IEEE 802.16j network for uplink transmissions using cooperative diversity was evaluated in [20] which can be used for analyzing the trade-off between relay deployment cost and capacity improvement in the network.

The RRM and network planning model for MMR networks presented in this paper is novel in that it considers both short-term resource allocation and long-term relay placement along with BS selection for relay stations in a single framework. This model considers uncertainty in network parameters (e.g., due to user mobility, varying traffic load) which is typical in a long-term network planning problem.

III. System Model and Assumptions

We consider a set of extended service areas $\mathbb{E}$ in each cell in an IEEE 802.16j MMR network [21] (Fig. 1). One RS is installed in each service area. The RS for service area e can be placed at location l, where $l \in \mathbb{X}_e$ for a certain duration ($\mathbb{X}_e$ denotes the set of candidate locations in service area e). Due to the mobility, the number of MSSs in each extended service area is random. The arrival rate of MSSs in service area $e \in \mathbb{E}$ follows a Poisson process with average value of λ_e. An MSS can choose to either transmit directly to a BS or transmit through the RS. For direct transmission, the cost (or price) P_{di} per connection per unit of time applies, while cost P_{re} applies for a relay-based transmission. For

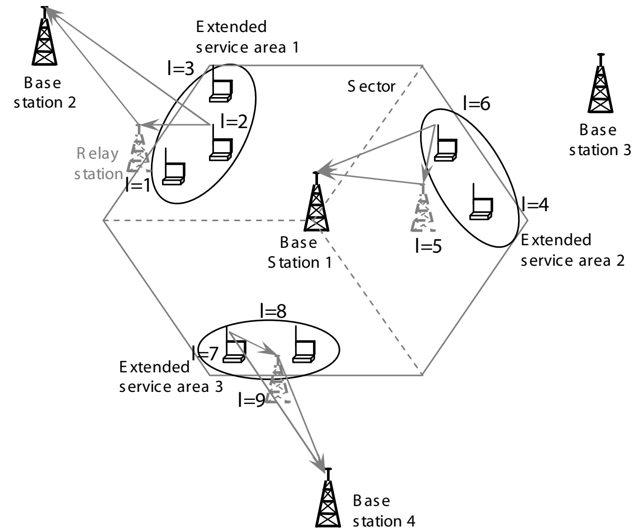

Fig. 1. System model for the MMR network.

example, P_{re} denotes the price to be paid by a mobile user to the MMR network operator (i.e., price paid by an MSS to the RS). Subscripts $_{\mathrm{di}}$ and $_{\mathrm{re}}$ stand for the direct and relay-based transmissions, respectively. For an MSS, the connection holding times for a direct transmission and a relay-based transmission are assumed to be exponentially distributed with mean $\mu_{\mathrm{di}}^{(e)}$ and $\mu_{\mathrm{re}}^{(e)}$, respectively. The decision of an MSS to use direct or relay-based transmission depends on both transmission rate and price.

The RS in a service area reserves u units of bandwidth for relaying transmissions from the MSSs to the BS (i.e., bandwidth reservation). The BS charges price P_{rl} per unit of bandwidth per unit of time to the RS. When an MSS requests the RS to relay its data to the BS, the RS may accept or reject the request (i.e., admission control). The decisions on admission control and bandwidth reservation are made by the RS in a short-term basis (e.g., few seconds). However, the decisions on relay placement and base station selection are made in a long-term basis (e.g., few weeks). These decisions can be obtained jointly since the location of relay will affect the channel quality of the transmission to the selected base station.

A. Transmission Rates for Direct and Relayed Communication

We consider an uplink transmission scenario for the MSSs using the frame structure proposed in [4]. The operating spectrum is divided into multiple subchannels and we refer to one subchannel as the *unit of bandwidth allocation/reservation*.

The average transmission rate of an MSS in extended service area e for direct communication to BS b is

$$C_{\mathrm{di}} = B_{\mathrm{di}} c_{\mathrm{di}}(e,b) = \log_2\left(1 + \gamma_{\mathrm{mb}}(b)\overline{h}_{\mathrm{mb}}(e,b)\right) \quad (1)$$

where $\gamma_{\mathrm{mb}}(b)\overline{h}_{\mathrm{mb}}(e,b)$ is the signal to interference plus noise ratio (SINR), $\overline{h}_{\mathrm{mb}}(e,b)$ is the average channel gain (i.e., due to user mobility in the extended service area), B_{di} is the bandwidth of a subchannel used by the MSS for direct transmission (subscript $_{\mathrm{mb}}$ stands for "MSS-to-BS"). Note that

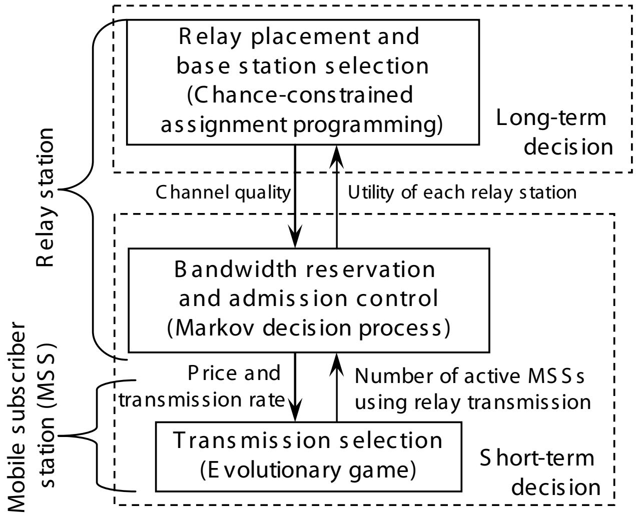

Fig. 2. Optimization framework for RRM and network planning.

$\gamma_{\rm mb}(b)$ can be obtained from [22]

$$\gamma_{\rm mb}(b) = \frac{E_{\rm b}}{I_b + N_0} \tag{2}$$

where I_b is cochannel interference caused to the direct transmission[1], and N_0 is the noise power.

For relay-based communication, the average rate of transmission for an MSS (in extended service area e) to the RS at location l and then to the BS b can be obtained from

$$C_{\rm re}(r,e,l,b) = \frac{uB_{\rm re}}{2r} \min\left\{\log_2\left(1+\gamma_{\rm mr}(e,l)\overline{h}_{\rm mr}(e,l)\right), \log_2\left(1+\gamma_{\rm rb}(l,b)\overline{h}_{\rm rb}(l,b)\right)\right\}. \tag{3}$$

Here, $\gamma_{\rm mr}(e,l)\overline{h}_{\rm mr}(e,l)$ is the SINR at the RS, and $\gamma_{\rm rb}(l,b)\overline{h}_{\rm rb}(l,b)$ is the SINR for transmission from the RS to the BS. $\gamma_{\rm mr}(e,l)$ and $\gamma_{\rm rb}(l,b)$ can be expressed in the same way as in (2). $\overline{h}_{\rm mr}(e,l)$ is the average channel gain from the MSS to the RS, and $\overline{h}_{\rm rb}(l,b)$ is the average channel gain from the RS to the BS. Subscripts $_{\rm mr}$ and $_{\rm rb}$ stand for "MSS-to-relay" and "relay-to-BS", respectively. $B_{\rm re}$ denotes the bandwidth of a subchannel used for relay-based transmission and u denotes the units of bandwidth (i.e., number of subchannels) reserved by the RS, and r is the number of MSSs in extended service area e using relay-based transmissions. Basically, the rate of the relay-based transmission is the minimum rate between MSS-to-RS and RS-to-BS.

We assume that the MSSs in an extended service area possess bounded rationality [23] and are independent to choose direct transmission to the BS or relay-based transmission through the RS. The utility of an MSS is defined as a function of transmission rates (i.e., $C_{\rm di}$ and $C_{\rm re}(r,e,l,b)$) and the cost of transmission (i.e., $P_{\rm di}$ and $P_{\rm re}$).

B. Relay-Centric Radio Resource Management (RRM) and Network Planning Framework

The relay-centric hierarchical optimization model for RRM and network planning framework consists of three parts as follows (Fig. 2):

[1]The calculation of cochannel interference I_b is, however, out of scope of this paper.

1) The first part is the *Markov-based evolutionary game* which is used to model the mobility, bounded rationality, and independence behavior of an MSS. This evolutionary game takes the transmission rate and price as inputs the transmission rate and price to determine the transmission mode (i.e., either direct or relay-based transmission) of an MSS in a particular extended service area. The details of this evolutionary game will be presented in Section IV-A.
2) The second part is the *Markov decision process (MDP)* formulation for RRM which is used to obtain optimal actions on bandwidth reservation and admission control at each RS. The details of this MDP formulation will be presented in Section IV-B.
3) The third part is the *chance-constrained assignment problem (CCAP)* formulation for network planning which is used to obtain optimal decisions on RS placement and BS selection given the solutions of MDP formulations (i.e., utilities of the RSs). The details of this CCAP formulation will be presented in Section V.

IV. Optimization of Radio Resource Management (RRM) at a Relay Station (RS)

The bandwidth reservation and admission control at a relay station are performed based on the dynamic behavior of the MSSs. First, an evolutionary game formulation is developed to model the mobility, bounded rationality and independence behavior of the MSS in a particular extended service area. Then, an MDP is formulated to obtain the optimal actions for a relay station.

A. Evolutionary Game Formulation for Transmission Mode Selection by an MSS

1) Transmission Mode Selection Algorithm: An MSS makes its decision $s \in \{{\rm di}, {\rm re}\}$ for direct and relay-based transmissions which yields the higher utility. As a function of transmission rate C_s and cost P_s (i.e., price paid to the RS), the utility is assumed to be equivalent to the rate utility per unit price, which is defined as follows:

$$U_s = \frac{\mathscr{U}(C_s)}{P_s} = \frac{\kappa_1 \log(1+\kappa_2 C_s)}{P_s}, \tag{4}$$

where

$$C_s = \begin{cases} C_{\rm di}, & s = {\rm di} \\ C_{\rm re}(r,e,l,b), & s = {\rm re} \end{cases} \tag{5}$$

and $\mathscr{U}(C_s)$ is the rate utility which is chosen to be a logarithmic function. κ_1 and κ_2 are the constants of this rate utility function. $U_{\rm di}$ and $U_{\rm re}$ denote the utility of an MSS gained from the direct and relay-based transmissions, respectively.

In the transmission mode selection algorithm (as given in Algorithm 1), the MSS maintains the knowledge about the utility given decision s made before. The knowledge $K_{\rm ut}(s)$ is defined as the exponential moving average of the perceived utility of the MSS. $K_{\rm ut}(s)$ is used by the MSS to make the current decision. Once the current decision is made, the resulting utility is used to update knowledge $K_{\rm ut}(s)$. To avoid local optimal decisions (e.g., due to the lack of complete network information), the MSS may make an irrational decision with small probability ρ to explore utility resulting from alternative decisions.

Algorithm 1 Transmission mode selection algorithm for an MSS

Initialize $K_{\mathrm{ut}}(s)$ which is the knowledge about the utility of the MSS
Prices of direct and relay-based transmissions, i.e., P_{di} and P_{re} are observed
repeat
  if $K_{\mathrm{ut}}(\mathrm{di}) > K_{\mathrm{ut}}(\mathrm{re})$ **then**
    if $RND() < \rho$ **then**
      MSS irrationally chooses relay-based transmission (i.e., $s = \mathrm{re}$)
    else
      MSS rationally chooses direct transmission (i.e., $s = \mathrm{di}$)
    end if
  else
    if $RND() < \rho$ **then**
      MSS irrationally chooses direct transmission (i.e., $s = \mathrm{di}$)
    else
      MSS irrationally chooses relay-based transmission (i.e., $s = \mathrm{re}$)
    end if
  end if
  MSS observes transmission rate C_s, and computes instantaneous utility U_{di} or U_{re} from (4)
  MSS updates knowledge: $K_{\mathrm{ut}}(s) = \beta U_s + (1 - \beta) K_{\mathrm{ut}}(s)$
until User terminates connection or leaves the extended service area

In Algorithm 1, $RND()$ is a random number generator function for $0 \leq RND() \leq 1$, and β $(0 < \beta < 1)$ is a constant used to update knowledge $K_{\mathrm{ut}}(s)$. Each loop corresponds to a decision epoch of the MSS to use either direct or relay-based transmission.

2) Evolutionary Game and Markov Chain Model: The above transmission mode selection algorithm for an MSS can be modeled as a Markov-based evolutionary game [24], where the *player* is the MSS, the *strategy* of the player is the decision to use direct or relay-based transmission, and the *population* is the group of MSSs in an extended service area. The *payoff* is the utility U_s. The solution of the evolutionary game is defined as the evolutionary equilibrium which determines the fraction of population choosing different strategies.

A continuous-time Markov chain can be developed for this evolutionary game for a group of MSSs in the same extended service area. The state space of this Markov chain is defined as follows $\Omega = \{(\mathcal{N}, \mathcal{R}); \mathcal{N} \in \{0, 1, \ldots, N_{\max}\}, \mathcal{R} \in \{0, 1, \ldots, \mathcal{N}\}\}$, where $\mathcal{N}$ and $\mathcal{R}$ are random variables (for $\mathcal{R} \leq \mathcal{N}$) denoting the total number of MSSs and the number of MSSs using relay-based transmission, respectively. $N_{\max}$ is the maximum number of MSSs in the extended service area. The transition rate of this Markov chain is controlled by the actions (i.e., the RRM method) of the corresponding RS. The derivation of the controlled transition rate matrix and the performance measures (e.g., evolutionary equilibrium for the MSSs and utility of the RS) can be obtained jointly based on the MDP formulation for bandwidth reservation and admission control at the RS.

B. MDP Formulation for Bandwidth Reservation and Admission Control

The RS optimizes its actions on bandwidth reservation and admission control. The state space of the MDP is defined as $(n, r) \in \Omega$. The set of actions is defined as $\mathbb{U} = \{(u, a), u \in \{0, 1, \ldots, U_{\max}\}, a \in \{0, 1\}\}$, where u is the amount of bandwidth to be reserved by the relay station, and $U_{\max}$ is the maximum reserved bandwidth. $a = 0$ and $a = 1$ correspond to the actions of rejecting and accepting an MSS to use relay-based transmission, respectively.

1) Transition Rate Matrix: The transition rate matrix of the MDP can be derived based on two cases, namely, when the RS accepts or rejects the request from an MSS to use relay-based transmission.

Accepting an MSS ($a = 1$): The transition rate matrix for the case of $u \in \{0, 1, \ldots, U_{\max}\}$ and $a = 1$ is denoted by $\mathbf{Q}(u, a = 1)$ whose element $\tilde{\mathbf{Q}}^{(u,a)}_{n,n'}$ of this matrix $\mathbf{Q}(u, a = 1)$ indicates the transition rate matrix for the number of MSSs in the extended service area changing from n to n'. This transition rate depends on the mobility of the MSSs. The matrices $\tilde{\mathbf{Q}}^{(u,a)}_{n,n+1}$ and $\tilde{\mathbf{Q}}^{(u,a)}_{n,n-1}$ account for the events that the number of MSSs in the extended service area increases and decreases, respectively (e.g., when an MSS enters or leaves extended service area). These matrices can be obtained as in (6), (7), and (9) for $n = \{0, 1, \ldots, N_{\max} - 1\}$.

$$\tilde{\mathbf{Q}}^{(u,a)}_{n,n+1} = \begin{bmatrix} \xi\lambda & (1-\xi)\lambda & & \\ & \xi\lambda & (1-\xi)\lambda & \\ & \ddots & \ddots & \\ & & \xi\lambda & (1-\xi)\lambda \end{bmatrix}. \quad (6)$$

In this case, ξ for $0 \leq \xi \leq 1$ indicates the fraction of the new MSS to initially choose direct transmission (e.g., $\xi = 0.5$). The size of matrix $\tilde{\mathbf{Q}}^{(u,a)}_{n,n+1}$ is $n \times n+1$, while that of $\tilde{\mathbf{Q}}^{(u,a)}_{n,n-1}$ is $n - 1 \times n$. The element $q^{(u,a)}_{n,n-1}(r, r')$ of matrix $\tilde{\mathbf{Q}}^{(u,a)}_{n,n-1}$ indicates the transition rate for the number of MSSs using relay-based transmission changing from r to r' for $r' \in \{r - 1, r\}$ when the total number of MSSs in the extended service area decreases. This element is obtained as follows:

$$q^{(u,a)}_{n,n-1}(r, r') = \begin{cases} (n - r)\mu_{\mathrm{di}}, & r' = r \\ r\mu_{\mathrm{re}}, & r' = r - 1. \end{cases} \quad (8)$$

The case of $r' = r$ accounts for the event that an MSS using direct transmission leaves the extended service area, and the case $r' = r - 1$ accounts for the same event for an MSS using relay-based transmission. Then, the matrix $\tilde{\mathbf{Q}}^{(u,a)}_{n,n}$ for the case that the number of MSSs in the extended service area remains the same (i.e., $n = n'$) is considered. This matrix accounts for the event that the number of MSSs using relay-based transmission changes. This matrix $\tilde{\mathbf{Q}}^{(u,a)}_{n,n}$ is defined in (9). The element $q^{(u,a)}_{n,n}(r, r')$ can be obtained from

$$q^{(u,a)}_{n,n}(r, r+1) = \begin{cases} (n - r)\left(U_{\mathrm{re}} - \overline{U}\right), & U_{\mathrm{re}} > U_{\mathrm{di}} \\ \rho, & U_{\mathrm{re}} \leq U_{\mathrm{di}} \end{cases} \quad (10)$$

$$\tilde{\mathbf{Q}}_{n,n-1}^{(u,a)} = \begin{bmatrix} q_{n,n-1}^{(u,a)}(0,0) & & & \\ q_{n,n-1}^{(u,a)}(1,0) & q_{n,n-1}^{(u,a)}(1,1) & & \\ & \ddots & \ddots & \\ & & q_{n,n-1}^{(u,a)}(n-1,n-2) & q_{n,n-1}^{(u,a)}(n-1,n-1) \\ & & & q_{n,n-1}^{(u,a)}(n,n-1) \end{bmatrix} \quad (7)$$

$$\tilde{\mathbf{Q}}_{n,n}^{(u,a)} = \begin{bmatrix} q_{n,n}^{(u,a)}(0,0) & q_{n,n}^{(u,a)}(0,1) & & \\ q_{n,n}^{(u,a)}(1,0) & q_{n,n}^{(u,a)}(1,1) & q_{n,n}^{(u,a)}(1,2) & \\ \ddots & \ddots & \ddots & \\ q_{n,n}^{(u,a)}(n-2,n-1) & q_{n,n}^{(u,a)}(n-1,n-1) & q_{n,n}^{(u,a)}(n-1,n) \\ & q_{n,n}^{(u,a)}(n,n-1) & q_{n,n}^{(u,a)}(n,n) \end{bmatrix}. \quad (9)$$

for $r = \{0, \ldots, n-1\}$

$$q_{n,n}^{(u,a)}(r, r-1) = \begin{cases} r\left(U_{\mathrm{di}} - \overline{U}\right), & U_{\mathrm{di}} > U_{\mathrm{re}} \\ \rho, & U_{\mathrm{di}} \leq U_{\mathrm{re}} \end{cases} \quad (11)$$

for $r = \{1, \ldots, n\}$ and

$$q_{n,n}^{(u,a)}(r,r) = -\sum_{n' \neq n} \sum_{r' \neq r} q_{n,n'}^{(u,a)}(r,r') \quad (12)$$

for $r = \{0, \ldots, n\}$, where $\overline{U} = \frac{rU_{\mathrm{re}} + (n-r)U_{\mathrm{di}}}{n}$ is the average utility of MSSs using direct and relay-based transmissions. Note that the number of MSSs can change due to either rational or irrational behavior of the MSSs in transmission mode selection. That is, a rational transmission mode switching will occur if the current utility of an MSS is lower than the average utility of the MSSs in the service area. On the other hand, an irrational switching occurs when an MSS explores alternative decisions to avoid locally optimal decision.

Rejecting an MSS ($a = 0$): If the relay station rejects the request from an MSS to use relay-based transmission (i.e., $a = 0$), the transition rate matrix can be obtained in a manner similar to that in the case of $a = 1$. However, the transition rate corresponding to the event that the number of MSSs using relay-based transmission increases (i.e., $r' = r + 1$) becomes zero. Therefore, matrix $\tilde{\mathbf{Q}}_{n,n+1}^{(u,a)}$ has λ as the diagonal element. Specifically, only the number of MSSs using direct transmission can increase. Also, the element of matrix $\tilde{\mathbf{Q}}_{n,n}^{(u,a)}$ becomes $q_{n,n}^{(u,a)}(r, r+1) = 0$, while the rest remains the same as in (11)-(12).

The transition rate matrix $\mathbf{Q}(u,a)$ can be transformed into an equivalent transition probability matrix $\mathbf{P}(u,a)$ by using uniformization method [25].

2) Immediate Reward: For the RS, the objective of bandwidth reservation and admission control is to maximize its utility gained from the MSSs in the corresponding extended service area. Therefore, the immediate reward of the MDP given the state $(n,r) \in \Omega$ and composite action $(u,a) \in \mathbb{U}$ is defined as follows:

$$\mathscr{R}((n,r),(u,a)) = rP_{\mathrm{re}} - uP_{\mathrm{rl}} \quad (13)$$

where n is the total number of MSSs in the extended service area, r is the number of MSSs using relay-based transmission, u is the amount of reserved bandwidth, and a is the admission control action. P_{re} is the price paid by the MSS to the RS, and P_{rl} is the price paid by the RS to the BS per unit of reserved bandwidth.

The *blocking probability* for an MSS to use relay-based transmission through an RS is defined as follows:

$$\mathscr{B}((n,r),(u,a)) = \begin{cases} 1, & (a=0) \vee (r = n = N_{\max}) \\ 0, & \text{otherwise} \end{cases} \quad (14)$$

where $\vee$ is the logical OR operator. An MSS requesting to use relay-based transmission is blocked if the action of the RS is $a = 0$ at any state, or when the number of MSSs using relay-based transmission reaches the maximum capacity of the extended service area (i.e., $r = n = N_{\max}$).

3) Optimal Policy: The solution of the MDP is defined as a policy π which is a mapping of the state $(n,r) \in \Omega$ to the composite action $(u,a) \in \mathbb{U}$, i.e., $(u,a) = \pi(m)$. This optimal policy maximizes stationary utility while maintaining stationary relay blocking probability below the threshold $B_{\max}$. An optimization problem based on MDP can be formulated to maximize $\mathscr{J}_{\mathrm{R}} = \lim_{t\to\infty} \inf \frac{1}{t}\sum_{t'=1}^{t} E_\pi\left(\mathscr{R}((\mathcal{N}_{t'}, \mathcal{R}_{t'}), (\mathcal{U}_{t'}, \mathcal{A}_{t'}))\right)$ subject to $\mathscr{J}_{\mathrm{B}} = \lim_{t\to\infty} \sup \frac{1}{t}\sum_{t'=1}^{t} E_\pi\left(\mathscr{B}((\mathcal{N}_{t'}, \mathcal{R}_{t'}), (\mathcal{U}_{t'}, \mathcal{A}_{t'}))\right) \leq B_{\max}$, where $(\mathcal{N}_{t'}, \mathcal{R}_{t'})$ and $(\mathcal{U}_{t'}, \mathcal{A}_{t'})$ denote the state and actions of the bandwidth reservation and admission control, respectively, at time t', and $E_\pi(\cdot)$ denotes the expectation over policy π.

To obtain the optimal policy π^*, the above MDP formulation can be transformed into an equivalent linear programming (LP) problem [26]. Let $\phi^*((n,r),(u,a))$ denote the optimal solution of the LP problem which indicates the probability for the RS to take action (u,a) when the state is (n,r). There is a one-to-one mapping between this optimal solution $\phi^*((n,r),(u,a))$ of the LP problem and the optimal policy π^*. Also, the solution of the LP problem is feasible if and only if a solution of the MDP formulation is feasible. The LP problem with decision variable $\phi((n,r),(u,a))$ corresponding to the MDP formulation can be expressed as in (15)-(18) for $(n,r)' \in \Omega$, where $P((n,r)'|(n,r),(u,a))$ (which is an element of matrix $\mathbf{P}(u,a)$ is the probability that the state changes from (n,r) to $(n,r)'$ when action (u,a) is taken. This matrix $\mathbf{P}(u,a)$ is obtained using uniformization method.

Given the optimal solution $\phi^*((n,r),(u,a))$ of the LP

$$\text{Maximize:} \quad \sum_{(n,r)\in\Omega}\sum_{(u,a)\in\mathbb{U}} \phi((n,r),(u,a))\mathscr{R}((n,r),(u,a)) \tag{15}$$

$$\text{Subject to:} \quad \sum_{(n,r)\in\Omega}\sum_{(u,a)\in\mathbb{U}} \phi((n,r),(u,a))\mathscr{B}((n,r),(u,a)) \leq B_{\max} \tag{16}$$

$$\sum_{(u,a)\in\mathbb{U}} \phi((n,r)',(u,a)) = \sum_{(n,r)\in\Omega}\sum_{(u,a)\in\mathbb{U}} P((n,r)'|(n,r),(u,a))\phi((n,r),(u,a)) \tag{17}$$

$$\sum_{(n,r)\in\Omega}\sum_{(u,a)\in\mathbb{U}} \phi((n,r),(u,a)) = 1, \quad \phi((n,r),(u,a)) \geq 0 \tag{18}$$

problem defined in (15)-(18), the optimal policy π^* is a randomized policy which can be obtained as follows:

$$\psi_{\pi^*}((n,r),(u,a)) = \frac{\phi^*((n,r),(u,a))}{\sum_{(u,a)'\in\mathbb{U}}\phi^*((n,r),(u,a)')} \tag{19}$$

for $\sum_{(u,a)'\in\mathbb{U}}\phi^*((n,r),(u,a)') > 0$, where $\psi_{\pi^*}((n,r),(u,a))$ is the probability for the RS to take action (u,a) for bandwidth reservation and admission control when the state is (n,r). If $\sum_{(u,a)'\in\mathbb{U}}\phi^*((n,r),(u,a)') = 0$ for any $(u,a)'$, the specific actions of $a=0$ and $u=U_{\max}$ are performed (i.e., rejecting request from an MSS to use relay-based transmission while reserving maximum amount of bandwidth). The optimal solution $\phi^*(s,u)$ can be obtained by using a standard method for solving LP problems.

C. Performance Measures

The performance measures of an RS can be obtained from the stationary state probability given the optimal actions of the RS. When optimal policy π^* is applied, the stationary state probability is denoted by $p_{\pi^*}(n,r)$ for state $(n,r)\in\Omega$. Let $\vec{\mathbf{p}}_{\pi^*} = \left[\begin{array}{ccccc} p_{\pi^*}(0,0) & \cdots & p_{\pi^*}(n,r) & \cdots & p_{\pi^*}(N_{\max},N_{\max})\end{array}\right]^T$ denote the stationary state probability vector which can be obtained by solving the following set of equations: $\vec{\mathbf{p}}_{\pi^*}^T\mathbf{P}_{\pi^*} = \vec{\mathbf{p}}_{\pi^*}^T$ and $\vec{\mathbf{p}}_{\pi^*}^T\vec{\mathbf{1}} = 1$, where $\vec{\mathbf{1}}$ is a vector of ones with proper size and

1) Performance Measures Related to MSSs in an Extended Service Area: These performance measures include the evolutionary equilibrium, average bandwidth usage, and average transmission rate. The evolutionary equilibrium of a group of MSSs in the extended service area is defined as the average number of MSSs using direct and relay-based transmissions, i.e., $\overline{n}$ and $\overline{r}$, respectively. This evolutionary equilibrium can be obtained from

$$\overline{n} = \sum_{n=1}^{N_{\max}} n\left(\sum_{r=1}^{n} p_{\pi^*}(n,r)\right), \quad \overline{r} = \sum_{n=1}^{N_{\max}}\left(\sum_{r=1}^{n} r p_{\pi^*}(n,r)\right). \tag{20}$$

The bandwidth usage indicates the average amount of bandwidth to be used by the MSSs for direct transmission and by the RS for relay-based transmission. This bandwidth usage can be obtained from

$$\theta = \sum_{n=0}^{N_{\max}}\sum_{r=0}^{n}\sum_{u=0}^{U_{\max}}\sum_{a=0}^{1} p_{\pi^*}(n,r)(nB_{\text{di}} + uB_{\text{re}}) \psi_{\pi^*}((n,r),(u,a)). \tag{21}$$

The average transmission rate of MSSs using relay-based transmission is obtained from

$$\overline{C}_{\text{re}} = \sum_{n=0}^{N_{\max}}\sum_{r=0}^{n}\sum_{u=0}^{U_{\max}}\sum_{a=0}^{1} p_{\pi^*}(n,r)\frac{C_{\text{re}}uB_{\text{re}}}{2r} \psi_{\pi^*}((n,r),(u,a)). \tag{22}$$

The average utility of an MSS can be obtained in a similar way.

2) Performance Measures for a Relay Station: These performance measures include average utility, average amount of reserved bandwidth, and relay blocking probability. The average utility of an RS can be obtained from

$$\overline{R} = \sum_{n=0}^{N_{\max}}\sum_{r=0}^{n}\sum_{u=0}^{U_{\max}}\sum_{a=0}^{1} p_{\pi^*}(n,r)\left(rP_{\text{re}} - uP_{\text{rl}}\right) \psi_{\pi^*}((n,r),(u,a)). \tag{23}$$

The average reserved bandwidth by an RS is obtained from

$$\overline{u} = \sum_{n=0}^{N_{\max}}\sum_{r=0}^{n}\sum_{u=1}^{U_{\max}}\sum_{a=0}^{1} p_{\pi^*}(n,r)u\psi_{\pi^*}((n,r),(u,a)). \tag{24}$$

For an MSS, the blocking probability at an RS is obtained from

$$B = \sum_{n=0}^{N_{\max}}\sum_{r=0}^{n}\sum_{u=0}^{U_{\max}}\sum_{a=1} p_{\pi^*}(n,r)\psi_{\pi^*}((n,r),(u,a)) + \sum_{n=N_{\max}}\sum_{r=n}\sum_{u=0}^{U_{\max}}\sum_{a=0} p_{\pi^*}(n,r)\psi_{\pi^*}((n,r),(u,a)). \tag{25}$$

Note that two of the above performance measures, namely, bandwidth usage θ and average utility $\overline{R}$, which is obtained from the short-term actions of bandwidth reservation and admission control will be used to make long-term decision on relay placement and BS selection considering multiple RSs in a cell in an MMR network.

V. Optimization of Network Planning for Relay Stations

Network planning is used to obtain the long-term decision on the locations of multiple RSs and their association with the BSs. However, in the long term, many network parameters such as connection arrival rate and connection holding times of an MSS are random. In this section, an optimization problem based on chance-constrained assignment problem (CCAP) is formulated to obtain the optimal long-term decisions.

$$\text{Maximize:} \quad \sum_{e\in\mathbb{E}}\sum_{l\in\mathbb{X}_e}\sum_{b\in\mathbb{B}_e} E_{\tilde{\lambda}_e,\tilde{\mu}_{\mathrm{di}}^{(e)},\tilde{\mu}_{\mathrm{re}}^{(e)}}\left(\overline{R}_{e,l,b}(\tilde{\lambda}_e,\tilde{\mu}_{\mathrm{di}}^{(e)},\tilde{\mu}_{\mathrm{re}}^{(e)}) - S_{e,l}\right) x_{e,l,b} \tag{26}$$

$$\text{Subject to:} \quad Pr\left(\sum_{e\in\mathbb{E}}\sum_{l\in\mathbb{X}_e} \theta_{e,l,b}(\tilde{\lambda}_e,\tilde{\mu}_{\mathrm{di}}^{(e)},\tilde{\mu}_{\mathrm{re}}^{(e)})x_{e,l,b} \geq \theta_{\max}^{(b)}\right) \leq \alpha, \quad \forall b \tag{27}$$

$$\sum_{l\in\mathbb{X}_e}\sum_{b\in\mathbb{B}_e} x_{e,l,b} \leq 1, \quad \forall e \tag{28}$$

$$\gamma_{\mathrm{mb}}x_{e,l,b} \geq \gamma_{\min}, \quad \gamma_{\mathrm{mr}}x_{e,l,b} \geq \gamma_{\min}, \quad \gamma_{\mathrm{rb}}x_{e,l,b} \geq \gamma_{\min} \tag{29}$$

$$x_{e,l,b} \in \{0,1\}. \tag{30}$$

A. Chance-Constrained Assignment Problem (CCAP) Formulation for RS Placement and BS Selection

The decisions on RS placement and BS selection are constrained by the bandwidth allocated by the BSs to the MSSs in the extended service areas. In particular, the total bandwidth usage $\theta_{e,l,b}$ of all RSs associated with the same BS b should be maintained below the threshold $\theta_{\max}^{(b)}$. The CCAP formulation for relay placement and base station selection with decision variable $x_{e,l,b}$ can then be formulated as in (26)-(30). $E_{\tilde{\lambda}_e,\tilde{\mu}_{\mathrm{di}}^{(e)},\tilde{\mu}_{\mathrm{re}}^{(e)}}(\cdot)$ is the expectation over random variables $\tilde{\lambda}_e$, $\tilde{\mu}_{\mathrm{di}}^{(e)}$, and $\tilde{\mu}_{\mathrm{re}}^{(e)}$. $\mathbb{E}$ is a set of all extended service areas in the MMR network. $\mathbb{X}_e$ and $\mathbb{B}_e$ denote, respectively, the sets of candidate locations and candidate base stations for the RS in extended service area e. $x_{e,l,b}$ is the binary variable with value of 1 if the RS is placed at location l of the extended service area e and selects to transmit to BS b. $S_{e,l}$ is a cost of installing the RS at location l. The constraint in (27) ensures that, the probability of total bandwidth usage at BS b by the corresponding RSs exceeding threshold $\theta_{\max}^{(b)}$ is maintained below the target threshold α. This is referred to as the probabilistic constraint. Note that the total bandwidth usage can exceed the threshold $\theta_{\max}^{(b)}$ of the BS b due to the uncertainty of connection arrival rate and connection holding times of MSSs. The constraint in (28) ensures that only one RS is placed in each extended service area, and a single BS is selected for each RS. The constraint in (29) ensures that the SNR is maintained above the minimum threshold $\gamma_{\min}$.

In this case, the average utility $\overline{R}_{e,l,b}(\lambda_e,\mu_{\mathrm{di}}^{(e)},\mu_{\mathrm{re}}^{(e)})$ and bandwidth usage $\theta_{e,l,b}(\lambda_e,\mu_{\mathrm{di}}^{(e)},\mu_{\mathrm{re}}^{(e)})$ are obtained (as expressed in (23) and (21), respectively) given that the optimal actions of bandwidth reservation and admission control obtained from the MDP formulation are used at each RS.

B. Deterministic Equivalent Assignment Problem

To obtain the optimal solution of the CCAP formulation for RS placement and BS selection defined in (26)-(30), a deterministic equivalent assignment problem can be formulated. Let $\mathbb{L}_e$, $\mathbb{M}_{\mathrm{di}}^{(e)}$, and $\mathbb{M}_{\mathrm{re}}^{(e)}$ denote the sample spaces (i.e., sets) for the connection arrival rate, and connection holding times of MSSs using direct and relay-based transmissions, respectively. These sets are assumed to be finite. The random variables $\tilde{\lambda}_e$, $\tilde{\mu}_{\mathrm{di}}^{(e)}$, and $\tilde{\mu}_{\mathrm{re}}^{(e)}$ take the values from these sets. To simplify the presentation, we define $\mathcal{C}_e = (\tilde{\lambda}_e,\tilde{\mu}_{\mathrm{di}}^{(e)},\tilde{\mu}_{\mathrm{re}}^{(e)})$ as the composite random variable, and $\mathcal{C}_e \in \mathbb{R}_e = \mathbb{L}_e \times \mathbb{M}_{\mathrm{di}}^{(e)} \times \mathbb{M}_{\mathrm{re}}^{(e)}$, where $\times$ denote the Cartesian product operator. The joint probability of connection arrival rate and connection holding times of MSSs, i.e., $Pr(\lambda_e,\mu_{\mathrm{di}}^{(e)},\mu_{\mathrm{re}}^{(e)})$, can be expressed as $Pr(\mathcal{C}_e)$ for extended service area e. The deterministic equivalent assignment problem with decision variables $x_{e,l,b}$ and $z_{c,b}$ corresponding to the aforementioned CCAP formulation can be expressed as in (31)-(34), where $c = (\lambda_e,\mu_{\mathrm{di}}^{(e)},\mu_{\mathrm{re}}^{(e)}) \in \mathbb{R}_e$ is a realization of random variable $\mathcal{C}_e$. The binary variable $z_{c,b}$ is used to indicate whether or not the total bandwidth usage at base station b exceeds the threshold $\theta_{\max}^{(b)}$ due to the uncertainty in connection arrival rate and connection holding times. ω is a constant corresponding to the weight for binary variable $z_{c,b}$ (e.g., $\omega = 1$). Y is a large number (e.g., $Y = 10^5$). The difference between (26) and (31) is that the expectation over random variables $\tilde{\lambda}_e$, $\tilde{\mu}_{\mathrm{di}}^{(e)}$, and $\tilde{\mu}_{\mathrm{re}}^{(e)}$ in (26) is replaced by the corresponding joint probability in (31).

This deterministic equivalent assignment problem for RS placement and BS selection can be solved using a standard method (e.g., binary integer linear programming [27]). Note that the transmit power of an RS is assumed to be fixed. To meet the constraints in (29), the location of the RS can be chosen such that γ_{mb}, γ_{mr}, and γ_{rb} are maintained above the required threshold $\gamma_{\min}$.

C. Algorithm to Obtain the Optimal RRM and Network Planning Solution

The algorithm to obtain optimal actions and optimal decisions on RRM and network planning is given in Algorithm 2. Basically, the optimal policy of MDP for bandwidth reservation and admission control is obtained given different values of random variables $\tilde{\lambda}_e$, $\tilde{\mu}_{\mathrm{di}}^{(e)}$, and $\tilde{\mu}_{\mathrm{re}}^{(e)}$. This optimal policy is then used to obtain the performance measure of each RS (i.e., average utility $\overline{R}_{e,l,b}(\lambda_e,\mu_{\mathrm{di}}^{(e)},\mu_{\mathrm{re}}^{(e)})$ and bandwidth usage $\theta_{e,l,b}(\lambda_e,\mu_{\mathrm{di}}^{(e)},\mu_{\mathrm{re}}^{(e)})$). Then, the deterministic equivalent assignment problem of CCAP is solved to obtain the optimal decisions of RS placement and BS selection.

VI. Performance Evaluation

A. Parameter Setting

We consider the MMR network shown in Fig. 1. The maximum number of MSSs in each extended service area is $N_{\max} = 20$. The bandwidth of a subchannel used for MSS-RS, MSS-BS, and RS-BS communication is $B_{\mathrm{di}} = B_{\mathrm{re}} = 400$ kHz, and the total number of subchannels available in a cell is 50. We assume $\gamma_{\mathrm{mb}} = \gamma_{\mathrm{mr}} = \gamma_{\mathrm{rb}} = 10$ dB, $P_{\mathrm{di}} = 1.0$, $P_{\mathrm{rl}} = 0.5$, and $P_{\mathrm{re}} = 1.0$. There are three candidate locations

$$\text{Maximize:} \quad \sum_{e\in\mathbb{E}}\sum_{l\in\mathbb{X}_e}\sum_{b\in\mathbb{B}_e}\left(\sum_{c=(\lambda_e,\mu_{\text{di}}^{(e)},\mu_{\text{re}}^{(e)})\in\mathbb{R}_e} Pr(c)\left(\overline{R}_{e,l,b}(c)-S_{e,l}\right)x_{e,l,b}+\omega z_{c,b}\right) \tag{31}$$

$$\text{Subject to:} \quad \sum_{e\in\mathbb{E}}\sum_{l\in\mathbb{X}_e}\theta_{e,l,b}(c)x_{e,l,b}-\theta_{\max}^{(b)}\leq Yz_{c,b}, \quad \forall b \tag{32}$$

$$\sum_{e\in\mathbb{E}}\sum_{c\in\mathbb{R}}Pr(c)z_{c,b}\leq\alpha, \quad \forall b, \quad \sum_{l\in\mathbb{X}_e}\sum_{b\in\mathbb{B}_e}x_{e,l,b}\leq 1, \quad \forall e \tag{33}$$

$$\gamma_{\text{mb}}x_{e,l,b}\geq\gamma_{\min}, \quad \gamma_{\text{mr}}x_{e,l,b}\geq\gamma_{\min}, \quad \gamma_{\text{rb}}x_{e,l,b}\geq\gamma_{\min}, \quad x_{e,l,b},z_{c,b}\in\{0,1\}. \tag{34}$$

Algorithm 2 Algorithm to obtain optimal actions and optimal decisions

1: **for** $e\in\mathbb{E}$, $l\in\mathbb{X}_e$, $b\in\mathbb{B}_e$ **do**
2: **for** $\lambda_e\in\mathbb{L}_e$, $\mu_{\text{di}}^{(e)}\in\mathbb{M}_{\text{di}}^{(e)}$, $\mu_{\text{re}}^{(e)}\in\mathbb{M}_{\text{re}}^{(e)}$ **do**
3: Compute SINR $\gamma_{\text{mb}}(b)\overline{h}_{\text{mb}}(e,b)$, $\gamma_{\text{mr}}(e,l)\overline{h}_{\text{mr}}(e,l)$, and $\gamma_{\text{rb}}(l,b)\overline{h}_{\text{rb}}(l,b)$
4: Solve the equivalent LP problem of the MDP defined in (15)-(18)
5: Obtain average utility $\overline{R}_{e,l,b}(\lambda_e,\mu_{\text{di}}^{(e)},\mu_{\text{re}}^{(e)})$ and bandwidth usage $\theta_{e,l,b}(\lambda_e,\mu_{\text{di}}^{(e)},\mu_{\text{re}}^{(e)})$ of RS for extended service area e
6: **end for**
7: **end for**
8: Solve the deterministic equivalent assignment problem for the CCAP defined in (31)-(34)

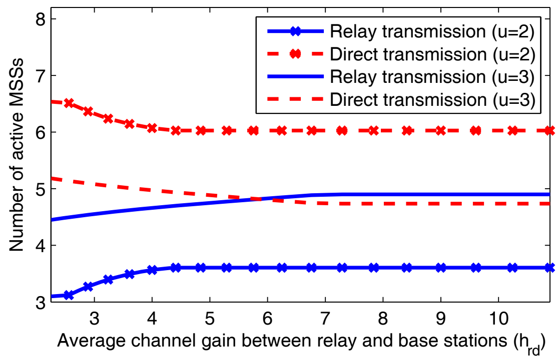

Fig. 3. The number of MSSs in a particular extended service area choosing direct and relay-based transmissions.

for the RS at each extended service area (i.e., $\mathbb{X}_1=\{1,2,3\}$, $\mathbb{X}_2=\{4,5,6\}$, and $\mathbb{X}_3=\{7,8,9\}$). The installation cost per unit of time (i.e., averaged over the service duration of an RS) for each location is $S_{e,l}=0.02$ for $l=1,\dots,9$. As shown in Fig. 1, the RS in extended service areas 1, 2, and 3 can select BS 2, 3, and 4, respectively. Also, all of the RSs can select BS 1 (i.e., $\mathbb{B}_1=\{1,2\}$, $\mathbb{B}_2=\{1,3\}$, and $\mathbb{B}_3=\{1,4\}$). For the transmission mode selection algorithm, the probability of irrational transmission mode switching by an MSS is $\rho=0.01$ and the knowledge update parameter is $\beta=0.3$. The maximum amount of bandwidth that can be reserved by an RS is $U_{\max}=4$.

We assume three connection arrival rates of $\lambda_e=0.5$, $\lambda_e=1.0$, and $\lambda_e=1.5$ per minute from the MSSs, which correspond to *low*, *medium*, and *high* traffic load, respectively. The average connection holding time is assumed to be $\mu_{\text{di}}^{(e)}=\mu_{\text{re}}^{(e)}=20$ minutes.

B. Numerical Results

The hierarchical optimization model can be used to investigate quantitatively the impacts of different system parameters such as the number of RSs, number of MSSs in the extended service areas, channel quality, cost of relay-based transmission on the system performance measures such as the average bandwidth usage in the network, utilities of the RSs, and blocking probability for an MSS at an RS. For the brevity of the paper, we only present selected numerical results.

1) Transmission Mode Selection by an MSS: We first consider the case of a single extended service area (i.e., extended service area $e=1$ as shown in Fig. 1). The RS in this service area selects to transmit data to base station $b=1$. The average MSS arrival rate in this service area is $\lambda_1=1.0$ per minute. The average channel gains are $\overline{h}_{\text{mb}}=1.02$, $\overline{h}_{\text{mr}}=5.29$, and $\overline{h}_{\text{rb}}=3.42$. The amount of bandwidth used by the RS is $u=2$.

Fig. 3 shows the number of MSSs using direct and relay-based transmissions under different channel gain between the RS and the BS (i.e., $\overline{h}_{\text{rb}}$). When this channel gain between relay and base stations improves, the transmission rate of the MSSs using relay-based transmission increases. As a result, more MSSs will choose relay-based transmission. However, when this channel gain reaches a certain point, the transmission rate no longer increases. Since in this case the transmission rate is limited by the channel quality from MSSs to the RS, the number of MSSs using relay-based transmission remains constant. With time-varying demand for relay-based transmission, the RS can reserve the proper amount of bandwidth u so that its utility is maximized.

2) Optimal Policy of an RS for Bandwidth Reservation and Admission Control: With a smaller average amount of reserved bandwidth, the optimal policy provides higher utility. This is also evident from Fig. 4 which shows the utility of an RS under different connection arrival rates. In this case the average amount of reserved bandwidth for the optimal policy lies between $\overline{u}=1.3$ and $\overline{u}=1.6$. As the price per unit of bandwidth charged by the BS, i.e., P_{rl} increases, the cost of the RS increases. Therefore, the amount of reserved bandwidth decreases.

Fig. 5 shows the average amount of reserved bandwidth by the RS under different values of ρ, the probability of

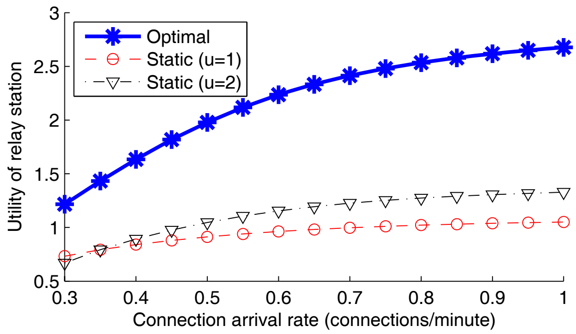

Fig. 4. Utility of a relay station under different connection arrival rate. The utility from optimal policy and static policy on bandwidth reservation and admission control are compared.

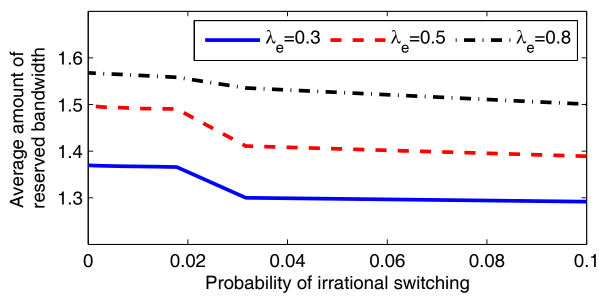

Fig. 5. Average amount of reserved bandwidth by the relay station under different probability of irrational mode switching by an MSS.

TABLE I
TRANSMISSION RATES OF RELAY STATIONS (AT DIFFERENT LOCATIONS) TO DIFFERENT BASE STATIONS

Relay station 1

	Location $l = 1$	Location $l = 2$	Location $l = 3$
Base station 1	**5.62135***	5.26401	5.46806
Base station 2	5.50545	5.56148	5.37424

Relay station 2

	Location $l = 4$	Location $l = 5$	Location $l = 6$
Base station 1	5.60446	5.28392	**5.61356***
Base station 3	5.50016	5.57459	5.39331

Relay station 3

	Location $l = 7$	Location $l = 8$	Location $l = 9$
Base station 1	5.52763*	5.18309	5.52180
Base station 4	5.43196	5.50846*	5.28429

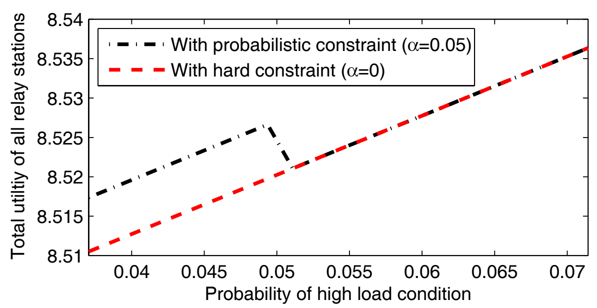

Fig. 6. Total utility of relay stations under different probability of high traffic load condition.

irrational transmission mode switching by an MSS. This irrational transmission mode switching allows an MSS to explore alternative decisions. As ρ increases, more of the MSSs switch to use direct transmission. As a result, the amount of reserved bandwidth by the RS decreases.

3) Performance of RS Placement and BS Selection under Varied Load Distribution: We consider three extended service areas as shown in Fig. 1 (i.e., $\mathbb{E} = \{1, 2, 3\}$) for which the CCAP formulation is used to obtain the decisions on RS placement and BS selection. The maximum amount of bandwidth to be used by MSSs in all extended service areas is $\theta^{(b)}_{\max} = 30$. The maximum probability that the total bandwidth usage can exceed threshold $\theta^{(b)}_{\max}$ is $\alpha = 0.05$. Table I shows the transmission rates of the RSs from the different locations to the BSs.

We vary the probability that all extended service areas have the high arrival rate of 1.5 connections/minute. When the traffic load of extended service area is light, the optimal locations for the RSs 1, 2, and 3 are given by $l^* = 1$, $l^* = 6$, and $l^* = 7$, respectively, and all the RSs transmit to BS $b^* = 1$ (Fig. 7). This result is consistent with the highest transmission rates shown in Table I. However, as the probability of high-load condition increases, the probability that total bandwidth usage of BS 1 exceeds the threshold is higher than the target value α. Therefore, RS 3 selects BS 4 (Fig. 7) so that the performance degradation at BS 1 can be avoided. In this case, RS 3 should be installed at location $l^* = 8$ instead due to the highest transmission rate (Table I). As expected, the utility increases as the probability of high-load condition increases. However, when RS 3 selects BS 4 instead of BS 1 due to the probabilistic constraint on total bandwidth usage, the utility decreases due to lower transmission rate (Fig. 6).

VII. CONCLUSION

A radio resource management and network planning framework has been proposed for IEEE 802.16j mobile multihop relay networks. For this framework, a relay-centric hierarchical optimization model has been developed to maximize the utilities of the relay stations. For radio resource management at a relay station, an optimization problem based on Markov decision process has been formulated to obtain the optimal amount of reserved bandwidth and the admission control strategy for mobile subscriber stations. This formulation considers the mobility, bounded rationality, and independence behavior of mobile subscriber stations. An optimization problem based on chance-constrained assignment problem has been formulated to obtain the optimal decisions on relay placement and base station selection. The objective is to maximize the long-term total utilities of all relay stations while the probabilistic constraint on total bandwidth usage of the base stations is met. The numerical results have shown the effectiveness of the proposed relay-centric radio resource management and network planning framework which can be used for optimization of cellular multihop relay networks in general. The problem of co-channel interference management and power allocation of the relay and base stations will be considered in our future work.

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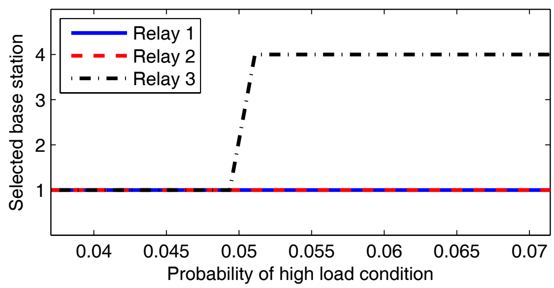

Fig. 7. Base station selection of a relay station under different probability of high arrival rate.

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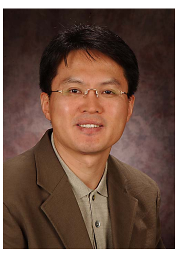

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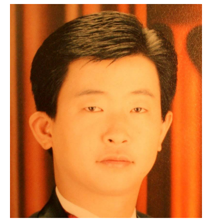

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