Abstract—In this paper, the network deployment problem for IEEE 802.16j networks is studied. We consider jointly deploying a number of base stations and relay stations to serve mobile stations distributed arbitrarily in a given geographic area such that the cost is within the budget and the system capacity is maximized. This problem is formulated as an Integer Linear Programming (ILP) model. We analyze the complexity of the problem and design an efficient two-stage network deployment algorithm which tackles both user fairness and capacity enhancement. Computational experiments are conducted to show the effect of network deployments in different traffic distribution scenarios. We also show the impact of different deployment profiles on network capacity and fairness and discuss the cost-efficiency tradeoffs between base stations and relay stations. Our numerical results indicate that deploying relay stations can enhance system capacity and fairness under the condition that the number of base stations deployed is not too small. The degree of enhancement is higher when the traffic demand distribution is concentrated in hotspots.

Keywords – IEEE 802.16j, wireless relay network, placement

I. INTRODUCTION

The increasing demand on ubiquitous wireless broadband access drives the development of the next generation wireless communications. Aiming at enhancing network capacity and coverage, multi-hop relaying is introduced to centralized wireless access networks. Many efforts have integrated the multi-hop relaying capability with cellular networks to deploy multi-hop cellular networks [1]. More recently, the IEEE 802.16 standard committees have been working on the extension of the basic 802.16 standard, known as IEEE 802.16j [2], to incorporate functions of relay stations into WiMAX networks.

In an IEEE 802.16j network, the base station (BS) is the entity that controls the resource allocation in both uplink and downlink to the mobile stations (MSs). The relay stations (RSs), connected to the backbone infrastructure through wireless links to BSs, function somewhat like a BS but are less capable and much less expensive. Multiple RSs can connect to the same BS. In addition, MSs can either connect to the BS directly or connect via RSs. By relaying data packets from a BS to an MS via RSs, a long distance link can be broken into several shorter distance links. Since the wireless signal attenuation is proportional to the link distance raised to the power of an environmental-dependent loss exponent, links with shorter distance suffer less attenuation, thus achieving better Signal-to-Noise Ratio (SNR) at the receiver. The achievable data rate of a channel is also increased with SNR. As a result, a good placement strategy of RSs can possibly improve the end-to-end achievable rate of MSs and enhance the system capacity.

RSs, however, have smaller coverage and less resource (e.g. transmission power or bandwidth) as compared with BSs. This leads to a tradeoff between the cost and efficiency between the BSs and RSs in the deployment problem. So far, not many works have been devoted to this problem. Existing works for wireless relay networks mainly focus on radio resource management and network planning [3]-[4]. In [3], an overview of various features of broadband wireless access network is presented. Several key issues for network deployment are identified and some deployment schemes are proposed toward realizing a high level of scalability. In [4], Liu et al. attempt to maximize the throughput of a centralized multi-hop relay network by calculating the best path and achievable data rate for each connection. This problem is proved to be NP-hard and a heuristic is proposed in that work.

The relay station placement problem can be found in different application scenarios, such as wireless sensor networks [5], wireless local area networks [6], and IEEE 802.16j networks [7]. In [6], Zou et al. consider placing a given number of relay stations in a multi-rate WLAN cell with a given MS distribution. This problem is then formulated as an optimization problem and solved by an iterative algorithm based on Lagrangian relaxation, under the assumption that the MS distribution is uniform. The results show that the best strategy is to have multiple ring structures of RSs evenly distributed in the cell. In [7], under the assumption of the dual-relay mode in an IEEE 802.16j network with uniformly distributed traffic, the RS placement within a single cell is formulated as a cost minimization problem. A heuristic is proposed to solve this problem.

The solutions proposed in related works [6]-[7] are only valid under the uniform traffic assumption. Such solutions may be impractical because MSs have different mobility and hotspots can be formed. Besides, related works consider the RS placements within only single cell. When considering large area deployments, they fail to handle issues such like the interferences across cells and different deployment options (i.e. whether to deploy a BS or an RS). In light of these reasons, in this paper, we tackle the joint BS and RS placement for the IEEE 802.16j network in a practical network scenario. Specifically, we consider a geographic area with non-uniformly distributed traffic demand. The objective of our problem is to maximize the system capacity under a pre-determined deployment budget constraint. We formulate this problem via an ILP model and propose a two-stage network deployment algorithm. We then evaluate the network performance with different deployment profiles.
and deduce important insights on the joint BS and RS placement problem.

The rest of this paper is organized as follows. In Section II, our system model is described. Then, the joint BS and RS placement problem is formulated in Section III. The problem analysis and solution algorithm are proposed in Section IV. The experimental results are shown in Section V. Finally, we conclude this paper in Section VI.

II. SYSTEM MODEL

We consider a geographic area with MSs distributed arbitrarily for the joint BS and RS deployment. Within this area, there are predefined sets of candidate locations for the deployment of BSs and RSs. Due to the mobility of MSs, the exact locations of MSs are hard to track; however, the number of MSs within a certain area can be pre-determined. Here, we make use of the Demand Node (DN) concept in [8] to represent the spatial distribution of traffic demand. A DN is a logical node located at the center of an area. The weight of a DN represents the quantum of traffic demand within that area. We divide the geographic area into grids. One DN lies in the center of each grid. Since traffic demand is proportional to the number of MSs, we set the weight of a DN to be the number of MSs distributed within the grid. To guarantee the service for each MS, all DNs should be covered by at least one access point (i.e., BS or RS).

Fig. 1 shows a simple example of our system architecture. Multiple BSs and RSs may be deployed in the network. For an RS to connect to a BS, it must be within the range of that BS. We assume that the RSs will always connect to the BS which gives the best channel quality. Namely, we only consider at most two-hop relaying in this paper, while our approach can also be generalized to a multi-hop scenario. Moreover, an RS can either connect directly to a BS or access the BS via an intermediate RS if it is within the BS’s or RS’s range. In our model, MSs will connect to the BS or RS that gives the maximum end-to-end achievable rate. Without loss of generality, we assume that the frequency bands for all RSs to communicate with their downstream MSs are the same. To avoid interference, the distance between any pair of RSs must exceed a certain threshold. Besides, the frequency band for the downstream communication of RSs is different from that for the upstream to BSs. Therefore, RSs are equipped with two radio interfaces operating on different frequencies for the communications with BSs and MSs simultaneously.

III. PROBLEM DEFINITION AND FORMULATION

The Joint BS and RS Deployment Problem (JBRDP) is defined as follows. Given the geographic area in which DNs are distributed, we want to determine the locations for a number of BSs and RSs, with the total cost within the pre-determined budget, such that each DN is covered by at least one BS or RS and the system capacity can be maximized.

Some notations for the JBRDP are defined as follows. $S_B$ and $S_R$ are the sets of candidate sites for BS and RS deployments, respectively, and $|S_B| = N, |S_R| = M$. Note that $S_B$ and $S_R$ are disjoint because the site selection criteria for BSs and RSs are quite different due to their different radiation power constraints and hardware installation constraints. To avoid interferences among RSs, the distance between any pair of RSs must exceed a threshold $L_i$. Let $C_B$ and $C_R$ be the deployment costs of a BS and an RS, respectively; $C^{U}$ is the deployment budget. Generally, $C_B > C_R$ and $C^{U}$ is a pre-determined constant given by the operators. The set of demand nodes is represented by $D$. Each demand node $d_i \in D$ is associated with a weight $w_i$.

The set of weights is denoted by $W$. Let $r_B$ and $r_R$ be the coverage radius of a BS and an RS, respectively, and $L(i,j)$ be the distance between any location $i$ and $j$. In this way, we can define the adjacency matrix $A_{ij} = \begin{cases} 1, & \text{if } d_i \text{ can define the adjacency matrix} \\
0, & \text{otherwise}
\end{cases}$.

We further define two decision vectors: $B = \{b_1, b_2, ..., b_N\}$ and $R = \{r_1, r_2, ..., r_M\}$, where $b_i$ (or $r_j$) equals one if and only if a BS (or RS) is deployed at the $i$th candidate site of $S_B$ (or $S_R$) is able to cover $d_i$, otherwise $b_i$ (or $r_j$) equals zero. In this way, the achievable data rate of a DN $d_i$ can be expressed as a function $r(d_i, B, R)$ because the achievable data rate is determined by the locations of BSs, RSs, and DNs. The JBRDP can be formulated as follows:

$$\max_{B, R} \sum_{d_i \in D} r(d_i, B, R) \cdot w_i$$

Subject to:

$$b_i \in \{0, 1\}, \forall i \in \{1, 2, ..., N\}$$

$$r_j \in \{0, 1\}, \forall j \in \{1, 2, ..., M\}$$

$$C_B \sum_{b_i \in B} b_i + C_R \sum_{r_j \in R} r_j \leq C^U$$

$$\sum_{i=1}^{N} a_{i,j} \cdot b_i + \sum_{i=1}^{M} a_{i,j} \cdot r_j \geq 1, \forall j \in \{1, 2, ..., M\}$$

$$L(s_{R,j}, s_{R,j}) > L_i, \forall r_i, r_j = 1$$
The objective function (1) maximizes the network aggregated achievable data rate and hence maximizes the network capacity. Constraints (2) and (3) state that the decision variables are binary. Constraint (4) ensures that the total deployment cost is less than the cost budget. Constraint (5) guarantees that each DN is covered by at least one BS or RS. Constraint (6) ensures the distance between any pair of deployed BSs to be larger than the interference threshold.

The closed form expression of $r(d_i,B,R)$ depends on the wireless channel model. We adopt the two-ray ground path loss model [10], which is generally used for estimating the signal strength over the distance of several kilometers. We define $x_i$ as the site of the serving BS for the RS at $s_{k,i}$. For $r_i=1$ (i.e., an RS is deployed at site $s_{k,i}$), $x_i$ can be calculated by $x_i = \arg \min_{s_{k,i}} L(S_{B,j},S_{R,i}) | b_j = 1 |$; for $r_i=0$, $x_i$ is null. Let $\psi(s_i,s_j) = W \log(1 + \frac{P \cdot G \cdot L^n(s_i,s_j)}{\sigma^2})$ be the achievable rate between site $s_i$ and $s_j$, where $W$ is the available bandwidth, $P$ is the transmission power, $G$ is the antenna gain, $\alpha$ is the path loss exponent and $\sigma^2$ is the white noise power. Given $B$ and $R$, the achievable data rate of demand node $d_i, r(d_i,B,R)$, can be calculated by

$$ r(d_i,B,R) = \max_{a_{ij}:B} \{1 \cdot \max_{s_{k,i}} (\psi(d_i,s_{B,j}) | a_{ij} \cdot b_j = 1), \max_{s_{k,i}} (\frac{1}{\psi(d_i,s_{B,j})} + \frac{1}{\psi(s_{B,j},x_i)} | a_{ij} \cdot b_j = 1) \} $$. 

### IV. PROBLEM ANALYSIS AND THE PROPOSED ALGORITHM

Consider a special case of JBRDP in which the traffic demand of MSs is uniformly distributed and the achievable rate of a DN is fixed regardless of where BSs and RSs are placed. In this case, the problem is equivalent to finding a number of BSs and RSs under the budget constraint such that all DNs are covered. This is actually the well-known Set Cover Problem, which is NP-complete. It follows that JBRDP is NP-hard. Since the problem is computationally intractable, we resort to designing an efficient heuristic to find sub-optimal solutions.

We start by examining the constraints of JBRDP. In constraint (4), let $n_B = \sum_{j \in B} b_j$ and $n_R = \sum_{j \in R} r_j$. Clearly, $n_B$ and $n_R$ are the number of BSs and RSs deployed in the network. The possible combinations of $(n_B,n_R)$ (i.e., not violating (4)) are referred to as the deployment profiles for the system. Given $C_B, C_R$ and $C_U$, all the deployment profiles can be enumerated with constant time computations. In this way, to solve JBRDP, we need to find the best placements of BSs and RSs for all deployment profiles.

To find the placement of BSs and RSs for a specific deployment profile $(n_B,n_R)$, we propose a two-stage network deployment algorithm. The rationale behind this algorithm is that we consider different impacts of BS locations and RS locations on the system capacity. The locations of BSs dominate the end-to-end delay and achievable data rate for DNs. Although the traffic distributions within the network may change with time, the locations of BSs can hardly be adjusted due to the hardware complexity and geographic constraints. Therefore, we do not consider traffic distributions when determining the locations of BSs. Instead, we consider giving all DNs equal priority access to the Internet through the BSs. In other words, the variance of the distance from each DN to its closest BS should be as small as possible. Therefore, in the first stage of our algorithm, we aim to determine a set of BS locations such that the longest distance between a DN and its nearest BS is minimized and the number of BSs deployed is equal to $n_B$. This problem is actually a well-known NP-complete problem: the $k$-supplier problem. The $k$-supplier problem is stated as follows. Given an edge-weighted complete graph $G = (V,E)$, where $V$ denotes the set of vertices and $E$ denotes the set of edges. The weight of edge $(i,j)$ can be considered as the distance between vertices $i$ and $j$. The set of vertices of the graph is partitioned into a supplier set $V_{sup}$ and a customer set $V_{cust}$, and each supplier vertex $i$ has a weight of $u_i$. The problem is to find a subset $V_{sup}$ of total weight at most $k$ such that every customer can be as close as possible (i.e., the edge weight is as small as possible) to the selected suppliers. For our problem, each candidate BS location...
corresponds to a supplier vertex and each DN corresponds to a customer vertex. The deployment cost of a BS for each candidate BS location corresponds to the weight of the supplier vertex. In [9], it is proved that for the \( k \)-supplier problem, the ratio of the feasible solution obtained by any approximation algorithm to the optimal solution is no less than three. Therefore, in the first stage of our algorithm, we can adopt a 3-approximation algorithm as proposed in [9] to find the BS locations for JBRDP.

The locations of BSs are determined in the first stage network deployment. However, some DNs may still be located outside the coverage of BSs. Moreover, due to different weights of DNs, the traffic load of each BS cell may be unbalanced. Since the function of RSs is to extend the coverage and enhance the throughput for the network, in the second stage of our algorithm, we intend to determine the locations of \( n_R \) RSs such that the network can cover as many DNs as possible while simultaneously improving the system capacity. To achieve this goal, we design an iterative RS locating algorithm motivated by the greedy heuristic for the Maximal Coverage Location Problem in [8]. In each iteration, the location of one RS is determined according to the marginal benefits of each candidate RS location. In other words, we calculate, for each candidate RS location \( s_{R,j} \in S_R \) on which RSs have not yet been deployed, the achievable rate gain it provides for the system, denoted by \( G(s_{R,j}, B, R) \). Given the BS placement set \( B \) determined in the first stage, and the current RS deployment vector \( R = [r_1, r_2, \ldots, r_M] \), \( G(s_{R,j}, B, R) \) can be expressed as in (7):

\[
G(s_{R,j}, B, R) = \sum_{d_i \in D} (r(d_i, B, R_j') - r(d_i, B, R)) \cdot w_i \tag{7}
\]

where \( R_j' = [r_1', r_2', \ldots, r_M'] \); \( r'_j = 1, r'_k = r_k, \forall k \neq j, k \in \{1, 2, \ldots, M\} \).

Note that \( G(s_{R,j}, B, R) \) is non-negative because \( r(d_i, B, R') \geq r(d_i, B, R) \). The RS deployment procedure stops once \( G(s_{R,j}, B, R) \) equals zero for all \( s_{R,j} \in S_R \). This may occur when the remaining candidate RS locations are all out of the BSs’ ranges. Otherwise, the candidate RS site with the maximum sum of achievable rate gain is chosen to deploy a new RS. Then, we delete the RS locations in \( S_R \) that would interfere with the currently deployed RSs, according to constraint (6). This process is repeated until either all the locations for \( n_R \) RSs are determined or \( S_R \) is empty.

The detailed operations of the two-stage network deployment algorithm are summarized in Fig. 2. The pseudo code for the \( k \)-supplier approximation algorithm can be found in [9]. The complexity of our algorithm is dominated by the sorting stage of the \( k \)-supplier approximation algorithm, which takes \( O((|S_B| + |D|)^2 \log(|S_B| + |D|)) \) time.

V. COMPUTATIONAL EXPERIMENTS AND DISCUSSIONS

In this section, we evaluate the performance of our proposed algorithm through a series of computational experiments. We generate two different MS distributions in a 25 km by 25 km geographic area: uniformly distributed or concentrated in hotspots. The geographic area is partitioned into DNs, each representing a 1 km by 1 km square area. The candidate locations for RSs are the same as the locations of DNs, and the candidate locations for BSs are the corners of all square areas. The coverage radius of a BS is 7 km, and that of an RS is 4 km. The interference threshold for RSs is 3 km. The transmission power of a BS and an RS is 7 W and 5 W, respectively. The bandwidths for a BS and an RS are both 20 MHz. The settings mentioned above are parsed into the C++ program in which our two-stage deployment algorithm is implemented. In our experiments, we set the cost of a BS and an RS to be 10 and 3 units, respectively. The deployment budget is 80 units. Since the input size for our problem (i.e., \( M+2N+|D| \), which is 1926 in our experiments) is large, it is very inefficient to find the optimal solutions by exhaustive search or by commercial tools. However, sub-optimal solutions can be found by our algorithm in a very short time.

In Fig. 3, we show the MS distributions along with the BS and RS placements calculated by the two-stage network deployment algorithm for different MS traffic distributions.
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When the deployed BSs is enough to cover most areas, the range of BSs’ and RSs cannot provide as much coverage as BSs because most candidate RS locations are outside the low, deploying more BSs is more beneficial than deploying RSs, the network achievable rate will also increase but will eventually saturate. However, incrementally deploying RSs, the network achievable rate increases with the number of BSs. Given a fixed number of BSs and RSs deployed for the MS hotspot scenario, the capacity enhancements from deploying one more BS or RS are similar, depending on the MS traffic distributions. In the MS hotspot scenario, deploying RSs gives slightly higher rate gain than BSs. Therefore, deploying RSs is more cost-efficient in the hotspot scenario.

In Fig. 5, we show the fairness index on the achievable data rate of all DNs. The fairness index is defined as follows.

$$f(\gamma_d, \gamma_o, ... \gamma_d) = \frac{(\sum_{d \in D} \gamma_d)^2}{D \sum_{d \in D} \gamma_d}$$

where $\gamma_d$ is the achievable data rate for DN $d$.

The range of the fairness index is between zero and one. The closer the fairness index to one, the lower the variance among the variables. Our numerical results in Fig. 5 indicate that deploying RSs can also help balance the rate variance among DNs. However, both Fig. 4 and Fig. 5 show that the deployment of RSs is beneficial only when the number of BSs is sufficient. Besides, the degree of capacity or fairness improvement from RSs may depend on the traffic demand distribution in the network, and the improvement is more significant when the traffic demand distribution is concentrated in hotspots.

VI. CONCLUSION

In this paper, we analyze the network deployment problem for IEEE 802.16j networks in depth. We formulate the joint BS and RS deployment problem under budget and coverage constraints as a capacity maximization problem, and prove that it is NP-hard. To tackle this computationally intractable problem, we analyze the different impacts of BSs and RSs on the system capacity and design a two-stage network deployment algorithm which considers both issues of capacity enhancement and user fairness. Through computational experiments, we show the network deployment results with different MS traffic distributions. We also show the system capacity with respect to different deployment profiles and discuss the cost-efficiency tradeoff between BSs and RSs. Our proposed algorithms and our observations can serve as guidelines for the planning of emerging IEEE 802.16j wireless networks.

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