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Coordinated Scheduling Algorithm for System Utility Maximization With Heterogeneous QoS Requirements in Wireless Relay Networks

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ABSTRACT In this paper, we focus on the radio resource management (RRM) issues in the two-hop Orthogonal Frequency Division Multiple Access (OFDMA) system with heterogeneous quality of service (QoS) requirements. To solve the RRM problem, we first propose a new two-hop frame structure to support the data relay operation from the base station to the relay station and cooperative transmission for the edge users. Then, a two-hop coordinated scheduling algorithm is proposed, which utilizes the proposed two-hop frame structure and considers the corresponding interference status. The proposed two-hop coordinated scheduling algorithm solves the RRM problem of the two-hop OFDMA system with heterogeneous QoS requirements in an iterative manner, and so maximizes the system utility.

INDEX TERMS OFDMA, heterogeneous QoS, two-hop networks, coordinated scheduling.

I. INTRODUCTION

As a hot topic with great application potential and the demand arising in the application field of big data technology [1]–[3], relay technologies associated with OFDMA have been actively studied in the standardization process of next-generation mobile communication system for the performance enhancement and deployment cost reduction, such as the systems of IEEE 802.16 [4] and 3GPP LTE-Advanced [5]. In both systems, two kinds of relay stations (RSs) are considered, transparent RS and non-transparent RS. Transparent RS is typically deployed for throughput enhancement, which is not capable of performing any resource management (RRM) function and usually controlled by a base station (BS) or a non-transparent RS depending on the cell layout. For the purpose of coverage extension, non-transparent RS is used, which is capable of transmitting its own different preamble and performing radio resource management function, as base station (BS) for its legacy users like BS.

Recently, many researches on the radio resource management in a two-hop OFDMA system have been done to maximize the system utility (i.e., system throughput or sum of normalized throughput according to the users' quality of service requirements). However, most of the researches are conducted with only transparent relay stations under the assumption of the simple 2-slot frame structure, where base station transmits to the relay station in the 1st time slot and in the 2nd time slot base and relay stations transmit to users simultaneously [6]–[8]. In addition, the problem of inter-cell interference in two-hop OFDMA system is not perfectly solved in literatures. In recent literatures, base station coordination has emerged as a means to mitigate inter-cell interference. Ideally, if both data and channel status information of all users could be shared in real time, adjacent base stations could act as a large distributed antenna array and employ joint beam forming, scheduling, and data encoding simultaneously to serve multiple co-channel users [9]–[13]. In [13], a water-filling based coordinated scheduling algorithm for the conventional single-hop OFDMA system is proposed, which utilizes the conventional general proportional fair (GPF) scheduler to allocate sub-carriers and a water-filling based power allocation algorithm to achieve the optimum trade-off between the transmission power and the

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inter-cell interference. However, the heterogeneous quality of service (QoS) requirements are not taken into consideration.

To solve the aforementioned problems, we first propose a two-hop frame structure to perform the data relay operation from the base station to the relay station and cooperative transmission for the edge users. Then, a two-hop coordinated scheduling algorithm is proposed, which considers the heterogeneous QoS requirements and special inter-cell interference environment in two-hop OFDMA systems induced by the proposed two-hop frame structure. Finally, suggestion on the deployment position of relay station is given based on the mufti-tier system-level Monte-Carlo simulation results.

The remaining part of this paper is organized as follows. Section II introduces the system model and the proposed frame structure for a two-hop OFDMA system with non-transparent RSs. Section III describes the proposed two-hop coordinated scheduling algorithm for the two-hop OFDMA system with non-transparent RSs and heterogeneous QoS requirements. Then, mufti-tier system-level Monte-Carlo evaluation results and discussions are made in section IV. Finally, conclusions are drawn in section V.

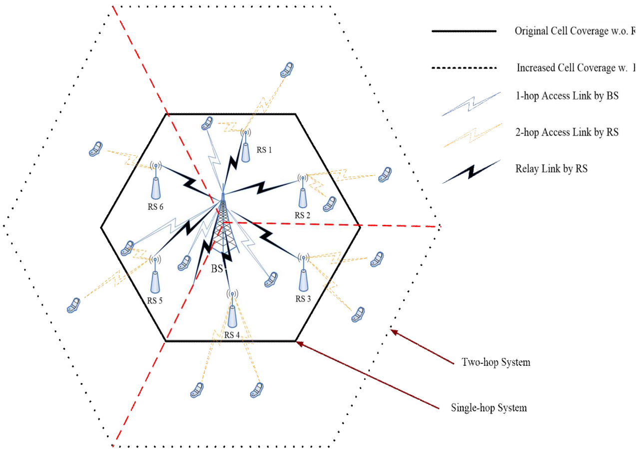


FIGURE 1. Example cell layout of a two-hop system.

II. SYSTEM MODEL AND THE PROPOSED FRAME STRUCTURE FOR A TWO-HOP OFDMA SYSTEM WITH NON-TRANSPARENT RELAY STATIONS

A. TWO-HOP SYSTEM MODEL

Figure 1 shows examples of two-hop systems, where the non-transparent RSs are deployed near the edge of its super ordinate station (i.e., BS is the super ordinate station of RS in a two-hop system), to enhance the performance and extend the cell coverage for deployment cost reduction. In a two-hop OFDMA system shown as Fig. 1, all the users are categorized into 1-hop and 2-hop users, which depends on whether they can receive the control information from BS or not. If a user can hear the control information such as preamble, frame control header (FCH) and resource mapping (MAP) information from BS, then it is considered as a 1-hop user. Otherwise, it is considered as a 2-hop user. To enhance the performance of 1-hop edge users who are located in the BS coverage edge and also in the coverage of non-transparent RS, cooperative transmission can be supported by using transmit maximal-ratio-combining (T-MRC) technique.

B. PROPOSED FRAME STRUCTURE FOR A TWO-HOP OFDMA SYSTEM WITH NON-TRANSPARENT RSs

In a two-hop OFDMA system, relay-oriented frame structures are required according to the multiplexing method between the direct and relayed transmissions. To reduce the hardware complexity and the system deployment expenditure on the carrier frequency, in-band relay system is usually considered, i.e., the direct and relayed transmissions use the same carrier frequency and different OFDM symbols. In this paper, we proposed a TDD-based down link (DL) in-band relay frame structure design concept for a two-hop OFDMA system with non-transparent RSs, where users out of the BS coverage can access the system through a non-transparent RS.

To facilitate the understanding, we take the M-WiMAX system as an example. The same design concept on frame structure can be easily applied in any other TDD-based in-band two-hop OFDMA system, e.g., 3GPP LTE-Advanced and IEEE 802.16j systems.

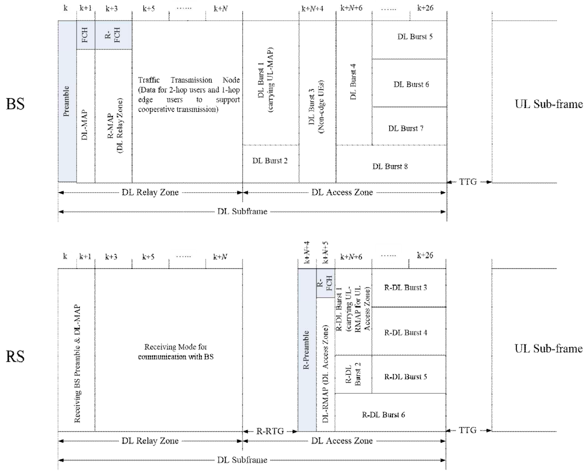


FIGURE 2. Proposed DL sub-frame structure for a two-hop M-WiMAX system.

Fig. 2 shows the proposed TDD-based DL in-band relay frame structure for a two-hop M-WiMAX system. In the two-hop system, BS and non-transparent RSs use different frame structures, and both are composed of one DL Relay Zone and one DL Access Zone. BS and RS perform different operations in each zone. The DL Relay Zone is used for the relayed traffic transmission from the BS to the RS, and the DL Access Zone is used for traffic transmission from the BS to the 1-hop user in the BS frame and from the RS to the 2-hop user in the RS frame, respectively. In the BS frame structure, BS transmits preamble first, which is used for the 1-hop users and the non-transparent RSs to perform synchronization and channel estimation. After preamble transmission, control information such as frame control header (FCH), relay frame control header (R-FCH), down link resource mapping information for 1-hop users (DL-MAP) and resource mapping information for relay stations (R-MAP) are transmitted. Then, the relayed traffic for 2-hop users will be transmitted in the DL Relay Zone. Finally, the traffic for the 1-hop user will be transmitted in the DL Access Zone. In the RS frame structure, the RS receives the traffic for the 1-hop edge users and 2-hop users in DL Relay Zone. At the end of DL Relay Zone, a relay receive-to-transmit guard interval (R-RTG) is inserted for the RS state transition from the receiving mode to the transmission mode. In the DL Access Zone, RS transmit its own preamble first, which is used by the 1-hop edge users and the 2-hop users to perform synchronization and channel estimation. After the preamble, control information and traffic for the 1-hop edge and 2-hop users are transmitted in the DL Access Zone of the RS frame structure. Based on the proposed frame structures, cooperative transmission for 1-hop edge users can be supported in the DL Access zone of the BS and RS frame structures to improve the user received data rate. In the cooperative transmission for 1-hop edge users, the resource mapping information of 1-hop edge users is contained in the DL-MAP from BS, and RS follows the same resource mapping for the 1-hop edge users.

III. PROPOSED TWO-HOP COORDINATED SCHEDULING ALGORITHM FOR TWO-HOP OFDMA SYSTEM WITH NON-TRANSPARENT RELAY STATIONS

A. PROBLEM FORMULATION

In this paper, we assume one BS with MRS RSs are deployed in each sector, and a cluster of $M \geq 2$ base stations with their legacy relay stations are coordinated together, which employ N sub-carriers and universal frequency reuse. There is one central control unit which controls all the resource of these M base stations and their legacy $M \cdot M_{RS}$ relay stations. Users, base and relay stations are all equipped with one receive and one transmit antenna, respectively. To reduce the level of coordination in our proposed algorithm, we assume the user data symbols are known only by the serving base and relay stations, and the channel quality measurement are shared among the coordinated base and relay stations. We also assume an infinitely backlogged traffic model, where each base station always has data available for transmission to all the connected users.

In the down link of a two-hop system with universal frequency reuse, users receive the inter-cell interference not only from the base stations, but also from the relay stations. Due to the random positions of users in each sector and the utilization of the proposed frame structure, base and relay stations in the system may be in different transmission manners (i.e., BS and RS cooperatively transmit data to 1-hop edge users, or BS transmits data to 1-hop user and RS transmits data to the 2-hop users).

Therefore, the sectors are classified into two categories:

1) Sectors where a base station and relay stations cooperatively transmit data to the 1-hop edge user;
2) Sectors where a base station transmits data to the 1-hop user, and a relay station transmits data to the 2-hop user.

Let k_m^n and $k_{m,l,2-hop}^n$ be the 1-hop and 2-hop users connected to base station m and its *l-th* legacy relay station on sub-carrier n, respectively. Assuming perfect synchronization, the received signal-to-interference-plus-noise ratio (SINR) for 1-hop user k_m^n is given by

$$\begin{aligned}
&\mathbf{SINR}^n_{m,k_m^n}(\mathbf{P}^n_{2-hop})\\
&\triangleq [P_m^n \cdot g(m,n,k_m^n) + a(m)\\
&\quad \cdot \sum_{l=1}^{M_{RS}} P^n_{RS_{(m-1)\times M_{RS}+l}} \cdot g_{RS}(m,l,n,k_m^n)]/\\
&\quad [N_0 + \sum_{j=1}^{M} P_j^n \cdot g(j,n,k_m^n)\\
&\quad + \sum_{\substack{j=1\\ j\neq m}}^{M} \sum_{i=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+i}} \cdot g_{RS}(j,i,n,k_m^n)\\
&\quad + (1-a(m)) \cdot \sum_{i=1}^{M_{RS}} P^n_{RS_{(m-1)\times M_{RS}+i}} \cdot g_{RS}(m,i,n,k_m^n)] \qquad (1)
\end{aligned}$$

where $\mathbf{P}^n_{2-hop} \triangleq [\mathbf{P}^n, \mathbf{P}^n_{RS}]$ with $\mathbf{P}^n \triangleq [P_1^n, P_2^n, \ldots, P_m^n]$ is the vector of transmission power on sub-carrier n for all the coordinated base stations; and $\mathbf{P}^n_{RS} \triangleq [P^n_{RS_1}, P^n_{RS_1}, \ldots, P^n_{RS_{M\times M_{RS}}}]$ is the vector of transmission power on sub-carrier n for all the relay stations controlled by the M coordinated base stations. $g(m, n, k_m^n)$ and $g(m, l, n, k_m^n)$ are complex channel response for the path from base station m to user k_m^n at sub-carrier n and the path from the l-*th* legacy relay station of the m-th base station to user k_m^n at sub-carrier n respectively, which include small-scale and large-scale fading; and $a(m)$ is the cooperative transmission indication function with the value of 1 if base station m is performing cooperative transmission with relay stations to user k_m^n, otherwise its value is zero.

The corresponding achievable information bits on sub-carrier n for user k_m^n is given by

$$R^n_{m,k_m^n}(\mathbf{P}^n_{2-hop}) \triangleq B_{sc} \cdot \log_2[1 + \mathbf{SINR}^n_{m,k_m^n}(\mathbf{P}^n_{2-hop})] \qquad (2)$$

where B_{sc} is the bandwidth per sub-carrier.

Similarly, we can calculate the received SINR for the 2-hop user $k^n_{m,l,2-hop}$ as in (3).

$$\begin{aligned}
&\mathbf{SINR}^n_{m,l,k^n_{m,l,2-hop}}(\mathbf{P}^n_{2-hop})\\
&\triangleq [P^n_{RS_{(m-1)\times M_{RS}+l}} \cdot g_{RS}(m,l,n,k^n_{m,l,2-hop})]\\
&\quad /[N_0 + \sum_{j=1}^{M} P_j^n \cdot g(j,n,k^n_{m,l,2-hop}) + \sum_{\substack{j=1\\ j\neq m}}^{M} \sum_{i=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+i}}\\
&\quad \cdot g_{RS}(j,i,n,k^n_{m,l,2-hop})\\
&\quad + \sum_{\substack{i=1,\\ i\neq l}}^{M_{RS}} P^n_{RS_{(M-1)\times M_{RS}+l}} \cdot g_{RS}(m,i,n,k^n_{m,l,2-hop})] \qquad (3)
\end{aligned}$$

$$\begin{cases} \underset{\substack{k_m^n \in \mathbf{K}, \\ k_{m,l,2-hop}^n \in \mathbf{K}_{2-hop}}}{\arg\max} \underbrace{\sum_{m=1}^{M_{coop}} \sum_{n=1}^{N} \frac{R_{m,k_m^n}^n(\mathbf{P}_{2-hop}^n)}{R_{req}(k_m^n)} + \sum_{m=M_{coop}+1}^{M} \sum_{n=1}^{N} \frac{R_{m,k_n^m}^n(\mathbf{P}_{2-hop}^n)}{R_{req}(k_m^n)} + \sum_{m=M_{coop}+1}^{M} \sum_{l=1}^{M_{RS}} \sum_{n=1}^{N} \frac{R_{m,l,k_{m,l,2-hop}^n}^n(\mathbf{P}_{2-hop}^n)}{R_{req}(k_{m,l,2-hop}^n)}}_{U_{2-hop}(\mathbf{P}_{2-hop},\, \mathbf{K},\, \mathbf{K}_{2-hop})} \\ \text{s.t. } \sum_{n=1}^{N} P_m^n \leqslant P_{\max}\ m = 1, 2, \ldots, M \\ \qquad \sum_{n=1}^{N} \mathrm{P}_{RS_l}^n \leqslant P_{RS,\max} l = 1, 2, \ldots, M \times M_{RS} \end{cases} \tag{5}$$

The corresponding achievable information bits on sub-carrier n for $k_{m,l,2-hop}^n$ is given by

$$R_{m,l,k_{m,l,2-hop}^n}^n(\mathbf{P}_{2-hop}^n) \triangleq B_{sc} \cdot \log_2[1 + \mathbf{SINR}_{m,l,k_{m,l,2-hop}^n}^n(\mathbf{P}_{2-hop}^n)] \tag{4}$$

The proposed two-hop coordinated scheduling (TH-CS) algorithm can jointly determine 1) the set of co-channel users scheduled on each sub-carrier; and 2) the power allocation across sub-carriers to optimize the system performance. In our proposed TH-CS algorithm, real time service is considered, so we consider the total system utility as a performance metric instead of the total system throughput. The system utility (i.e., the sum of weighted rates) U is presented by the sum of the ratios that users' received data rates are divided by their corresponding data rate requirements. Then, we can form the optimization problem as shown in (5), at the top of the page, where K and $\mathrm{K}_{2-\mathrm{hop}}$ is the co-channel user set for base and relay stations, respectively; $R_{req}(k_m^n)$ and $R_{req}(k_{m,2-hop}^n)$ are required data rates of user k_m^n and $k_{m,2-hop}^n$, respectively; M_{coop} is the number of sectors where base stations are currently performing cooperative transmission with their legacy relay stations in DL; P_{max} *and* $P_{RS,max}$ are transmission power constraints for base and relay stations, respectively; and $U_{2-hop}(\mathbf{P}_{2-hop},\ \mathbf{K},\ \mathbf{K}_{2-hop})$ is the total system utility function given power allocation vector $\mathbf{P}_{2-hop}$ and the co-channel user sets K and $\mathrm{K}_{2-\mathrm{hop}}$.

By differentiating (5) with respect to vector $\mathbf{P}_{2-hop}$ on sub-carrier n, we obtain (6), as shown at the top of the next page.

In (6), Part 1 corresponds to the scenario of base station performing cooperative transmission. Part 2 and 3 correspond to the scenarios of base station transmitting data to 1-hop users, and relay station transmitting data to 2-hop users, respectively.

B. PROPOSED TWO-HOP COORDINATED SCHEDULING ALGORITHM

Since (5) is a non-convex combinatorial optimization problem, computing its globally optimal solution may not be feasible in practice [13]. Therefore, we find the near-optimal solution to (5) in an iterative manner. To guarantee the fairness in real time service, the 2-step radio resource management algorithm for heterogeneous QoS requirements in [14] is used in the proposed two-hop coordinated scheduling algorithm for the sub-carrier allocation before the power update process. Then, we can update the transmission power station by station to maximize the objective function in (5) according to the interference status. For example, we first update the transmission power for one base station and its legacy relay stations, while keeping the transmission power of other stations unchanged, and then proceed to the next base station and its legacy relay stations. In the power update process of base and relay stations, their communication manners should be considered, i.e., the base station directly or cooperatively transmits data to the 1-hop users. Based on the different data transmission manner, the following four power allocation scenarios can be derived.

Scenario 1] *Base station performs cooperative transmission.*

If base station m^* is performing cooperative transmission with its legacy relay stations, the optimal power allocation on the *n-th* sub-carrier of base station m^* should satisfy (7), as shown at the top of page 6, according to the Karush-Kuhn-Tucker (KKT) conditions, where

$$Extra_{m^*,BS\ in\ Coop}^n = \text{Part 1 } (m \neq m^*) + \text{Part 2} + \text{Part 3} \tag{8}$$

According to (7) and (20), we obtain the optimal power allocation on sub-carrier n of base station m^* as shown in (9), where (10) holds, as shown at the top of the page 6.

Scenario 2] *Relay station performs cooperative transmission.*

According to (6) – (20), the optimal power allocation for the relay station l^* controlled by the base station m^* on sub-carrier n is calculated as (11) and (12), as shown at the top of page 7.

Let (11) hold. Then (12) holds.

Scenario 3] *Base station performs direct transmission to 1-hop users.*

If base station m^* is performing direct transmission to the 1-hop users, the optimal power allocation on the *n-th* sub-carrier of base station m^* can be calculated as in (13)–(15), as shown at the top of page 7.

Scenario 4] *Relay station performs direct transmission to 2-hop users.*

$$
\begin{aligned}
&\frac{d}{d\mathbf{P}}[\Lambda(\mathbf{P}^n_{2-hop},\ \mathbf{K},\ \mathbf{K}_{2-hop},\ \lambda_{BS},\ \lambda_{RS})] \\
&= \sum_{m=1}^{M_{coop}} \left[\frac{1}{\ln 2} \cdot \left(\frac{\frac{1}{R_{req}(k_m^n)} \cdot \left(g(m,n,k_m^n) + \sum\limits_{l=1}^{M_{RS}} g_{RS}(m,l,n,k_m^n) \right)}{N_0 + \sum\limits_{j=1}^{M} P_j^n \cdot g(j,n,k_m^n) + \sum\limits_{j=1}^{M}\sum\limits_{l=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+l}} \cdot g_{RS}(j,l,n,k_m^n)} \right.\right. \\
&\quad - \frac{-\sum\limits_{j=1,j\neq m}^{M} g(j,n,k_m^n)\cdot \mathbf{SINR}^n_{j,k_j^n}(\mathbf{P}^n_{2-hop})\cdot \frac{1}{R_{req}(k_j^n)}}{N_0 + \sum\limits_{j=1}^{M} P_j^n \cdot g(j,n,k_m^n) + \sum\limits_{j=1}^{M}\sum\limits_{l=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+l}} \cdot g_{RS}(j,l,n,k_m^n)} \\
&\quad \left. - \frac{\sum\limits_{j=1,j\neq m}^{M}\sum\limits_{l=1}^{M_{RS}} g_{RS}(j,l,n,k_m^n)\cdot\mathbf{SINR}^n_{j,l,k^n_{m,l,2-hop}}(\mathbf{P}^n_{2-hop})\cdot\frac{1}{R_{req}(k^n_{m,l,2-hop})}}{N_0+\sum\limits_{j=1}^{M} P_j^n\cdot g(j,n,k)+\sum\limits_{m=1}^{M}\sum\limits_{l=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+l}}\cdot g_{RS}(j,l,n,k_m^n)} \right) \\
&\quad \left. -\lambda_{BS}(m) - \sum_{l=1}^{M_{RS}} \lambda_{RS}(m,l) \right] \qquad \text{(Part 1)} \\
&+ \sum_{m=M_{coop}+1}^{M} \left[\frac{1}{\ln 2}\cdot \left(\frac{\frac{1}{R_{req}(k_m^n)}\cdot g(m,n,k_m^n)}{N_0 + \sum\limits_{j=1}^{M} P_j^n \cdot g(j,n,k_m^n) + \sum\limits_{j=1}^{M}\sum\limits_{l=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+l}} \cdot g_{RS}(j,l,n,k_m^n)} \right.\right. \\
&\quad - \frac{-\sum\limits_{j=1,j\neq m}^{M} g(j,n,k_m^n)\cdot \mathbf{SINR}^n_{j,k_j^n}(\mathbf{P}^n_{2-hop})\cdot \frac{1}{R_{req}(k_j^n)}}{N_0 + \sum\limits_{j=1}^{M} P_j^n \cdot g(j,n,k_m^n) + \sum\limits_{j=1}^{M}\sum\limits_{l=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+l}} \cdot g_{RS}(j,l,n,k_m^n)} \\
&\quad \left. - \frac{\sum\limits_{j=1}^{M}\sum\limits_{l=1}^{M_{RS}} g_{RS}(j,l,n,k_m^n)\cdot\mathbf{SINR}^n_{j,l,k^n_{m,l,2-hop}}(\mathbf{P}^n_{2-hop})\cdot\frac{1}{R_{req}(k^n_{m,l,2-hop})}}{N_0+\sum\limits_{j=1}^{M} P_j^n\cdot g(j,n,k_m^n)+\sum\limits_{j=1}^{M}\sum\limits_{l=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+l}}\cdot g_{RS}(j,l,n,k_m^n)} \right) \\
&\quad \left. - \lambda_{BS}(m) \right] \qquad \text{(Part 2)} \\
&+ \sum_{m=M_{coop}+1}^{M}\sum_{l=1}^{M_{RS}} \left[\frac{1}{\ln 2}\cdot \left(\frac{\frac{1}{R_{req}(k^n_{m,l,2-hop})}\cdot g_{RS}(m,l,n,k^n_{m,l,2-hop})}{N_0 + \sum\limits_{j=1}^{M} P_j^n \cdot g(j,n,k^n_{m,l,2-hop}) + \sum\limits_{j=1}^{M}\sum\limits_{i=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+i}} \cdot g_{RS}(j,i,n,k^n_{m,l,2-hop})} \right.\right. \\
&\quad - \frac{-\sum\limits_{j=1,j\neq m}^{M} g(j,n,k^n_{m,l,2-hop})\cdot \mathbf{SINR}^n_{j,k_j^n}(\mathbf{P}^n_{2-hop})\cdot \frac{1}{R_{req}(k_j^n)}}{N_0 + \sum\limits_{j=1}^{M} P_j^n \cdot g(j,n,k^n_{m,l,2-hop}) + \sum\limits_{j=1}^{M}\sum\limits_{i=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+i}} \cdot g_{RS}(j,i,n,k^n_{m,l,2-hop})} \\
&\quad \left. - \frac{\sum\limits_{j=1}^{M}\sum\limits_{i=1}^{M_{RS}} g_{RS}(j,i,n,k^n_{m,l,2-hop})\cdot\mathbf{SINR}^n_{j,i,k^n_{j,l,2-hop}}(\mathbf{P}^n_{2-hop})\cdot\frac{1}{R_{req}(k^n_{j,l,2-hop})}}{N_0+\sum\limits_{j=1}^{M} P_j^n\cdot g(j,n,k)+\sum\limits_{j=1}^{M}\sum\limits_{i=1}^{M_{RS}} P^n_{(j-1)\times M_{RS}+i}\cdot g_{RS}(m,l,n,k_{2-hop,j,i,n})} \right) \\
&\quad \left. - \lambda_{RS}((m-1)\times M_{RS}+l) \right] \qquad \text{(Part 3)}
\end{aligned} \tag{6}
$$

If base station m^* is not performing cooperative transmission, then the relay stations in the same sector of base station m^* are in the DL access zone for 2-hop users. The optimal power allocation on the *n-th* sub-carrier of the relay station l^* controlled by base m^* can be calculated as in (16)–(18), as shown at the top of page 8. Let (16) and (17) hold.

Then (18) holds.

$$\left[\frac{1}{\ln 2}\cdot\left(\frac{\frac{1}{R_{req}(k^n_{m^*})}\cdot\left(g(m,n,k^n_{m^*})+\sum_{l=1}^{M_{RS}} g_{RS}(m,l,n,k^n_{m^*})\right)}{N_0+\sum_{j=1}^{M} P_j^n\cdot g(j,n,k_{m^*,n})+\sum_{j=1}^{M}\sum_{l=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+l}}\cdot g_{RS}(j,l,n,k^n_{m^*})} \right.\right.$$
$$-\frac{\sum_{j=1,j\neq m^*}^{M} g(j,n,k^n_{m^*})\cdot \mathbf{SINR}^n_{j,k^n_j}(\mathbf{P}^n_{2-hop})\cdot\frac{1}{R_{req}(k^n_j)}}{N_0+\sum_{j=1}^{M} P_j^n\cdot g(j,n,k_{m^*,n})+\sum_{j=1}^{M}\sum_{l=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+l}}\cdot g_{RS}(j,l,n,k^n_{m^*})}$$
$$\left.-\frac{\sum_{j=1,j\neq m^*}^{M}\sum_{l=1}^{M_{RS}} g_{RS}(j,l,n,k^n_{m^*})\cdot \mathbf{SINR}^n_{j,l,k^n_{j,l,2-hop}}(\mathbf{P}^n_{2-hop})\cdot\frac{1}{R_{req}(k^n_{j,l,2-hop})}}{N_0+\sum_{j=1}^{M} P_j^n\cdot g(j,n,k_{m^*,n})+\sum_{j=1}^{M}\sum_{l=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+l}}\cdot g_{RS}(j,l,n,k^n_{m^*})}\right)$$
$$\left.-\lambda_{BS}(m^*)-\sum_{l=1}^{M_{RS}}\lambda_{RS}((m^*-1)\times M_{RS}+l)\right]+Extra^n_{m^*,BS\ in\ Coop}=0 \tag{7}$$

$$P^n_{m^*}+\frac{N_0+\sum_{j=1}^{M} P_j^n\cdot g(j,n,k^n_{m^*})+\sum_{j=1}^{M}\sum_{l=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+l}}\cdot g_{RS}(j,l,n,k^n_{m^*})}{g(m^*,n,k^n_{m^*})+\sum_{l=1}^{M_{RS}} g_{RS}(m^*,l,n,k^n_{m^*})}$$
$$=\frac{1}{R_{req}(k^n_{m^*})\cdot\left(\lambda_{BS}(m^*)\cdot\ln 2+A^n_{m^*}-Extra^n_{m^*,BS\ in\ Coop}\cdot\ln 2\right)} \tag{9}$$

$$A^n_{m^*}=\sum_{l=1}^{M_{RS}}\lambda_{RS}((m^*-1)\times M_{RS}+l)$$
$$+\frac{\sum_{j=1,j\neq m^*}^{M} g(j,n,k^n_{m^*})\cdot \mathbf{SINR}^n_{j,k^n_j}(\mathbf{P}^n_{2-hop})\cdot\frac{1}{R_{req}(k^n_j)}}{N_0+\sum_{j=1}^{M} P_j^n\cdot g(j,n,k^n_{m^*})+\sum_{j=1}^{M}\sum_{l=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+l}}\cdot g_{RS}(j,l,n,k^n_{m^*})}$$
$$+\frac{\sum_{j=1,j\neq m^*}^{M}\sum_{l=1}^{M_{RS}} g_{RS}(j,l,n,k^n_{m^*})\cdot \mathbf{SINR}^n_{j,l,k^n_{j,l,2-hop}}(\mathbf{P}^n_{2-hop})\cdot\frac{1}{R_{req}(k^n_{j,l,2-hop})}}{N_0+\sum_{j=1}^{M} P_j^n\cdot g(j,n,k^n_{m^*})+\sum_{j=1}^{M}\sum_{l=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+l}}\cdot g_{RS}(j,l,n,k^n_{m^*})} \tag{10}$$

Based on (7) – (18), we can update the transmission power for base and relay stations. To facilitate the understanding, we present the 2-step RRM algorithm of [14], and the detail procedure of the proposed two-hop coordinated scheduling algorithm is shown in Fig. 3.

IV. PERFORMANCE EVALUATION

A. EVALUATION ENVIRONMENTS

In this paper, we build up a 3-tier two-hop mufti-cell OFDMA system with non-transparent RSs to verify proposed two-hop coordinated scheduling algorithm. The proposed two-hop frame structure in section II is also applied here, with 27 OFDM symbols for DL sub-frame, 15 OFDM symbols for UL sub-frame, and the total frame length of 5 ms [15], [16]. In [17]–[20], different assumptions on the number and transmission power of RSs deployed in a cell are made for the performance evaluation. In this paper, we simply assume 6 non-transparent RSs are deployed in a cell, which are located at the edge of BS coverage instead of the boundary, to extend the coverage and support cooperative transmission between the BS and non-transparent RS for the 1-hop edge users. Because the system coverage is determined by the

$$\begin{aligned}
A^n_{m^*,l^*} &= \lambda_{BS}(m^*) + \sum_{\substack{l=1\\ l\neq l^*}}^{M_{RS}} \lambda_{RS}((m^*-1)\times M_{RS}+l) - Extra^n_{m^*,BS\ in\ Coop}\cdot \ln 2\\
&\quad + \frac{\sum\limits_{j=1,j\neq m^*}^{M} g(j,n,k^n_{m^*})\cdot \mathbf{SINR}^n_{j,k^n_j}(\mathbf{P}^n_{2-hop})\cdot \frac{1}{R_{req}(k^n_j)}}{N_0+\sum\limits_{j=1}^{M}P^n_j\cdot g(j,n,k^n_{m^*})+\sum\limits_{j=1}^{M}\sum\limits_{i=1}^{M_{RS}}P^n_{RS_{(j-1)\times M_{RS}+i}}\cdot g_{RS}(j,i,n,k^n_{m^*})}\\
&\quad + \frac{\sum\limits_{j=1,j\neq m^*}^{M}\sum\limits_{i=1}^{M_{RS}} g_{RS}(j,l,n,k^n_{m^*})\cdot \mathbf{SINR}^n_{j,i,k^n_{j,i,2-hop}}(\mathbf{P}^n_{2-hop})\cdot \frac{1}{R_{req}(k^n_{j,i,2-hop})}}{N_0+\sum\limits_{j=1}^{M}P^n_j\cdot g(j,n,k^n_{m^*})+\sum\limits_{j=1}^{M}\sum\limits_{i=1}^{M_{RS}}P^n_{RS_{(j-1)\times M_{RS}+i}}\cdot g_{RS}(j,i,n,k^n_{m^*})}
\end{aligned} \tag{11}$$

$$\begin{aligned}
&P^n_{RS_{(m^*-1)\times M_{RS}+l^*}} + \frac{N_0+\sum\limits_{j=1}^{M}P^n_m\cdot g(j,n,k^n_{m^*})+\sum\limits_{\substack{j=1\\ m\neq m^*}}^{M}\sum\limits_{i=1}^{M_{RS}}P^n_{(j-1)\times M_{RS}+i}\cdot g_{RS}(j,i,n,k^n_{m^*})}{g_{RS}(m^*,l^*,n,k^n_{m^*})}\\
&\quad = \frac{1}{R_{req}(k^n_{m^*})\cdot\left(\lambda_{RS}((m^*-1)\times M_{RS}+l^*)\cdot\ln 2 + A^n_{m^*,l^*}\right)}\\
&\quad - \frac{\sum\limits_{\substack{i=1\\ l\neq l^*}}^{M_{RS}} P^n_{(m^*-1)\times M_{RS}+i}\cdot g_{RS}(m^*,i,n,k^n_{m^*})}{g_{RS}(m^*,l^*,n,k^n_{m^*})}
\end{aligned} \tag{12}$$

$$\begin{aligned}
&P^n_{m^*} + \frac{N_0+\sum\limits_{\substack{j=1\\ j\neq m^*}}^{M}P^n_j\cdot g(j,n,k^n_{m^*})+\sum\limits_{j=1}^{M}\sum\limits_{l=1}^{M_{RS}}P^n_{RS_{(j-1)\times M_{RS}+l}}\cdot g_{RS}(j,i,n,k^n_{m^*})}{g(m^*,n,k^n_{m^*})+\sum\limits_{l=1}^{M_{RS}}g_{RS}(m^*,l,n,k^n_{m^*})}\\
&\quad = \frac{1}{R_{req}(k^n_{m^*})\cdot\left(\lambda_{BS}(m^*)\cdot\ln 2 + A^n_{m^*}\right)}
\end{aligned} \tag{13}$$

$$\begin{aligned}
A^n_{m^*} &= -Extra^n_{m^*,BS\ out\ Coop}\cdot\ln 2\\
&\quad + \frac{\sum\limits_{j=1,j\neq m^*}^{M} g(j,n,k^n_{m^*})\cdot \mathbf{SINR}^n_{j,k_{j,n}}(\mathbf{P}^n_{2-hop})\cdot \frac{1}{R_{req}(k_{j,n})}}{N_0+\sum\limits_{j=1}^{M}P^n_j\cdot g(j,n,k^n_{m^*})+\sum\limits_{j=1}^{M}\sum\limits_{l=1}^{M_{RS}}P^n_{RS_{(j-1)\times M_{RS}+l}}\cdot g_{RS}(j,l,n,k^n_{m^*})}\\
&\quad + \frac{\sum\limits_{j=1}^{M}\sum\limits_{l=1}^{M_{RS}} g_{RS}(j,l,n,k^n_{m^*})\cdot \mathbf{SINR}^n_{j,l,k^n_{j,i,2-hop}}(\mathbf{P}^n_{2-hop})\cdot \frac{1}{R_{req}(k^n_{j,i,2-hop})}}{N_0+\sum\limits_{j=1}^{M}P^n_j\cdot g(j,n,k^n_{m^*})+\sum\limits_{j=1}^{M}\sum\limits_{l=1}^{M_{RS}}P^n_{RS_{(j-1)\times M_{RS}+l}}\cdot g_{RS}(j,l,n,k^n_{m^*})}
\end{aligned} \tag{14}$$

$$Extra^n_{m^*,BS\ out\ Coop} = \text{Part 1} + \text{Part 2 } (m\neq m^*) + \text{Part 3} \tag{15}$$

user transmission power other than the transmission power of relay or base stations, we simply assume both base and relay stations have the same coverage radius. Fig. 4 shows the 3-tier 3-sector cell layout used in this paper with the RSs deployed in each cell as Fig. 1. In this paper, only the central 7 cells are grouped as a coordinated base and relay station cluster.

$$\begin{aligned} A^n_{m^*,l^*} &= -Extra^n_{m^*,l^*,RS\ out\ Coop} \cdot \ln 2 \\ &+ \frac{\sum\limits_{j=1}^{M} g(j, n, k^n_{m^*,l^*,2-hop}) \cdot \mathbf{SINR}^n_{j,k^n_j}(\mathbf{P}^n_{2-hop}) \cdot \frac{1}{R_{req}(k^n_j)}}{N_0 + \sum\limits_{j=1}^{M} P^n_j \cdot g(j, n, k^n_{m^*,l^*,2-hop}) + \sum\limits_{j=1}^{M}\sum\limits_{i=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+i}} \cdot g_{RS}(j, i, n, k^n_{m^*,l^*,2-hop})} \\ &+ \frac{\sum\limits_{\substack{j=1,\\ j\neq m}}^{M}\sum\limits_{i=1}^{M_{RS}} g_{RS}(j, i, n, k^n_{m^*,l^*,2-hop}) \cdot \mathbf{SINR}^n_{j,i,k^n_{j,i,2-hop}}(\mathbf{P}^n_{2-hop}) \cdot \frac{1}{R_{req}(k^n_{j,i,2-hop})}}{N_0 + \sum\limits_{j=1}^{M} P^n_j \cdot g(j, n, k^n_{m^*,l^*,2-hop}) + \sum\limits_{j=1}^{M}\sum\limits_{i=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+i}} \cdot g_{RS}(j, i, n, k^n_{m^*,l^*,2-hop})} \\ &+ \frac{\sum\limits_{\substack{l=1\\ l\neq l^*}}^{M_{RS}} g_{RS}(m^*, l, n, k^n_{m^*,l^*,2-hop}) \cdot \mathbf{SINR}^n_{j,l,k^n_{m^*,l,2-hop}}(\mathbf{P}^n_{2-hop}) \cdot \frac{1}{R_{req}(k^n_{m^*,l,2-hop})}}{N_0 + \sum\limits_{j=1}^{M} P^n_j \cdot g(j, n, k^n_{m^*,l^*,2-hop}) + \sum\limits_{j=1}^{M}\sum\limits_{i=1}^{M_{RS}} P^n_{RS_{(j-1)\times M_{RS}+i}} \cdot g_{RS}(j, i, n, k^n_{m^*,l^*,2-hop})} \end{aligned} \tag{16}$$

$$Extra^n_{m^*,l^*,BS\ out\ Coop} = \text{Part 1} + \text{Part 2} + \text{Part 3}\ (m \neq m^*, l \neq l^*) \tag{17}$$

$$\begin{aligned} &P^n_{RS_{(m^*-1)\times M_{RS}+l^*}} + \frac{N_0 + \sum\limits_{j=1}^{M} P^n_j \cdot g(j, n, k^n_{m^*,l^*,2-hop}) + \sum\limits_{j=1}^{M}\sum\limits_{i=1}^{M_{RS}} P^n_{(j-1)\times M_{RS}+i} \cdot g_{RS}(j, i, n, k^n_{m^*,l^*,2-hop})}{g_{RS}(m^*, l^*, n, k^n_{m^*,l^*,2-hop})} \\ &= \frac{1}{R_{req}(k^n_{m^*,l^*,2-hop}) \cdot \Big(\lambda_{RS}((m^* - 1) \times M_{RS} + l^*) \cdot \ln 2 + A^n_{m^*,l^*}\Big)} \end{aligned} \tag{18}$$

All the users in these 7 cells report their channel status information of the desired path and the interfering path from base and relay stations in the other 6 cells to the central control unit for the resource management. The interference from the base and relay stations out of the coordinated base and relay station cluster is called UN-coordinated interference, which is treated like the additive thermal noise. The detailed system-level Monte-Carlo simulation parameters are presented in Table I, which follows the M-WiMAX system configuration [5], [15]. Table II and III show the target SINR thresholds for each modulation and coding level with respect to the direct and cooperative transmissions to guarantee PER of 1 %, which are obtained from a link-level simulation using conventional turbo codes with 6 iterations under ITU-R Veh-A channel model with mobility of 60 km/h [16]. To address the heterogeneous QoS requirements, the following three user QoS classes are considered in this paper:

1) Class 1) $R_k = 768$ kbps, $T_k = 20$ OFDM Symbols $= 2.38$ ms
2) Class 2) $R_k = 512$ kbps, $T_k = 30$ OFDM Symbols $= 3.57$ ms
3) Class 3) $R_k = 256$ kbps, $T_k = 40$ OFDM Symbols $= 4.76$ ms

B. METRIC FOR THE SELECTION OF OPTIMUM RELAY POSITION

In case of a two-hop system with non-transparent relay stations, there will be trade-off between the system efficiency (i.e., some OFDM symbols will be used for data relay from BS to RS, which is not required in single-hop system), and coverage enhancement. Because the two-hop and single-hop systems have different coverage area, we take the area efficiency (i.e., total system throughput divide by the covered area, whose unit is *bps*/m^2) instead of throughput for comparison. The optimum relay position of the two-hop system should make the system have the same area efficiency as the single-hop system while the cell coverage is enhanced. With the enhanced cell coverage, the deployment cost will be reduced.

C. SYSTEM-LEVEL MONTE-CARLO SIMULATION RESULTS

Figure 5 (a) and (b) present cumulative distribution function on the users' received data rate and the area efficiency increase ratio of the two-hop system over the 1-hop system with different relay station deployment position, respectively. In the single-hop system, the sub-carrier allocation algorithms in [14] and the power allocation algorithm in [13] are adopted to obtain the performance. From these figures,

```
Perform 2-step sub-carrier allocation algorithm in [14]
Initialize $L_{max}$, $\mathbf{P}^{n}_{2-hop}$, and set $l$=0
repeat
    for $m$=1 to $M$ do
        Check the transmission manner of base and relay stations in sector $m$
        Find the optimum value of $\lambda$ for the base and relay stations in sector $m$
        via bisection search
        Update transmission power on each sub-carrier for both base and relay
        stations according to the proper Eq. among (7)-(18)
    end for
    Re-allocate the sub-carriers accroding to updated $\mathbf{P}^{n}_{2-hop}$ using the 2-step
    sub-carrier allocation algorithm
    set $l$=$l$+1
until system utility convergence or $l$=$L_{max}$
```

FIGURE 3. The detailed procedure of the proposed TH-CS algorithm.

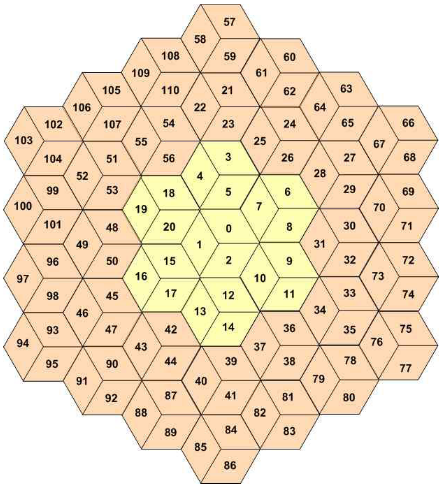


FIGURE 4. 3-tier cell layout with the central 7 cells coordinated together.

we find that when the relay stations are deployed around 410 m away from its super-ordinate base station, the two-hop system has no gain on the area efficiency compared to the single-hop system (That is, the two-hop system has same area efficiency as the single-hop system.), but the coverage area is around 2 times as large as that of single-hop system. To facilitate the understanding of the advantage by the hybrid deployment with non-transparent relay stations, we make a simple example here. Assuming the price of the BS is 10 times of RS. Then, the total deployment cost of conventional single-hop system to coverage area A is

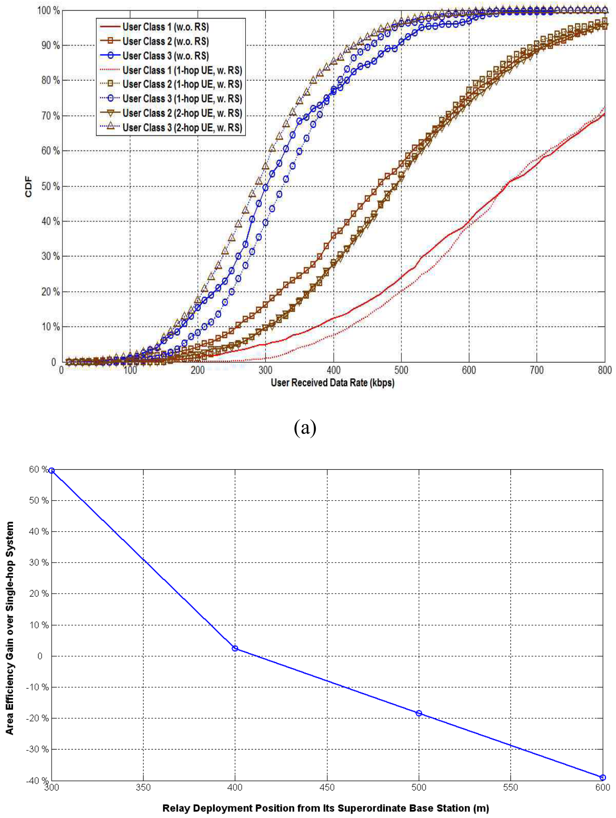
$$\frac{A}{\pi} \times 10 \cdot (\text{RS Price}). \tag{19}$$

The deployment cost of a two-hop system with non-transparent RSs and same coverage area is

$$\frac{A}{\pi(1+\text{Pos}_{\text{RS}})^2} \times 10 \cdot (\text{RS Price}) + \frac{A}{\pi(1+\text{Pos}_{\text{RS}})^2} \times 6 \cdot (\text{RS Price})\,. \tag{20}$$

TABLE 1. Numerical evaluation parameters.

Parameter	Value
Carrier Frequency	2.35 GHz
Effective BW	8.75 MHz
Nr. of Data Sub-carriers	768
Tx Power	BS : 36dBm RS : 30 dBm
Antenna Gain	BS : 18 dBi RS : 12 dBi UE : 0 dBi
Thermal Noise	-174.0 dBm / Hz
Path Loss Model	ITU Veh.
Fading Channel	ITU-R Veh A 60 km/h
Channel Knowledge	Perfect
Nr. of Cells	37
Cell Configuration	Hexagonal
Cell Radius	1 km
UE Position	Uniformly Distributed



(a)

(b)

FIGURE 5. (a) CDF on the users' received data rate; (b) gain of two-hop system over 1-hop system with different deployment position for relay station in the aspect of area efficiency.

According to fig.5 (b), the replay station should be placed 410 m away from the BS. Then $\text{Pos}_{\text{RS}} = 0.41$, and the deployment cost will be reduced by 20 % compared to the conventional single-hop system.

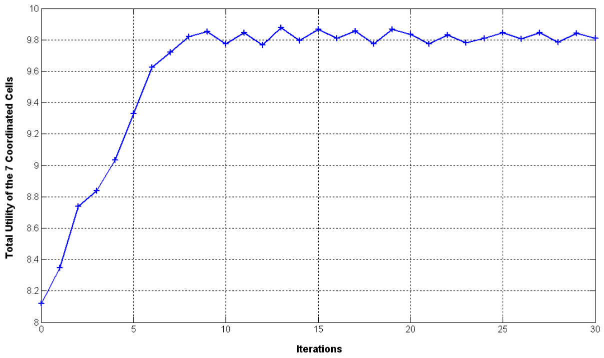


FIGURE 6. Convergence of the proposed TH-CS algorithm with relay station deployed at 410 m from its superordinate base station.

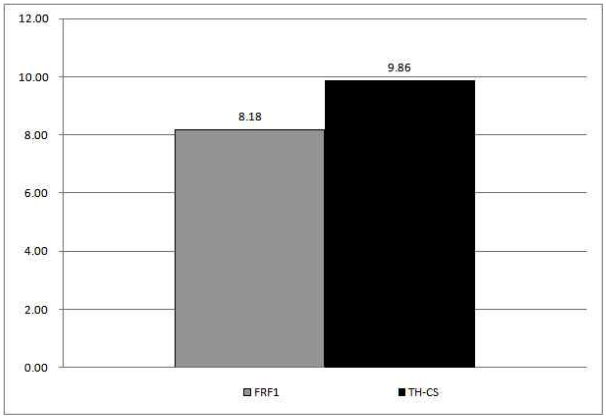


FIGURE 7. System utility provided by the proposed TH-CS algorithm, compared to the case of FRF = 1 (conventional case) with relay station deployed at 410 m from its superordinate base station.

TABLE 2. Required SINR threshold for each MCS level to guarantee 1% PER using direct transmission.

MCS Level	Required SINR (dB)
QPSK, 1/12	3.9
QPSK, 1/8	5.4
QPSK, 1/4	8.2
QPSK, 1/2	12.0
QPSK, 3/4	17.8
16QAM, 1/2	17.2
16QAM, 3/4	23.5
64QAM, 1/2	22.0
64QAM, 2/3	26.7
64QAM, 3/4	29.2
64QAM, 5/6	34.7

TABLE 3. Required SINR threshold for each MCS level to guarantee 1% PER using cooperative transmission.

MCS Level	Required SINR (dB)
QPSK, 1/12	-0.7
QPSK, 1/8	0.3
QPSK, 1/4	2.9
QPSK, 1/2	5.8
QPSK, 3/4	9.6
16QAM, 1/2	10.9
16QAM, 3/4	15.2
64QAM, 1/2	15.3
64QAM, 2/3	18.9
64QAM, 3/4	20.4
64QAM, 5/6	23.0

Figure 6 presents the convergence of the proposed TH-CS algorithm. From this figure, we observe that the total system utility with the central 7 coordinated cells converges at 9.8 through several iterations. The system utility gain provided by the proposed TH-CS algorithm is presented in Fig. 7, where gain of 17 % is observed compared to the conventional FRF = 1 case without any interference mitigation algorithm.

V. CONCLUSIONS

In this paper, we solve the radio resource management problems in two-hop OFDMA system with non-transparent relay stations and heterogeneous QoS requirements. To perform the data relay procedure and to improve the performance of edge users, a two-hop frame structure is proposed, which supports the cooperative transmission. Then, a two-hop coordinated scheduling algorithm is proposed to efficiently utilize the spectrum and power resources of the two-hop OFDMA system with heterogeneous QoS requirements. From the muftitier system-level Monte-Carlo simulation results, we observe that the proposed two-hop coordinated scheduling provides 17 % gain on the system utility, compared to the conventional case without any interference mitigation schemes. In addition, the two-hop system achieves the nearly same area efficiency as the single-hop system when the relay stations are deployed around 410 m away from their super ordinate base stations, but the coverage area of the two-hop system is around twice as large as that of single-hop system. With the above relay station deployment, the optimum trade-off between system efficiency and coverage for the two-hop system is achieved, and the total system deployment costs are greatly reduced.

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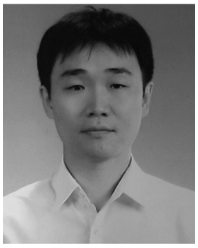

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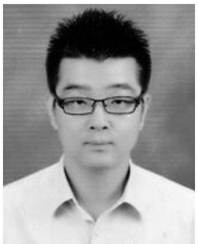

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