Energy-efficient IPTV Simulcast over Fixed WiMAX Access Systems

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Abstract—**In this paper, we study the problem of how to design an energy-efficient simulcast scheme for *base stations* (BSs) to deliver multiple resolutions of IPTV programs simultaneously in a fixed wireless network. We refer to this problem as the *energy-efficient IPTV simulcast* (EES) problem. We first provide the problem definition of EES and prove that EES is NP-complete. We then formulate the problem as a mixed integer linear program (MILP) and provide a heuristic approach, named VD-RingCover. We prove that the RingCover algorithm, which is a subroutine of VD-RingCover, can obtain the minimum energy consumption for the single base station case (named EES-SB). Our numerical results show that the MILP can solve the small scale problem properly and that the VD-RingCover achieves good results in both large and small scale problems.**

I. INTRODUCTION

Internet protocol television (IPTV) refers to multimedia services (e.g. television programs, video on demand, audio, graphs, etc.) that are distributed over an Internet protocol (IP) network. Compared to traditional cable TV, IPTV is now widely used for entertainment, health care, education, and finance due to its flexible storage, retrieval, and archiving, its high quality of image, and its cost saving [1].

A. Network Architecture and Display Resolution

Typically, an IPTV delivery starts from a video *head end* (HE) and terminates at an end user's home device. Figure 1 gives a possible architecture for IPTV delivery from service providers to clients. In Fig. 1, HEs, or *video hub offices* (VHOs) are sources that store and encode multimedia IPTV programs into IP flows and then send such flows to the core network (such as the *multicast capable automatically switched optical network* (MC-ASON)), via edge routers in VHOs. The core network sets up an optical multicast channel which delivers IP flows to the requesting access routers [2].

In the access network, the *worldwide interoperability for microwave access* (WiMAX) system may be implemented, since it is proved to be least expensive broadband technology [3], has wide area coverage [4], and supports point-to-multipoint (PtMP) bandwidth-efficient service [5]. The access routers, which are connected to *WiMAX base stations* (BSs) in the *video service office* (VSO), collect the requests of end users through *access points* (APs) in houses and forward these requests to HEs. When the access routers receive programs from the core network, they will send these programs to APs through WiMAX BS broadcasting. When an AP receives the required program, it will deliver programs to the particular home devices in the small home network [6]. In this paper, we address the IPTV delivery problem in the fixed WiMAX system because APs are fixed for each house in the local area [7]. Since each BS has a limited transmission range, several BS's may be placed to cover the entire target region.

Usually, home devices, such as television sets, PCs, and mobile phones, can receive a continuous interval range of resolutions for display. On the other hand, different devices require different ranges of resolutions for display. Therefore, IPTV delivery should satisfy the heterogeneity requirements of resolutions from different end users for the same program. In this paper, we assume that each AP requires an interval range of resolutions for its home devices. To satisfy different resolution requirements, WiMAX BSs choose multi-rate broadcast which has two modes: layered mode (a.k.a *scalable video coding* (SVC)) and simulcast mode. Although authors in [8-9] show that the layered mode is bandwidth efficient and scalable for a wider range of quality requirements, the simulcast mode is proved to be more efficient than SVC mode in bandwidth usage [10], because SVC requires more information (acquired as coding penalty) to show the relationship between layers, and it has lower reliability, since data lost at the base layer or lower layer will cause the loss of all images with higher resolution. Therefore, in our paper, we consider simulcast mode when broadcasting IPTV programs in the WiMAX network. For simplicity, we use term "simulcast" to represent a broadcasting scheme with simulcast mode, in which each version of the same program will be independently broadcasted on a different channel over a certain range.

B. Problems, Contributions, and Assumptions

In current systems, the BS consumes the major portion of energy [16] when it broadcasts a multimedia packet. This is even worse when a BS does simulcast since the BS treats the same content in different resolutions as different packets. To satisfy heterogeneous position and resolution requirements from end users, a BS broadcasts a program in different versions, each via a different channel over the maximum

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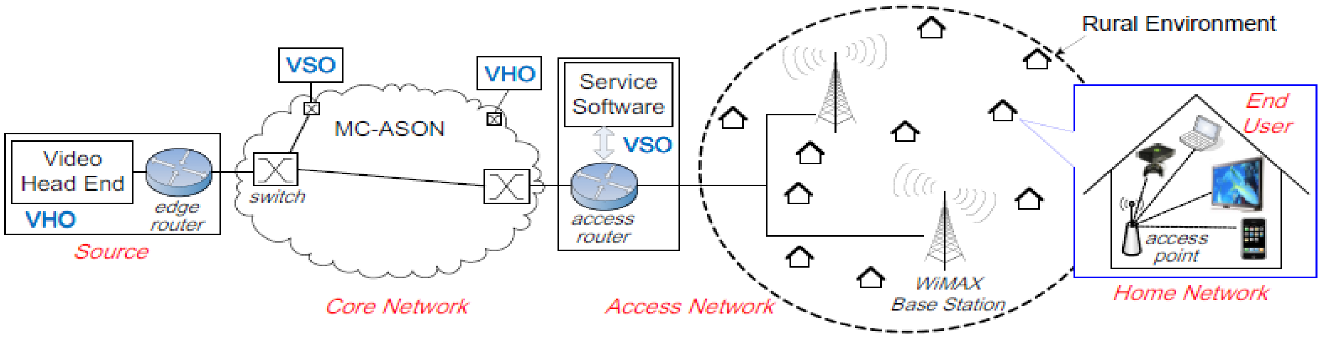


Fig.1. Network Architecture for IPTV Delivery

transmission range, regardless of necessity. Such simulcast wastes tremendous energy. Therefore, we want to find a better way for a BS to simulcast, such that every end user, within its broadcast range, can receive its required program with minimum energy consumed at the base station. We name this problem, which flexibly determines different broadcast ranges at a WiMAX BS for IPTV simulcast to meet all users' heterogeneous resolution requirements, the *single base station energy-efficient IPTV simulcast* (EES-SB) problem. In detail, based on the sets of acceptable resolution requirements from the end users for a particular program, the BS determines the transmission range for different resolution versions of the program. The goal of EES-SB is that the energy consumption is minimized and all end users receive the program within their acceptable resolution sets.

Furthermore, since a target area may have more than one BS, one reasonable extension of EES-SB, *named energy-efficient IPTV simulcast* (EES), has multiple BSs, but each end user only needs data from one of the BSs.

In this paper, we first provide the model to show the relationship among the energy consumption, the bit rate of certain resolutions, and the transmission range. We then provide the mathematical definition of EES as well as EES-SB. After the definition, we prove that EES in general is NP-hard while EES-SB can be solved optimally through a dynamic algorithm, named RingCover. When using Voronoi Division (VD) as an initial phase, EES can be approximately solved through VDRingCover. Finally, we evaluate the performance of VD-RingCover both theoretically and practically. The simulation results demonstrate that VD-RingCover solves EES efficiently.

We also make the following assumptions: 1) a WiMAX BS can communicate directly to APs, but APs will not retransmit the data; 2) only end users who request the particular program are considered; and 3) different versions of the simulcast will occupy different wireless channels, which utilize MIMO technology, to avoid interference.

C. *Organization*

The rest of this paper is organized as follows. In Section II, we investigate some previous problems related to EES. In Section III, we provide a detailed problem description of EES. A heuristic algorithm and the performance analysis are studied in Section IV and V, respectly. In Section VI, we report some numerical results. Finally, we give a summary of our work in Section VII.

II. Related Works

Previously, ESS has been studied in three different contexts. The first group of works (power management) attempt to save the energy in ad hoc and sensor networks through alternative sleeping and waking [11] or adjusting transmission power for each node [12-13]. Our work is different from power management in that 1) the fundamental objective for power management is to extend system life while our objective is to utilize power efficiently at the base station, a similar consideration in [14]; and 2) we consider the transmission for the same program in different resolutions (multiple copies) while in the ad hoc network, the data only has one copy.

The second group determines the transmission range dynamically using a smart antenna for a CDMA based wireless network [15]. The authors extend the concept of adaptive beam forming to dynamically changing cell size so as to provide dynamic mobile cellular coverage, which means that the maximum transmission range for a BS may shrink or expand due to the traffic. Our work is different from dynamic cell since we determine different transmission ranges for each BS.

The last group of work is energy-efficient multi-lingual cell broadcasting (EEML-CB) in [16], which is the literature most related to our work. The authors proved that EEML-CB is NP-complete, and developed an ILP model and heuristic to study EEML-CB. EES-SB is similar to EEML-CB, but the end users usually request a range of resolutions in EES, which is continuous on resolution. On the other hand, the multi-lingual application does not have this attribute, which means that the elements in the language set are independent. Because of this, EES-SB is not NP-complete although EEML-CB and EES are NP-complete.

III. Energy-efficient IPTV Simulcast

In this section, we first analyze the energy consumption model to determine the crucial factors which consume the most BS energy. Then, we define EES and EES-SB. Thirdly, we prove that EES is NP-complete. Finally, we provide a MILP model to provide insight of our problem.

A. *Energy Consumption Model*

The energy consumption in IPTV simulcast depends on the distance between a BS and end users, and the size of packets the

BS transmits. In detail, let's consider one BS and one end user with distance *d* in Euclidean free space as an example. Define *E* as the energy needed for the BS to transmit a packet with length *s* to the user, E_r as the receiving energy at the user, P_{th} as the receiving power threshold for 1 bit length packet, P_r as the receiving power for the user, and P_t as the transmission power for the BS. According to Friis equation,

$$P_r = G_t \cdot G_r \cdot (\frac{\lambda}{4\pi d})^2 \cdot P_t, \quad (1)$$

where G_t is the transmission antenna gain, and G_r is the receiving antenna gain. The receiving energy can be shown as

$$E_r = P_r \cdot s = G_t \cdot G_r \cdot (\frac{\lambda}{4\pi d})^2 \cdot P_t \cdot s. \quad (2)$$

In order to decode the data correctly, the receiving power P_r should be greater than the power threshold P_{th}, which is $P_r \geq P_{th}$. Then the minimum energy needed for the user to successfully receive the packet can be calculated in Eq. (3):

$$E = P_t \cdot s = \frac{P_{th}}{G_t \cdot G_r} \cdot (\frac{4\pi d}{\lambda})^2 \cdot s. \quad (3)$$

Usually, the image resolution can be determined in different ways, the most common of which is *pixel resolution*. Since the original image based on the pixel resolution may be too large to adopt in the network, the original video can be compressed using different standards, e.g., MPEG-2 and MPEG-4. The output of the compression procedure is measured by B_j, the bit rate of the video for resolution r_j. The bit rate is a function of the pixel resolution, with a higher resolution leading to a higher bit rate. Thus, *s* can be determined as $s = B_j \cdot t$, where *t* is the total duration of the video. Then, the energy E can be formulated as

$$E = P_t \cdot s = \frac{P_{th}}{G_t \cdot G_r} \cdot \left(\frac{4\pi d}{\lambda}\right)^2 \cdot B_j \cdot t = w_j \cdot t, \quad (4)$$

where $w_j = \frac{16\pi^2 \cdot P_{th} \cdot B_j \cdot t}{G_t \cdot G_r \cdot \lambda^2}$. We consider w_j the weight of resolution r_j, which can be viewed as a given parameter.

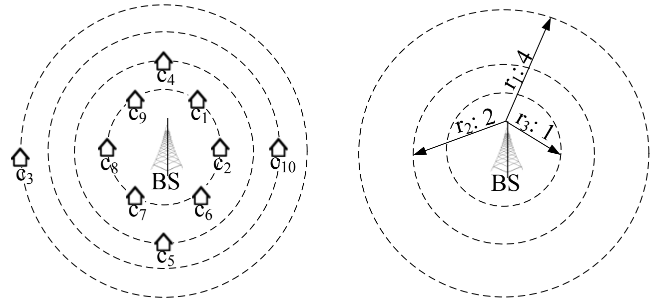
B. Problem formulation

In this subsection, we provide the formal definition of our optimization problem.

Table I User Information for a Single Base Station

c_j	ds_j	$[r_l, r_h]_j$	*PRR*[1]	c_j	ds_j	$[r_l, r_h]_j$	*PRR*[1]
c_1	1	$[r_3, r_3]$	r_3	c_6	1	$[r_1, r_2]$	r_1&r_2
c_2	1	$[r_2, r_3]$	r_2&r_3	c_7	1	$[r_1, r_1]$	r_1
c_3	4	$[r_1, r_3]$	r_1	c_8	1	$[r_2, r_2]$	r_2
c_4	2	$[r_1, r_3]$	r_1&r_2	c_9	1	$[r_1, r_3]$	r_1&r_2&r_3
c_5	2	$[r_2, r_2]$	r_2	c_{10}	3	$[r_1, r_3]$	r_1

1. PRR is the possible received resolution for each user.



(a) Client Distribution (b) EES-SB Results

Fig. 2. Example of EES-SB

Definition 1 (EES) Given *n* clients $C = \{c_1, c_2, \cdots, c_n\}$, and *m* BS's $B = \{b_1, b_2, \cdots, b_m\}$ in a given region with fixed locations, a distance matrix $DS = [ds_{i,j}]_{m\times n}$, k resolutions $R = \{r_1, r_2, \cdots, r_k\}$ with corresponding weight set $W = \{w_1, w_2, \cdots, w_k\}$ (R is ordered increasingly). Each client c_j has an accepted resolution interval $[r_l, r_h]_j$ $(l \leq h)$. The *energy-efficient IPTV simulcast* (EES) problem is to find minimum energy broadcasting, such that each client can receive at least one copy of program within its acceptable resolution interval.

If we know the broadcast domain of each BS beforehand, then EES can be simplified as EES-SB, defined as follows.

Definition 2 (EES-SB) Given n clients $C = \{c_1, c_2, \cdots, c_n\}$ within a BS's domain with fixed locations, a distance matrix $DS = [ds_j]_n$, k resolutions $R = \{r_1, r_2, \cdots, r_k\}$ with weight set $W = \{w_1, w_2, \cdots, w_k\}$ (R is ordered increasingly). Each user c_j has an accepted resolution interval $[r_l, r_h]_j$ $(l \leq h)$. The *single base station energy- efficient IPTV simulcast* (EES-SB) problem is to find minimum energy broadcasting for the BS, such that each client can receive at least one copy of program within its acceptable resolution interval.

Figure 2(a) shows an example for a single BS with 10 clients and 3 resolutions. Table I gives distance information and resolution requirement for each user. The weights for the resolution are set as follows: $w_1 = 2$, $w_2 = 4$, and $w_3 = 5$.

Figure 2(b) shows the broadcast range for each resolution from the BS. The total energy required is 53 units (based on Eq. (4)). However, the BS requires 176 units of energy if applying the traditional method. Table I also shows the received resolution for each client.

C. NP-completeness

The decision form of EES is that: given C, B, DS, R with weight set W, and energy bound K. Each user c_j has an accepted resolution interval $[r_l, r_h]_j$ $(l \leq h)$. Find a broadcast scheme such that each client can receive at least one copy of program within its acceptable resolution interval and the total energy required is less than *K*. Obviously, we can check the receiving resolution of each client and total energy consumption in polynomial time. Therefore, EES belongs to NP class.

We know that the *minimum weighted set cover* (MWSC) problem is NP-complete. MWSC is a special case of EES when we set each client to some BSs is unit distance and to other BSs is infinite distance. Therefore, EES is also NP-complete. For the detail reduction, please see Chapter 6.1.2 in [17].

D. MILP Model

In this subsection, we introduce a mixed integer linear programming (MILP) model for EES. We first list some useful inputs as follows:

n	total number of clients;
m	total number of BSs;
k	total number of resolutions;
Z	very large number
$R = [r_q]_{k\|}$	available resolution vector;
$W = [w_q]_k$	resolution weight vector;
$DS = [ds_{i,j}]_{m\times n}$	distance vector;

$RE = [re_{j,q}]_{n\times k}$	Receiving resolution matrix, $re_{j,q} = 1$ if $q \in [r_l, r_h]_j$, otherwise $re_{j,q} = 0$.

We then provide variables of MILP:

$X = [x_{j,q}]_{n\times k}$	user-resolution matrix, $x_{j,q} = 1$ if client c_j receives resolution r_q, otherwise 0;
$Y = [y_{i,j}]_{m\times n}$	BS-user matrix, $y_{i,j} = 1$ if c_j receivesdata from BS b_i, otherwise 0;
$V = [v_{i,q}]_{m\times k}$ $v'_{i,q} = v^2_{i,q}$	maximum transmission range for resolution r_q at BS b_i.

Now we give the MILP model as follows.

$$\min \quad E = \sum_{i=1}^{m}\sum_{q=1}^{k} w_q \cdot v'_{i,q} \qquad (5)$$

$$s.t. \quad \sum_{q=1}^{k} x_{j,q} = 1, \qquad \forall c_j \qquad (6)$$

$$\sum_{i=1}^{m} y_{i,j} = 1, \qquad \forall c_j \qquad (7)$$

$$x_{j,q} \leq re_{j,q}, \qquad \forall c_j, b_i \qquad (8)$$

$$\frac{(v'_{i,q} - x_{j,q} \cdot ds^2_{i,j})}{Z} + 1 - y_{i,j} \geq 0, \quad \forall c_j, b_i, r_k. \qquad (9)$$

Eq. (5) calculates the energy needed to broadcast data to every client. The objective is to minimize this energy consumption. Eq. (6) means that every client should receive one copy of data. Eq. (7) guarantees that every client should receive data from one of the BSs. Eq. (8) means that we should assign an acceptable resolution to each client. Finally, Eq. (9) guarantees that if a client c_j is assigned to BS b_i with resolution r_q, then the broadcast range for r_q at BS b_i should be greater than $ds_{i,j}$, otherwise, $v'_{i,q}$ can be any value. Since our objective is to minimize the total energy which is related to $v'_{i,q}$. Therefore, we do not need any more constraint for $v'_{i,q}$.

IV. VD-RINGCOVER ALGORITHM

Although the MILP formulation can provide insight regarding EES, it can only solve small scale problems because EES is NP-complete. In this section, we propose an algorithm to solve large scale problems. We name our algorithm VD-RingCover, which contains two steps. In the first step, we use *Voronoi Division* (VD) to clarify the region for each BS by assigning each client to its closest BS. In the second step, we process RingCover for each single BS, which will be discussed in Section IV.A. We then provide the whole algorithm in Section IV. B.

A. Description of RingCover

RingCover can be divided into two consecutive phases: Phase I: initialization by client elimination, and Phase II: dynamic programming for minimum energy coverage.

For the first phase, we can eliminate the clients based on the following three observations. Suppose two clients c_i and c_j request resolution ranges as $[r_l, r_h]_i$ and $[r_s, r_t]_j$, respectively. Furthermore, suppose that the distances from the two users to the BS are d_i and d_j, respectively.

Observation 1. If $l = s$, $h = t$, and $d_i \leq d_j$, then we can eliminate user c_i, since any transmission to c_j would also satisfy user c_i. For example, client c_{10} is eliminated due to client c_3 in Table I due to this observation.

From this observation, we can get a higher triangle matrix $D = [d_{l,h}]_{k\times k}$, where $d_{l,h}$ is the farthest distance from a user to BS b_i with resolution interval $[r_l, r_h]$.

Observation 2. If $l < s$, $h = t$, and $d_i \leq d_j$, then we can eliminate user c_i. For example, c_9 is eliminated due to c_2.

Observation 3. If $l = s$, $h > t$, and $d_i \leq d_j$, then we can eliminate user c_i. For example, c_6 is eliminated due to c_7.

We obtain matrix $\widetilde{D}$ from D by setting $d_{l,h} = 0$ if all clients that request resolution interval $[r_l, r_h]$ are eliminated by Observations 2 and 3. From Observation 2, we transfer $\widetilde{D}$ to $D"$, which guarantees that each column in $D"$ is in non-increasing order. From Observation 3, we further transform $D"$ to D', which guarantees that each row in D' is in non-decreasing order. Note that all distance matrices are higher triangular matrices.

As for the second phase, the basic technique we use in this phase is dynamic programming starting from the lowest resolution (r_1) to the highest one (r_k). After finishing calculation for the resolution subset $\{r_1, r_2, \cdots, r_{q-1}\}$, the algorithm starts to schedule simulcast for the resolution subset $\{r_1, r_2, \cdots, r_{q-1}, r_q\}$, with the sub-matrices $D"$ and D', which include the first q rows and q columns. The key idea is to transfer the minimum energy problem to the shortest path problem by creating a complete auxiliary graph $A_q = (V, E, W)$, where $V = \{v_0, v_q, v_{q-1}, \cdots, v_1\}$ and W is the weight set corresponding to edge set E. Each v_j $(1 \leq j \leq q)$ corresponds a resolution r_j and v_0 is the virtual source node representing a BS. As for the weight on each edge, two parts are considered.

1) Cover the clients who request r_q as the highest acceptable resolution. Two cases need to be considered. i) Broadcasting r_j $(1 \leq j < q)$: we use distance information in D' since r_j can also satisfy the clients who request r_j as their acceptable resolution. ii) Broadcasting r_q: we only need to use distance information in $D"$ since r_q is the highest resolution.

2) Cover the clients who request r_j $(1 \leq j < q)$ as the highest acceptable resolution. Some clients may not be satisfied due to their strict resolution requirement. To solve this problem, we need to consider additional broadcasts to cover these clients. Since $1 \leq j < q$, the minimum additional energy has already been determined by the previous calculation.

We denote $opt_{j,q}$ as the minimum energy consumption for a BS to deliver data to the users whose resolution requirement interval is a subset of $[r_j, r_q]$ $(1 \leq j \leq q)$. $opt_{j,q} = 0$ if $j > q$. We will use shortest path algorithm to find the best solution. The correctness will be proved in Section IV.C. Algorithm 1 shows the whole algorithm for the second phase.

Algorithm 1 RingCover

```
**BEGIN**
//Phase I: initialization by client elimination
Create $D = [d_{i,h}]_{k\times k}$ for the BS $b_i$ based on Observation 1.
**For** $l = k$ to 2 // Modify matrix $D$ based on Observations 2 and 3.
  **For** $h = l$ to 2
    **If** $(d_{h-1,l} \leq d_{h,l})$ **Then** $d_{h-1,l} = 0$
**For** $l = 1$ to $k - 1$
  **For** $h = l + 1$ to $k$
    **If** $(d_{l,h} \leq d_{l,h-1})$ **Then** $d_{l,h} = 0$
Set $\widetilde{D} \leftarrow D$
**For** $h = k$ to 2  // Start to transform from $\widetilde{D}$ to $D"$ based on Observation 2.
```

```
  For $l = h$ to 2
    If $(d_{l-1,h} \leq d_{l,h})$ Then $d_{l-1,h} = d_{l,h}$
Set $D" \leftarrow D$
For $l = 1$ to $k$ // Start to transform from $D"$ to $D'$ based on Observation 3.
  For $h = l + 1$ to $k$
    If $(d_{l,h} \leq d_{l,h-1})$ Then $d_{l,h} = d_{j,h-1}$
Set $D' \leftarrow D$
//Phase II: dynamic programming for minimum energy coverage
For $q = 1$ to $k$
  Construct a complete graph $A_q = (V, E, W)$, where $V = \{v_0, v_q, v_{q-1}, \cdots, v_1\}$.
  For $j = q$ to 1 // assign weight on each edge in $A_q$.
    $w(0, j) = w_q \cdot d"^2_{j,q} + opt_{j,q-1}$ // weight for broadcasting resolution $r_q$.
    For $i = j - 1$ to 1
      $w(j, i) = w_{j-1} \cdot d'^2_{i,q} + opt_{i,j-2}$//weight for broadcasting $r_{j-1}$ $(1 \leq j \leq q)$.
  Run single source (at $v_0$) shortest path algorithm for $A_q$.
  $opt_{j,q}$ is the value of the shortest path from $v_0$ to $v_j$, where $1 \leq j \leq q$.
END
```

B. VD-RingCover Algorithm

In this subsection, we provide the whole VD-RingCover algorithm for EES, which is shown in Algorithm 2.

Algorithm 2 VD-RingCover

```
BEGIN
// Step 1: Voronoi Division (VD)
$\mathbf{C}_i = \emptyset$ for all $1 \leq i \leq m$ // $m$ is the total number of base stations
For each client $c_j$,
  Find the closest base station $b_i$ based on distance matrix $DS$
  $\mathbf{C}_i = \mathbf{C}_i \cup \{c_j\}$
//Step 2: RingCover algorithm for each base station
For each base station $b_i$,
  Call Algorithm 1(Ringcover) with the client set $\mathbf{C}_i$ and corresponding distance matrix and weight set.
Total energy consumption is the sum of the optimal energy consumption of each base station.
END
```

V. PERFORMANCE ANALYSIS

In this section, we prove that RingCover can find an optimal solution for EES-SB, and then show the time complexity of VD-RingCover. Finally, we will provide an example to show why VD-RingCover cannot achieve an optimal solution to EES.

Definition 3 (User Set): We define $C(r_i, r_j)$ as a user set whose resolution requirement interval is a subset of $[r_i, r_j]$ $(i \leq j)$. For convenience, if $i > j$, then $C(r_i, r_j) = \emptyset$.

Lemma 1 RingCover always finds a shortest path in A_q using edge from v_j to v_i, where $j > i > 0$.

Due to space limitation, we do not show the proof, which can be found in [17]. Through Lemma 1, we have that the higher resolution will prefer smaller broadcast range than the lower resolution to achieve optimal solution.

Theorem 1 $opt_{j,q}$ outputs the minimum energy consumption for the BS to deliver data to $C(r_j, r_q)$.

Proof sketch. Due to the space limitation, we do not provide the whole proof in detail, which can be found in [17]. Instead, we provide the key steps to prove the theorem as follows.

We can prove this theorem by strong induction on q, where q increases from 1 to k.

The basic step is to determine the minimum energy consumption when we only have one resolution required by the customers. Obviously, $opt_{1,1} = w_1 \cdot d"^2_{1,1}$, which is definitely an optimal solution for clients in $C(r_1, r_1)$.

The inductive step is to prove the statement that suppose for all $1 < q < x$, we can get $opt_{j,q}$ for the BS to deliver data to $C(r_j, r_q)$ with optimal energy consumption. We obtain three facts to prove our statement: 1) the weight on link $v_s \rightarrow v_t$ denotes the energy consumption for the BS to successfully deliver data to $C(r_t, r_x) - C(r_s, r_x)$, which can be proved directly from *Lemma 1*; 2) the path from v_0 to v_j can cover all clients in $C(r_j, r_x)$ through the union of all covered user sets; 3) the total weight of the shortest path from v_0 to v_j in A_x is $opt_{j,x}$ $(j \leq x)$, which represents the minimum energy to satisfy the requirements by all clients in $C(r_j, r_x)$.

Based on the Basis and Inductive steps, we obtain the conclusion that $opt_{j,q}$ $(j \leq q)$ outputs the minimum energy consumption for the BS to deliver data to $C(r_j, r_q)$ in A_q. ■

According to *Theorem 1*, $opt_{1,k}$ represents the minimum energy (the optimal solution) for EES-SB.

We then analyze the time complexity of VD-RingCover through the proof of the following theorem.

Theorem 2 VD-RingCover requires $O(n + m \cdot k^3)$ time.

Proof: As for the first step, we use Voronoi Division to set up the relationship between clients and BSs, which requires $O(n)$ time. Next, calculating D in the first line of Step 2 also requires $O(n)$ time. For RingCover, transforming D to $\widetilde{D}$, $D"$, and D' requires $O(k^2)$ time. Constructing one A_q requires $O(q^2)$, where $1 \leq q \leq k$. The shortest path algorithm can be done within $O(q^2)$ for the graph A_q. Therefore, for RingCover, the total time complexity is $\sum_{q=1}^{k} O(q^2) = O(k^3)$. Since there are m BSs, we need to run RingCover m times. The total time complexity for VD-RingCover is $O(n + m \cdot k^3)$. ■

Finally, Fig. 3 shows an example to illustrate that although Ringcover can find the optimal solution for a single BS, VD-RingCover cannot find the minimum energy broadcast strategy for the whole target region due to the partition. In Fig. 3, there are 2 BSs (b_1 and b_2) and 3 clients (c_1, c_2, and c_3). The dotted line is the Voronoi boundary between b_1 and b_2. Thus, b_1 should send data to c_1, and b_2 should communicate to c_2 and c_3. Let distance matrix D be $d_{11} = 10$, $d_{12} = 11$, $d_{22} = 10$, and $d_{23} = 2$. Clients c_1 and c_2 only accept resolution r_4 with weight $w_4 = 9$, and client c_3 accepts resolution interval $[r_1, r_3]$ with weight $w_1 = 4$, $w_2 = 5$, and $w_3 = 6$. The total energy consumption achieved by VD-RingCover is $(w_4 \cdot d^2_{11}) + (w_4 \cdot d^2_{22} + w_1 \cdot d^2_{23}) = 1816$. However, in the optimal solution, b_1 takes care of clients c_1 and c_2, and b_2 takes care of clients c_3. The energy consumed is $w_4 \cdot d^2_{12} + w_1 \cdot d^2_{23} = 1105$, which is smaller than 1816. Thus the coverage region for each BS is the key point to the performance of the algorithm.

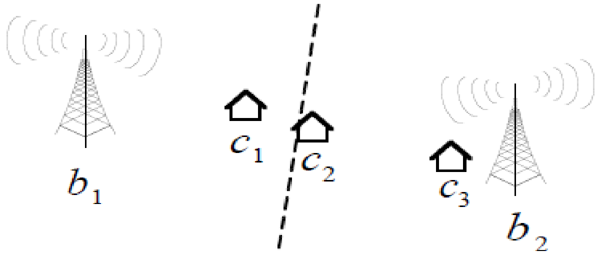


Fig. 3. An Example to Illustrate the Performance of VD-RingCover

Table II Comparison among Optimal Solution, VD-RingCover and Traditional Method

m	k	Energy per BS (Watt)			Energy Saving[2](%)	Diff[3] (%)
		OPT[1]	RC[1]	TM[1]		
1	2	14881	14881	34131	43.6	0
	3	22837	22837	52378	43.6	0
	4	83943	83943	192530	43.6	0
	5	122652	122652	281312	43.6	0
2	2	14138	14600	33563	43.5	3.27
	3	21014	21377	49143	43.5	1.73
	4	65282	66211	152209	43.5	1.42
	5	88826	89810	206465	43.5	1.11
3	2	14095	14571	33651	43.3	3.38
	3	20255	20892	48249	43.3	3.15
	4	56325	56656	130845	43.3	0.59
	5	83823	84083	194187	43.3	0.31

1. OPT: optimal results; RC: VD-RingCover results; TM: traditional results.
2. Energy saving: difference between VD-RingCover and traditional method.
3. Diff: difference between VD-RingCover and optimal solution.

VI. NUMERICAL RESULTS

In this section, we present some numerical examples to show that our MILP model can solve small scale problems very well, while our heuristic algorithm (VD-RingCover) can achieve good performance for both small and large scale problems with millions of clients and tens of resolutions. The MILP model was solved using CPLEX 7.0 [18]. Each point in the figure is average over 100,000 experiments.

A. *Small Scale Experiment*

In this experiment, we check the performance of the MILP model and show that VD-RingCover can obtain results equal to the MILP model for a single BS, close to the MILP model for multiple BSs, and much less energy consumption than the traditional approach. We set the total number of clients as 40, set the maximum weight (W) for the highest resolution as 100, and set the maximum transmission range as 1. We also randomly generate 1) the highest and lowest resolutions requested by each client; 2) the distance from client to BS; and 3) the weight of other resolutions, which are smaller than W.

Table II gives the results of the MILP model as well as the heuristic approach (CD-RingCover) and traditional approach. From this table, we find that the energy consumption for each BS obtained by MILP increases when the number of resolutions (k) increases. The reason is that, as k increases, the clients have a greater chance to request different ranges of resolutions, and BSs have to broadcast a greater number of different resolutions to meet these different requests. When we increase the number (m) of BSs, the energy consumption for each BS can be reduced a little since the BS can reduce the broadcast range for some resolutions. The table also shows that compared with the traditional approach (broadcasting each resolution to the maximum transmission range), our approach is energy efficient, using only around 43% of the total energy consumed by the traditional approach.

Table II also shows that our VD-RingCover achieves good performance, and achieves the same trends as the optimal solution. As we proved in Section IV.C, RingCover itself can obtain the optimal result for a single BS; while for multiple BSs, VD-RingCover is close to the optimal solution with a difference of around 0.3% to 3%.

B. *Large Scale Experiment 1*

In this experiment, we show how the number of BSs (m) and the number of resolutions (k) affect the energy consumption with 10 thousand clients. We set maximum weight $W = 100$ and maximum transmission range $L = 50$ for a single BS. The region for all BSs to cover is a circle with diameter $2L$, and we randomly put the clients within this region. We also randomly generate 1) the highest and lowest resolutions provided by the BS and requested by each client; and 2) the weights of other resolutions, which are smaller than W.

All these randomly generated data should meet the requirement that each BS should broadcast the program on at least one resolution to some clients.

Figure 4 gives the results obtained by VD-RingCover. Similar to the small scale problem, as k increases, the total energy consumption for each BS increases linearly because the BS will broadcast more copies with different resolutions to the clients. When m increases from 1 to 3, we do not find great energy saving because for some extreme points (clients) in the region, BSs still need to broadcast by using range R to meet these clients' requests. When m is 4 or 5, BSs only need $0.707L$ for $m = 4$ and $0.618L$ for $m = 5$, respectively, to cover the whole region based on Voronoi Division. Because of this, we find the energy consumption for each BS is tremendously reduced (e.g. $k = 40$). Our simulation also demonstrates the energy efficiency of our approach compared to the traditional approach. The total energy savings range from 55% (when $k = 2$) to 33% (when $k = 40$) for any number of BSs.

C. *Large Scale Experiment 2*

This experiment checks the performance of VD-RingCover under different regions, different maximum weight for the highest resolutions, and different number of BSs. The total number of resolutions (k) is set to 20. Similar to the last experiment, we randomly generate the other parameters to meet the requirements.

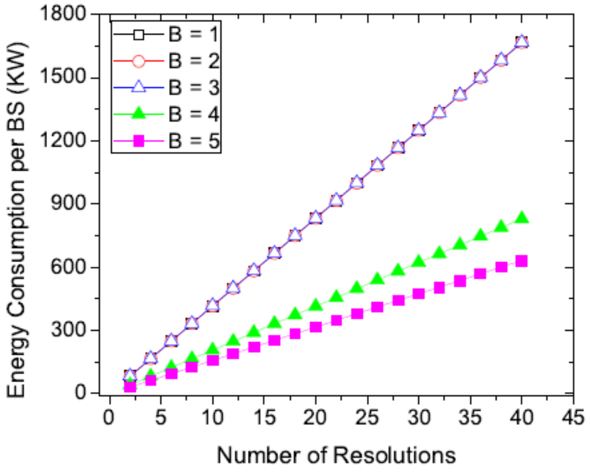
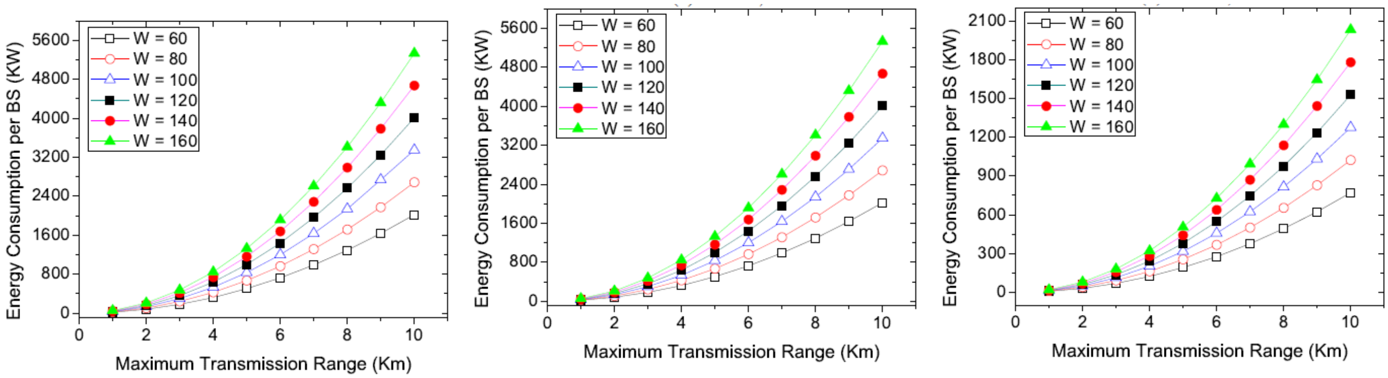


Fig. 4. Energy Consumption per BS vs. No. of Resolutions



(a) $m = 1$; (b) $m = 3$; (c) $m = 5$.

Fig. 5. Energy Consumption per BS vs. Maximum Transmission Range

Figures 5 (a), (b), and (c) show the results we obtain from VD-RingCover. From these three figures, we find that when we keep W fixed, the energy consumption is almost the square of the maximum transmission range L. On the other hand, the energy consumption is almost linearly dependent on W when we fix L. This matches the energy function given in Section II. Comparing these three figures, the energy consumption for each BS increases when $m = 1$ and 3 compared to $m = 5$. The reason behind this is that, although the maximum transmission range is the same, if the number of BSs increases, then each BS will cover fewer regions based on Voronoi Division. However, as the number of BSs increases, the total energy consumption for all BSs also increases. Therefore, if we want to save energy for each BS, we need to put more BSs in the given region. On the other hand, if we want to save the total energy as well as cover the whole region, fewer BSs is a good choice.

VII. CONCLUSION

In this paper, we focus on the *energy-efficient IPTV Simulcast* (EES) problem, which aims to minimize the total energy consumption for BSs and to guarantee that end users will receive programs to satisfy their resolution requirement through WiMAX access networks. We prove that EES is NP-complete, and then formulate a mixed integer linear programming (MILP) model for it. We propose a heuristic, named VD-RingCover, to solve large scale cases. We also demonstrate that RingCover, the subroutine of VD-RingCover, achieves optimal solution for EES-SB. The numerical results show that MILP can solve small scale problem properly and that VD-RingCover reduces the energy consumption by more than half compared to the original simulcast in small scale problems and reduces the energy by two thirds in large scale problem.

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