Multi-hop Relay based Coverage Extension in the IEEE802.16j based Mobile WiMAX Systems

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Abstract

In this paper, we investigate various issues of cost-effective coverage extension in a multi-hop relay based WiBro/WiMAX systems. Since the coverage extension problem may occur in metropolitan areas as well as suburban or rural areas where user density is relatively low or moderate, we first introduce several topologies and the resulting cost-effective coverage extension methods for each case. Secondly, we propose two cost-effective coverage extension methods using two sectorized cellular approaches, one using the wide-beam tri-sector cell (WBTC) and the other using the narrow-beam tri-sector cell (NBTC). Finally, we present a practical deployment scenario consisting of three phases depending on user traffic density.

1. Introduction

Recently, there have been numerous standardization activities for making the IEEE 802.16e system highly effective in supporting mobile users based on orthogonal frequency division multiple access (OFDMA) with TDD mode [1,2]. Standardization activities of the IEEE802.16e system were completed in 2005, and currently enhancements of the IEEE802.16e standard are under discussion. One such enhancement effort is cell coverage extension and link throughput enhancement which is being studied in IEEE802.16j TG. In order to achieve these goals, the IEEE802.16j TG introduces mobile multi-hop relay technology to the IEEE802.16e system. The other enhancement effort is being discussed in IEEE802.16m TG. The IEEE802.16m system, called the gigabit WiMAX, mainly aims to enhance system throughput up to 1Gbps. Besides, this system aims to support legacy IEEE802.16 standards including the IEEE802.16j, and to interworking with other wireless systems such as 3GPP LTE and IMT-advanced system [2, 3].

In particular, in Korea, the IEEE802.16e standard-based wireless broadband (WiBro) system was developed in 2005 and WiBro service was launched in 2006 covering isolated areas in Seoul [4]. Since the initial launch, WiBro service providers have been trying to extend service areas from Seoul to regions nationwide. In order to cover the entire region of Korea, however, deployment cost for the traditional infrastructure consisting of only Base Stations (BSs) is estimated to be astronomical. For this reason, it is necessary to adopt a cost-effective service coverage extension method, and the mobile multi-hop relay (MMR) WiBro system is considered as a strong candidate for possible implementation.

In this paper, we investigate various issues on multi-hop relay based WiBro/WiMAX systems, i.e., the IEEE802.16j system, with a focus on cost-effective cell coverage extension under various deployment situations. Since the coverage extension problem may occur in both of metropolitan areas and rural areas when the user-traffic density is relatively moderate or low, we first introduce several topologies and the resulting cost-effective coverage extension methods for each case. Secondly, we propose two sectorized cellular based cost-effective coverage extension methods, the WBTC and NBTC system based approaches. Finally, we present a practical deployment scenario consisting of three phases depending on the user-traffic density and the number of traffic relaying hops.

The remainder of this paper is organized as follows. In the next section, we analyze cost-effective coverage extension methods under various MMR topologies that may occur in metropolitan and rural areas. Then we
present sectored cellular-based coverage extension approaches. Based on the above analysis results, we propose a practical deployment scenario in the section 4. Finally, we conclude this paper by suggesting future research issues.

2. Coverage extension with minimal deployment cost

In this section, we propose and analyze various MMR topologies for cell-coverage extension using omni-directional antennas. Under such topologies, we investigate deployment cost and optimal numbers of BSs and Relay Stations (RSs) with respect to various user traffic densities.

2.1. Omni-directional antenna based multi-hop relay topologies

We propose various MMR topologies for both metropolitan and rural areas. We assume that omni-directional antennae are used in both a BS and RSs. We also assume that the maximum number of hops is 4 which means that there could be at most 3-tiers of RSs from the BS. For the convenience of analysis, we also assume that the unit coverage areas in the metropolitan area topologies and the rural area topologies are a square and a hexagon respectively. A BS is assumed to have different sizes of coverage area according to its transmission power. In other words, in terms of the unit coverage area, a BS could have a different number of unit areas for its coverage. In general, RSs have less transmission power compare to the BS, and thus, in this paper, we assume that each RS covers one unit of coverage area regardless of topologies. Figure 1 shows three types of different topologies for each case of the metropolitan and rural areas, i.e., Type-A, B, and C, for the metropolitan areas and Type-D, E, and F are for the rural areas. For the metropolitan areas, we use grid topology models which are generally used for metropolitan topology. On the other hand, for the rural areas, we use hexagonal topology models.

2.2. Modeling of a cost-effective coverage extension problem

When a target service area is given, the cost-effective coverage enhancement problem of the MMR WiBro/ WiMAX system is generally solved with respect to the traffic density per unit area. Since each BS and RS has its own coverage area in terms of unit service area and the user traffic is generated proportional to the size of service area, each BS and RS has a maximum number of accommodating MSs for its coverage area. In addition, since a BS has limited capacity, a limited number of RSs can be connected to a BS for coverage extension. From the characteristics of each proposed MMR topology, the number of RSs in each tier is also limited. For example, in case of type B, there could be at most 8, 12, or 18 RSs in each tier, respectively.

As a result, the cost-effective coverage extension problem can be formulated as a cost minimization problem with several constraints for a given user-traffic density. Then, it can be expressed in terms of the number of BSs and RSs that are required to cover the target service area for a given user-traffic density. The object function and constraints for the minimum deployment cost are evaluated by the following optimization problem:

Minimize

$$C_T = C_{RS}X_{RS} + C_{RS}X_{RS,1} + C_{RS}X_{RS,2} + C_{RS}X_{RS,3} \quad (1)$$

Subject to

$$A_{RS}X_{RS} + A_{RS}X_{RS,1} + A_{RS}X_{RS,2} + A_{RS}X_{RS,3} \geq A_T \quad (2)$$

$$(C - \rho^* A_{RS})X_{RS} - \rho^* A_{RS}X_{RS,1} \geq 0 \quad (3)$$

$$X_{RS,1} - N_1 \cdot X_{RS} \leq 0 \quad (4)$$

$$N_1 \cdot X_{RS,2} - N_2 \cdot X_{RS,1} \leq 0 \quad (5)$$

$$N_2 \cdot X_{RS,3} - N_3 \cdot X_{RS,2} \leq 0$$

$$X_{RS, j} \in \{1, 2, \cdots \} \quad (6)$$

$$X_{RS, j} \in \{0, 1, 2, \cdots \}, j \in \{1, 2, 3\} \quad (7)$$

Fig. 1. Multihop-based topologies in metropolitan (Type-A, B, and C) and rural (Type-D, E, and F) area.

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where, \( C_T \) is total deployment cost for a given user traffic density, \( X_{BS} \) is the number of BSs and \( X_{RS,j} \) is the number of RSs at \( i \)-th tier. \( C_{BS} \) and \( C_{RS} \) are the costs of a BS and an RS, respectively. There are four constraints in the optimization problem; constraints for seamless covering of the target service area in (2) where \( A_{RS} \) and \( A_{BS} \) are the coverages of a BS and an RS, constraints for the capacity limitation of a BS in (3) where \( C \) is the capacity of a BS and \( \rho \) is a given user traffic density, constraints for the maximum number of RSs (\( N_{i,j} \)) at each tier in (4), and constraints for the integrality of the number of BSs and RSs in (5) and (6).

2.3. Performance analysis of coverage extension and deployment cost

In order to analyze the cost-effective coverage extension problem for each topology under a given user-traffic density, several modeling parameters shown in Table 1 are used. In the analysis, for the sake of modeling convenience, it is assumed that user traffic is uniformly distributed and no Adaptive Modulation Coding (AMC) option and no interference models are used. In addition, the cost of an RS is assumed to be a portion of the cost of a BS. In this paper, three different RS cost levels, 10%, 20% and 30% of a BS cost, are used.

Table 1: Model Parameters for Metropolitan and Rural area systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total area ((A_1))</td>
<td>Metropolitan Area: 300 Km²</td>
</tr>
<tr>
<td></td>
<td>Rural Area: 150 Km²</td>
</tr>
<tr>
<td>BS coverage ((A_2))</td>
<td>Type-A: 1 Km²</td>
</tr>
<tr>
<td></td>
<td>Type-B: 2 Km²</td>
</tr>
<tr>
<td></td>
<td>Type-C: 3 Km²</td>
</tr>
<tr>
<td>RS coverage ((A_2))</td>
<td>Type-A: 1 Km² (a square)</td>
</tr>
<tr>
<td></td>
<td>Type-B: 2 Km² (a hexagon)</td>
</tr>
<tr>
<td>Traffic density ((\rho))</td>
<td>0.1–10bps/m² (0.1–10Mbps/km²)</td>
</tr>
<tr>
<td>RS Cost ((C_{RS}))</td>
<td>10%, 20%, 30% BS cost / RS</td>
</tr>
<tr>
<td>BS total capacity ((C))</td>
<td>50 Mbps</td>
</tr>
</tbody>
</table>

Figure 2 and 3 show efficiency of the MMR-based coverage extension approach in terms of the coverage extension and the total deployment cost for the case of metropolitan areas and rural areas, respectively. Figure 2a shows that the coverage area with the type-C approach is bigger than with type-A when the same number of BSs is used. However, as the traffic density increases, the difference between each MMR approach and the difference between MMR approaches and BS-only approach tend to vanish due to the limited capacity of a BS. Figure 2b shows the total deployment cost of three MMR approaches and BS-only approaches for seamless covering of the target metropolitan service area with respect to the traffic density. As shown in Figure 2b, type-C topology covers the target area with the lowest cost while type-A covers with the highest cost. The reason is that because of small coverage of a BS, type-A requires more number of BSs to cover the target area, and thus results higher deployment cost. Meanwhile, when RS costs of type-B and type-C are 30%, and 20% and 30% of BS cost, deployment of such MMR topologies are not beneficial than the BS-only approach because of the higher RS cost compared to the coverage extension effect.
difference between MMR approaches and BS-only approach are tend to vanish due to the limited capacity of a BS. Figure 3b shows the total deployment cost of three MMR approaches and BS-only approaches for seamless covering of the target rural service area with respect to the traffic density. As shown in Figure 3b, type-E topology covers the target area with the lowest cost while type-D covers with the highest cost due to the same reason explained in figure 2b. In addition, similar to the figure 2b, when RS costs of type-E are 20% and 30% of BS cost, deployment of such MMR topologies are not beneficial than the BS only approach because of the same reason explained in figure 2b.

Fig. 3. Analysis results on coverage extension (up) and deployment cost (down) under various topologies for rural area.

3. Coverage extension with sectrization approaches

In this section, we propose and analyze various MMR topologies for cell-coverage extension using directional-antennas. Under such topologies, we investigate deployment cost and optimal numbers of BSs and RSs with respect to various user traffic densities.

3.1. Sectored BS based Multi-hop relay approaches

In the conventional cellular system with omni-directional antenna, the contour of a cell for equal received power from the antenna is approximately a circular, and generally assumed to be a hexagonal shape [7]. Consequently, in order to increase a BS capacity through decreasing radio frequency interference, sectorized cell structures such as the WBTC and NBTC systems was introduced [8, 9]. The number of sectors in a cell is depend on the characters of antenna but three sectored (120˚) or six sectored (60˚) antenna is normally used. In general, the representative three sector cell structures are the WBTC and NBTC. A BS is covered with three 60˚ directional antennas in the NBTC. The coverage area of a sector in the NBTC assumed to be a hexagonal shape because the narrow beam radiation pattern matches well a hypothetical hexagonal shape. With three such antennas, the coverage contour of the

Fig. 4. Multihop-based NBTC and WBTC systems
NBTC cell composed of three sectors is therefore like a clover leaf. On the other hand, the coverage area of a sector in the WBTC assumed to be a rhombus shape because the wide beam radiation pattern with 120° antennas matches well a rhombus shape, and thus the coverage area of the WBTC is a hexagonal shape consisting of three rhombus shape sectors.

We propose two multi-hop approaches based on NBTC and WBTC BS sectorization. Figure 4 shows two multi-hop relay approaches based on the NBTC and WBTC BS structure. As shown in figure 4a, an NBTC BS is assumed to have three hexagonal shape sectors \((S_i, i = 1,2,3)\), and the shape of each RS is assumed to be a hexagon. On the other hand, as shown in figure 4b, a WBTC BS is assumed to have three rhombus shape sectors \((S_i, i = 1,2,3)\), and the shape of each RS is assumed to be a rhombus.

In this paper, we only consider the NBTC and the WBTC based MMR approaches having up to 3 tiers. \(S_i\) means \(i\)-th sector of a BS and \(R_{ij}\) means the \(j\)-th RS at \(i\)-th tier. For example, every sector in NBTC based MMR system may have at most three RSs at the first tier, five RSs at the second tier, and seven RSs at the third tier as illustrated in figure 4a. On the other hand, every sector in WBTC based MMR system may have at most two RSs at the first tier, four RSs at the second tier, and five RSs at the third tier as illustrated in figure 4b.

### 3.2. Problem formulation and performance analysis

In order to analyze the cost-effective coverage extension problem for each sectorized BS based MMR approaches under a given user traffic density, we formulate similar optimization problem introduced in the previous section where omni-directional antenna is assumed to use. The object function of the sectorized BS based MMR approach is slightly different from the previous model. In the sectorized BS based MMR approach, the BS cost is divided into two parts, one for BS tower construction cost and the other for sector antenna related cost. Therefore, the objective function and constraints can be expressed as below.

Minimize

\[
C_T = C_{BS} X_{BS} + C_{RS} \sum_{i=1}^{3} \sum_{j=1}^{I} X_{RS_{i,j}}
\]

\[
= C_{BS}^{*} X_{BS} + \frac{3}{2} C_{BS}^{*} X_{RS_{1,0}} + C_{RS} \sum_{i=1}^{3} \sum_{j=1}^{I} X_{RS_{i,j}}
\]  

subject to

\[
A_{BS} X_{BS} + A_{RS} \sum_{i=1}^{3} \sum_{j=1}^{I} X_{RS_{i,j}} \geq A_r
\]

\[
C \cdot X_{BS} - \rho \left( \sum_{i=1}^{3} \sum_{j=0}^{I} X_{RS_{i,j}} \right) \geq 0
\]

\[
N_i \cdot X_{RS_{i,0}} - N_i \cdot X_{RS_{i,j}} \leq 0, \quad N_i \cdot X_{RS_{i,0}} - N_i \cdot X_{RS_{i,j}}, \quad \text{for } i \in \{1,2,3\}
\]

\[
x_{BS} = X_{RS_{i,0}} \Rightarrow \begin{cases} X_{RS_{i,0}} - X_{RS_{i,j}} \leq 0, \\ X_{RS_{i,0}} - X_{RS_{i,j}} \geq 0, \end{cases}
\]

\[
x_{RS_{i,j}} \geq X_{RS_{i,0}} \Rightarrow \begin{cases} X_{RS_{i,0}} - X_{RS_{i,j}} \geq 0, \\ X_{RS_{i,0}} - X_{RS_{i,j}} \leq 0, \end{cases}
\]

where, \(C_T\), \(C_{BS}\) and \(C_{RS}\) are the same cost values used in (1), and \(X_{BS}\) is the number of BS. In order to consider sectorized BS based MMR approach, several variables are introduced. \(X_{RS_{i,j}}\) is the number of RS at \(i\)-th tier of \(j\)-th BS sector, and \(X_{RS_{i,0}}\) is the number of sector antenna in BSs. \(C_{BS}^{*}\) is the BS tower construction costs, and \(C_{RS}\) is the \(i\)-th sector antenna related cost in a BS. Constraints of the optimization problem and assumptions are similar to the previous optimization model in section 2. The constraint for seamless covering of the target service area is in (8) where \(A_{BS}\) is the coverage of a directional-antenna in a BS and (9) is the constraints for the capacity limitation of a BS. (10-1) is the constraints for the maximum number of RSs at each tier where \(N_i\) are variables and (10-2) is the constraint about that a BS can have three directional-antennas. (10-3) is the constraint about a BS must have a sectored antenna and (10-4) is the order of sectored antennas in a BS. The constraints of (11) and (12) are the integrality of the number of BSs and RSs.

Figure 5 shows analytical results on coverage extension and deployment cost for NBTC and WBTC BS-based MMR systems. Modeling parameters are the similar to the previous model shown in table 2.
Table 2: Model Parameters for NBTC and WBTC Systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total area ($A_T$)</td>
<td>300 Km$^2$</td>
</tr>
<tr>
<td>BS coverage ($A_{BS}$)</td>
<td>3 Km$^2$ (Three sector antennas)</td>
</tr>
<tr>
<td>RS coverage ($A_R$)</td>
<td>1 Km$^2$</td>
</tr>
<tr>
<td>Traffic density ($\rho$)</td>
<td>0.1<del>15.9bps/m$^2$ (0.1</del>15.9Mbps/km$^2$)</td>
</tr>
<tr>
<td>RS Cost ($C_{RS}$)</td>
<td>10%, 20%, 30% of BS cost / RS</td>
</tr>
<tr>
<td>BS total capacity ($C$)</td>
<td>60 Mbps (Each antenna has 20 Mbps)</td>
</tr>
</tbody>
</table>

while, the coverage of the NBTC BS-based MMR system is shown to be larger than that of the WBTC BS-based MMR system when the traffic density is less than 0.4 Mbps/Km$^2$. However, there is no significant difference between those two approaches in terms of coverage extension.

As shown in figure 5b, the deployment cost of the WBTC BS based MMR approach is shown to be lower than that of the NBTC BS based MMR system when the RS cost is 10% or 20% of the BS cost. However, there is no difference between two approaches when the RS cost is 30% of BS. Therefore, we could conclude that the WBTC BS-based MMR system is better than the NBTC BS-based MMR system in terms of the coverage extension and deployment cost except for the case when the traffic density is less than 0.4 Mbps/Km$^2$.

4. Multi-hop system deployment scenario

In previous two sections, we analyze various MMR WiBro/WiMAX systems for cost-effective coverage extension under various topologies and BS sectorizations. From the above analytical results, we can conclude that the multi-hop relay based WiBro/WiMAX system can be deployed in several phases according to the user-traffic density and resulting system performance. Figure 6 shows a practical deployment scenario of the MMR WiBro/WiMAX system consisting of three deployment scenarios in terms of the user-traffic density and the number of tiers. In this scenario we assume that the minimum required data rate per user 128kbps. Phase 1 corresponds to the situation when the traffic density per unit area is less than 1.5 Mbps. In this phase, due to the low traffic density a BS has enough capacity to accommodate many users, and thus the MMR system could have more than 2 tiers to cover large service area. Phase 2 corresponds to the situation when the traffic density is 1.5~5 Mbps/Km$^2$. In this case, a BS could have 1 or 2 tiers to cover a service area. Phase 3 corresponds to the moderate traffic density situation having more than 5 Mbps/Km$^2$. In this phase, there could be less than 1 tier RSs connected to a BS, and thus RSs are used to extend BS coverage toward a specific direction from a BS or to cover radio shadowing areas.
5. Conclusions

In this paper, we first obtained the optimum numbers of BSs and RSs for minimizing total system cost using optimization problem given maximum system capacity of WiBro/WiMAX systems. We proposed various multi-hop based network topologies using omni-directional antenna for metropolitan area network and rural area network. We, also, proposed multi-hop based network topologies using directional antenna, the NBTC BS-based and the WBTC BS-based MMR systems. Through analytical methods, we obtained the optimal network configuration given traffic density for various topologies and compared the cost with the traditional topology. Finally, we presented practical deployment scenario consisting of three phases depending on user-traffic density and the number of traffic relaying hops. We presented the basic studies of the multi-hop based NBTC BS-based and WBTC BS-based MMR systems without considering interference in this work. However, the WBTC system has generally the bigger interference than the NBTC system. We are planning to investigate and compare the performance of various topologies taking interference into consideration in MMR WiBro/WiMAX systems.

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References