Investigations of Resource Allocation Schemes Between Multi-hop Backhaul Network and Access Network

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***Abstract*—In this paper, the trade-off on resource allocation between multi-hop backhaul and access is investigated. Multi-hop, treated as a special case of mesh, is very useful in non-contention based network. We assume in-band relay backhaul and access share the same resource. Based on calculation and simulation, the relationship among resource allocation, cell coverage and channel status is revealed under two relay schemes.**

Keywords-Multi-hop; resource allocation; Shannon capactiy; in-band;out-band; relay.

I. INTRODUCTION

Wireless multi-hop networks have attracted lots of attentions in recent years as the next evolutionary step for wireless data networks. It is more feasible and effective than pure mesh structure, especially in non-contention based wireless network. Non-contention wireless network contains, such as Worldwide Interoperability for Microwave Access (WiMAX) [1], Long Term Evolution (LTE) [2], High Speed Uplink Packet Access (HSPA) [3] and so on. These networks carefully schedule the radio resource to avoid interference and efficiently utilize the radio resource. Pure mesh structure is not so easy to be implemented in such a network, due to synchronization, interference and so on.

Currently, WiMAX and LTE both setup relay work group to study how to build multi-hop backhaul in access cell.

WiMAX technology is becoming increasingly popular as a number of service providers are deploying WiMAX to provide wireless broadband connectivity to customers. IEEE 802.16j work group is focusing on multi-hop relay networks that will enable multi-hop communication in mobile WiMAX (IEEE 802.16e) networks. In such a network, mobile stations or subscriber stations may communicate with a Relay Station (RS) instead of communicating directly with the Base Station (BS) [4][5].

Similarly, people also proposed relay system in LTE-Advanced [6][7]. Generally, relay is essentially backhaul function plus access function in one node. LTE based wireless backhaul can be classified into in-band and out-band backhaul solutions. In-band backhaul, such as LTE in-band relay and IEEE802.16j [4][5], will share the radio resource with access. Out-band backhaul will use another independent radio resource from access. In this paper, we focus on in-band multi-hop relay.

In [9], the coverage and capacity of in-band relay in urban area were simulated. The realistic performance of relay in suburban area was illustrated in [10].

In this paper, we will build an Orthogonal Frequency Division Multiplexing (OFDM)-based two-hop relay network to cover most cases, e.g., LTE, WiMAX. Then we will study the resource allocation balance between backhaul and access under different cell radius, various channel status, and different relay schemes. The performance will be compared in in-band and out-band relay, so as to indicate the respective use cases.

This paper is organized as follows. In Section II, system model is described and two relay schemes are defined for multi-hop backhaul part. Here, we will investigate a two-hop in-band backhaul system with access. The assumptions are also given. In Section III, the calculation steps are given and a static system level simulation is built to help get the final results [8]. The obtained results are analyzed in detail as well. In Section IV, we get the final conclusions.

II. SYSTEM MODEL

Since access and backhaul parts share the same radio resource, an efficient resource management will be very important to avoid congestion regardless in access or backhaul. Generally, there are two kinds of methods—dynamic allocation and static allocation.

Comparatively, dynamic allocation is more efficient. The system obtains the statistics of the access/backhaul requirement and the channel qualities, and calculates the resource trade-off between access part and backhaul part instantly.

Here, we assume an ideal dynamic allocation to avoid any congestion or unbalance between backhaul and access, which means that BS knows all instant channel information of all links and allocation granularity is very small.

We also assume two configurations at two-hop relay part. The first scheme is the traditional one, which means different relay backhaul links will use orthogonal resources. The

 ISBN: 978-1-61208-193-9

second scheme allows relay backhaul links to utilize Spatial Division Multiplex Access (SDMA) to save radio resource. That means same resources can be spatially reused among different backhaul links with directional antennas.

Details are as follows.

A. Relay Scheme 1

We assume a cell deployment structure shown in Figure 1. All base stations (BSs) or relays are located at the center of hexagon cell. The access radio resource is separated into three parts as shown in Figure 2 and reused among the cells shown in Figure 1. Similarly, the backhaul resource is also reused as shown in Figure 1 and Figure 2. Different backhaul links will use orthogonal resources.

Additionally, we call the central cell as egress cell. In egress cell as shown in Figure 1, all access traffics from these 19 cells are collected and backhauled to this egress BS, which is called Donor eNB in LTE-A [6][7]. We treat this node as wireless backhaul egress, since generally there will be a fiber connection on this node to continue to backhaul all traffics to core network.

Around egress cell, there are 6 cells called 1st tier cells as shown in Figure 1. Around 1st tier, 2nd tier consists of 12 cells. Backhaul links connecting egress cell and 1st tier cells are called 1st hop, while those connecting 1st tier and 2nd tier are called 2nd hop.

Note that the first hop backhaul generally occupies more resources than the second hop due to the much more backhaul traffic. In Figure 1 thicker backhaul line means more radio resource occupation.

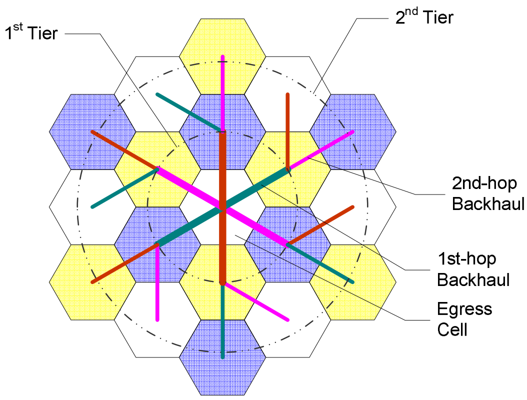

Figure 1. Cell structure of relay scheme 1.

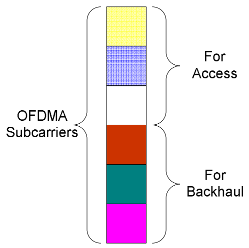

Figure 2. OFDM subcarrier assignment for relay scheme 1.

B. Relay Scheme 2

We assume another cell deployment shown in Figure 3. Similarly, the access radio resource is separated into three parts as shown in Figure 4 and orthogonally reused in Figure 3. Here, the backhaul resource is spatially reused as shown in Figures 3 and 4. Different backhaul links will use the same resource by for example Spatial Division Multiplex Access (SDMA) through directional antennas. Note that the first hop still occupies more resource than the second hop due to the much more backhaul traffic. In Figure 3, thicker backhaul line means more radio resource occupation.

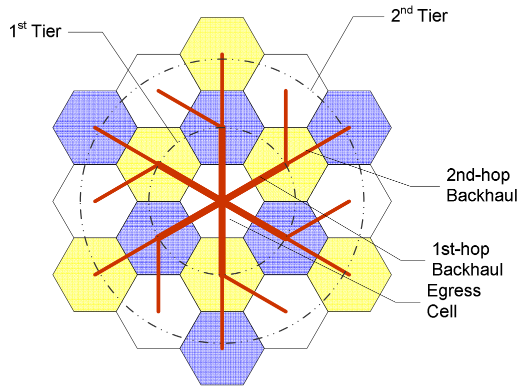

Figure 3. Cell structure of relay scheme 2.

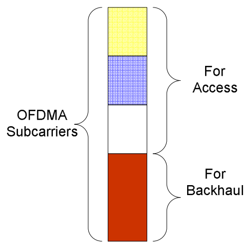

Figure 4. OFDM subcarrier assignment for relay scheme 2.

C. Assumptions in System Model

We assume that each cell has the same user density and the same traffic requirement of each user (calculated by Shannon Capacity). All cells have many users and are full-loaded.

Obviously, if a cell is close to the backhaul egress, the backhaul requirement will be much higher, because this cell has to backhaul not only its own traffic but also those of its child nodes. The cell close to the egress surely will consume more radio resource for backhaul.

Here, we assume all cells have the same radius r.

The other assumptions are as follows. All the cell access parts have the same path loss factor γ_A, and all the backhaul channels also have the same path loss factor γ_{BH}. Assuming carrier frequency is f_c; the transmit powers for access and backhaul are $\boldsymbol{P_A}$ and $\boldsymbol{P_{BH}}$ respectively; the noise power is $\boldsymbol{N}$. B_A and B_{BH} are the bandwidths for access and backhaul parts *in the second tier and second hop* respectively. The total bandwidth is $\boldsymbol{B}$. $\boldsymbol{E(.)}$ is the expectation operation.

 ISBN: 978-1-61208-193-9

The path loss for access in each cell is

$$PL_A(d,\gamma_A)[dB] = PL(d_0,\gamma_A)[dB] + 10\gamma_A \log\left(\frac{d}{d_0}\right) + X_\sigma \quad (1)$$

Similarly, the path loss for backhaul is

$$PL_{BH}(d,\gamma_{BH})[dB] = PL(d_0,\gamma_{BH})[dB] + 10\gamma_{BH} \log\left(\frac{d}{d_0}\right) + X_\sigma, \quad (2)$$

where $PL(d,\gamma) = \left(\frac{4\pi f_c}{c}\right)^2 d^\gamma$.

Here, d is the distance from transmitter to receiver (e.g., BS to User Equipment (UE)), d_0 is the reference distant, and X_σ is the shadow fading.

In following simulation and analysis, we follow the parameters defined in Table I.

TABLE I. SYSTEM PARAMETERS

Parameters		***Value***
Access channel path loss factor γ_A		3.5
Two-hop backhaul channel path loss factor γ_{BH}		2.5
Carrier frequency f_c		2.5GHz
Cell radius		1 km
Downlink transmit power of BS and relay		33dBm@BS; 18dBm@relay
Total bandwidth ***B***		10MHz
UE antenna gain		0dBi
BS or relay node antenna gain		11dBi
Noise Figure		5dB@BS or Relay, 9dB@UE
Traffic Density	district town	D=9.196bps/m^2
	semi rural area	D=1.522bps/m^2
	rural area	D=0.298bps/m^2
Antenna Configuration		SISO
Shadow fading standard deviation, X_σ		8dB

Since access downlink (DL) always has higher power and higher throughput, we only consider DL here.

III. CALCULATION AND SIMULATION RESULTS

Here, we build a static system level simulation, and use Monte-Carlo method to get the results according to [8].

We use Shannon Capacity to calculate the throughput for users and backhaul part.

A. Relay Scheme 1

At the second tier, in order to get the balance between access and backhaul parts, we have

$$B_A \cdot E\left[\log_2\left(1+\frac{P_A * G_A}{N * PL_A}\right)\right] = B_{BH} \cdot E\left[\log_2\left(1+\frac{P_{BH} * G_{BH}}{N * PL_{BH}}\right)\right] \quad (3)$$

Here, B_A and B_{BH} are the bandwidths for access in each cell and backhaul parts in the second tier respectively. $\boldsymbol{G_A}$ and $\boldsymbol{G_{BH}}$ are the antenna gains in access part and in backhaul part respectively. As shown in Figure 1, the backhaul link in the first tier will transmit more traffic, including its own and its child cells'. Therefore, the backhaul bandwidth in first tier should be **3***$\boldsymbol{B_{BH}}$, since it will backhaul three cells' traffic.

Finally, assuming the total bandwidth is B, according to Figure 1, we have

$$3 * B_A + 5 * B_{BH} \le B \quad (4)$$

It is hard to obtain a close-form result of the left side in (3). One way is to use static system level simulator to do Monte Carlo simulation [8].

An example is as follows. With the parameters in Table I and $\boldsymbol{B}$=10MHz, according to Monte Carlo simulation, we have

$$E\left[\log_2\left(1+\frac{P_A * G_A}{N * PL_A}\right)\right] = 1.91 \quad \text{and}$$

$$E\left[\log_2\left(1+\frac{P_{BH} * G_{BH}}{N * PL_{BH}}\right)\right] = 6.014 \quad (5)$$

According to (3), (4) and (5), we can obtain the bandwidth requirement for access and backhaul in the second tier as

$\boldsymbol{B_A}$: $\boldsymbol{B_{BH}}$=6.014:1.91

We use equal mark in (4) and obtain

$\boldsymbol{B_A}$=2.18MHz and $\boldsymbol{B_{BH}}$=0.6922MHz

For the egress cell and the cells in the first tier and the second tier, the resource for access in each cell is same, i.e., $\boldsymbol{B_A}$. For the 1st hop backhaul from the first tier to the egress cell, we require 3*$\boldsymbol{B_{BH}}$. For the 2nd hop backhaul from the second tier to the first tier, we require $\boldsymbol{B_{BH}}$.

According to the mentioned example, we can calculate the bandwidth for access and backhaul in case of different parameters.

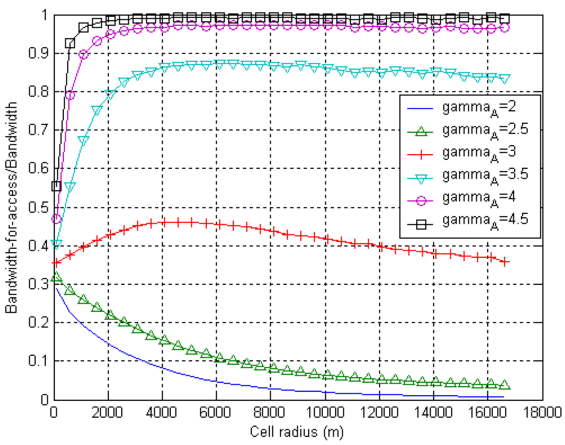

Figure 5. Proportion of Total Access Bandwidth over Total Bandwidth for Realy Scheme 1.

 ISBN: 978-1-61208-193-9

With the parameters in the mentioned example and different path loss factors γ_A in access (gamma$_A$ in Figure 5), we can get Figure 5. In Figure 5, the proportion of total access bandwidth in case of different path loss factors in access is shown, i.e., $(3*B_A)/B$. It is shown that we require more access resource with higher path loss in access.

B. Relay Scheme 2

At the second tier, in order to get the resource balance between access and backhaul parts, we have

$$B_A \cdot E\left[\log_2\left(1+\frac{P_A * G_A}{N * PL_A}\right)\right] = B_{BH} \cdot E\left[\log_2\left(1+\frac{P_{BH} * G_{BH}}{N * PL_{BH}}\right)\right] \quad (6)$$

Here, B_A and B_{BH} are the bandwidths for access in each cell and backhaul parts in the second tier. Similarly, the backhaul bandwidth in first tier should be $\boldsymbol{3*B_{BH}}$. Assuming the total bandwidth is $\boldsymbol{B}$, according to Figure 3, we have

$$3*B_A + 3*B_{BH} \le B \quad (7)$$

Similarly, we use Monte Carlo simulation to obtain the result of left side in (6).

An example is as follows. With the parameters in Table I and $\boldsymbol{B}$=10MHz, according to Monte Carlo simulation [8], we can get

$$E\left[\log_2\left(1+\frac{P_A * G_A}{N * PL_A}\right)\right]=1.91 \text{ and}$$

$$E\left[\log_2\left(1+\frac{P_{BH} * G_{BH}}{N * PL_{BH}}\right)\right]=6.014 \quad (8)$$

According to (6), (7) and (8), we can obtain the bandwidth requirement for access in each cell and backhaul in the second tier as

$\boldsymbol{B_A}$**:** $\boldsymbol{B_{BH}}$=6.014:1.91

We use equal mark in (7) and obtain

$\boldsymbol{B_A}$=2.53MHz and $\boldsymbol{B_{BH}}$=0.80347MHz

For the egress cell and the cells in the first tier and the second tier, the resource for access in each cell is same, i.e., $\boldsymbol{B_A}$. For the 1st hop backhaul link, we require 3*$\boldsymbol{B_{BH}}$ for each. For the 2nd hop backhaul link, we require $\boldsymbol{B_{BH}}$ for each.

With the parameters in the mentioned example and different path loss factors γ_A in access (gamma$_A$ in Figure 6), we can get Figure 6. In Figure 6, the proportion of total access bandwidth in case of different path loss factors in access is shown, i.e., $(3*B_A)/B$. It is shown that we require more access resource with higher path loss in access.

C. Simulation Results Analysis

According to Figure 5 and Figure 6, it is shown that when access has bad channel status, i.e., high path loss factor, access will occupy more bandwidth. In this case, backhaul will consume little bandwidth due to good channel status. If we meet large cell radius, access will occupy almost all bandwidth as shown in figures.

If access has relatively good channel status (γ_A=3), i.e., low path loss factor, the proportion of access bandwidth has a peak value. As shown in Figure 5 and Figure 6, the peak value of scheme 1 is about 0.46 at cell radius equal to about 4000 meters, while the peak value of scheme 2 is about 0.6 at cell radius equal to about 4500 meters.

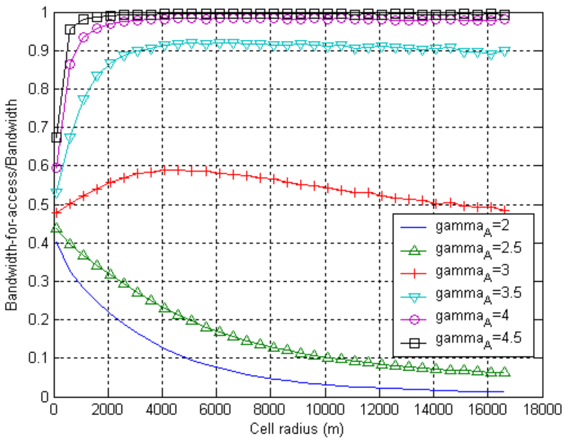

Figure 6. Proportion of Total Access Bandwidth over Total Bandwidth for Relay Scheme 2.

In this case, as cell radius enlarging, the proportion of access bandwidth will increase, but after achieving peak value, the proportion will decrease. The reason is that if the cell radius is too large, path loss in multi-hop backhaul part will relatively increase faster and require more bandwidth.

In a word, the radio resource trade-off between multi-hop backhaul and access yields different characteristics under different channel status.

D. Impact on Access Coverage

The throughput in each cell is $B_A \cdot E\left[\log_2\left(1+\frac{P_A * G_A}{N * PL_A}\right)\right]$, where PL_A is a function of distance. Here, we assume that the access traffic density is $\boldsymbol{D}$bps/m^2 shown in Table I. The access traffic requirement in a cell is $D*\frac{3\sqrt{3}}{2}r^2$ bps. With the parameters in Table I, we can get Figure 7 for scheme 1 and scheme 2. The capacity of traditional cell without *in-band* multi-hop backhaul (BH) is also shown (*"cell capacity w/o in-band backhaul" in Figure 7*).

Note that a cell without in-band backhaul can be a cell with out-band wireless backhaul or wired backhaul, such as fiber, ATM, and so on. We also call this cell as *traditional cell*.

In Figure 7, the real throughput requirements in each cell based on different traffic densities are shown (different ***D*** in Figure 7). It also shows the throughput provided by access cells in case of schemes 1 and 2.

Obviously, only if the provided cell throughput is larger than the real traffic requirement, the user communication can be satisfied, i.e., the three red lines in Figure 7 should be on the upper of the other lines. According to Figure 7, we can get the coverage radius limit under different cases in Table II.

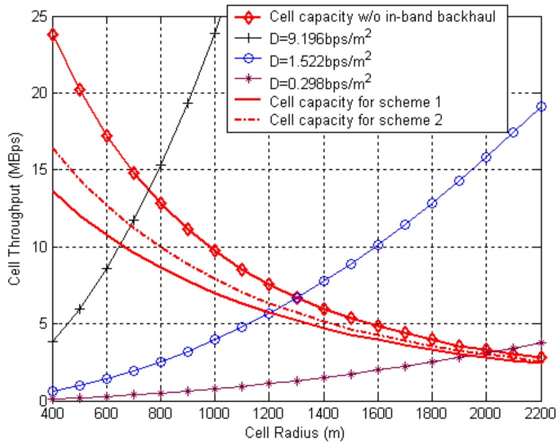

Figure 7. Cell Throughput and Throughput Requirement..

TABLE II. COVERAGE RADIUS LIMITATION

Senarios	district town D=9.196bps/m^2	semi rural area *D*=1.522bps/m^2	rural area *D*=0.298bps/m^2
Scheme 1	651m	1200m	1950m
Scheme 2	690m	1240m	1985m
w/o in-band BH (traditional cell)	755m	1301m	2036m

Thus in order to cover a specific area of 100km^2, the required number of BSs is listed in Table III. *Here, BS means BS or relay, i.e., any access node.*

TABLE III. NUMBER OF BSS TO COVER A SPECIFIC AREA OF 100KM^2

Parameters	district town D=9.196bps/m^2	semi rural area *D*=1.522bps/m^2	rural area *D*=0.298bps/m^2
Scheme 1	91	27	11
Scheme 2	81	25	10
w/o in-band BH (traditional cell)	68	23	10

From this table, we can see that schemes 1 and 2, i.e., in-band backhaul, are more suitable for rural area or the area of low traffic density, since in-band relay results in similar number of access nodes as traditional cells.

In urban area, scheme 1 and 2 result in much more BSs than traditional cell, which may cause cost increasing and more handoff overhead. However, scheme 2 causes fewer BSs than scheme 1, which means that SDMA among multi-hop backhaul is an efficient method to save radio resource.

In rural area or semi rural area, comparison between scheme 1 and scheme 2 shows that SDMA yield little gain. Scheme 2 even results in same number of BSs as traditional cell.

IV. CONCLUSIONS

In this paper, we studied a non-contention based OFDM in-band multi-hop system. Under two relay schemes, the allocation results for multi-hop backhaul and access are analyzed. It is shown that if access part has much worse channel status than backhaul part, the access will occupy more and more resources with increased cell radius. If backhaul part has similar channel status with access part, the access part will occupy more resources at the beginning, but the occupied resources will be decreased with continuing increased cell radius.

If we use SDMA at multi-hop backhaul part, resource will be saved, and relay can cover larger area. However, it is much more effective in urban area than in rural area. Further study revealed that in-band relay is more suitable for low traffic density area.

ACKNOWLEDGMENT

This work is sponsored by Nokia Siemens Networks Technology（Beijing）Co. Ltd.

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