A multi-hop relay path selection algorithm considering path channel quality and coordinating with bandwidth allocation

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A multi-hop relay path selection algorithm considering path channel quality and coordinating with bandwidth allocation

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Abstract. Many multi-hop relay path selection algorithms were proposed. However, these algorithms do not consider the channel condition of the overall path and coordinate with the bandwidth allocation algorithm. In this paper, we proposed a greedy based multi-hop relay path selection algorithm considering channel quality and available bandwidth of overall path to provide high throughput in varying channel conditions. From the simulation results, our proposed algorithm actually provides higher throughput and outperforms the previous works.

1. Introduction

The wireless network is generally constructed by a base station (BS) and some subscriber stations (SSs), where the former is responsible for managing bandwidth resource and the latter support the connectivity between subscribers and the BS [1]. In order to fill the BS coverage gap shadowed by buildings, enable rapid network deployment, and reduce the construction cost, the multi-hop technology and a new station, called the relay stations (RS) are introduced [2]. RS adopts the multi-hop relaying technique to extend the radio coverage of the network, increase the signal-to-noise-ratio (SNR), and promote the transmission rate. Therefore, by leveraging the RS to transmit packet on the relay path, the bandwidth resource can be well utilized to maximize network throughput. RS can be a specific station in a cellular network or a general mobile station in device-to-device communication [3].

Although the specification of the physical layer and the signaling mechanism in the MAC layer of the RS is well defined, the method to decide the packet transmission path is still vendor-dependent and an open issue. In order to determine the most suitable route between BS and SS for packet transmission, many factors should be considered including the number of hop and channel quality of each link on the selected path. Therefore, some multi-hop relay path selection algorithms are proposed. BFH [4] chooses the path with the best modulation coding scheme of its first hop link, and Markov-BFH [5] selects the relay path according to the future state of the channel quality by using Markov chain model. However, they do not consider the channel quality of links after the first hop. To compensate the lacks of BFH and Markov-BFH, DPS [6] uses the signal-to-noise ratio (SNR), link transmission rate (bits/second), and number of hops of the path as the weight for relay path selection.

On the other hand, in order to transmit relay packets, the BS not only allocates the bandwidth of current frame to the first hop of the relayed connection, but also reserves the bandwidth of the
following frame to the remaining hops. This leads that the relay packets will congest and starve on the relay link without coordinating the path selection and bandwidth allocation. Therefore, the path selection algorithm should contemplate the available bandwidth of each link on the selected path that is not reserved for relay packets by the BS. Nevertheless, the proposed path selection algorithms [3-5] described above does not consider this special characteristic.

As a consequence of analyzing the lacks of previous works, a path selection algorithm considering the channel quality and the number of hops of the path and coordinating the bandwidth allocation is needed. Therefore, in this paper, we propose a novel path selection algorithm, which is named Bandwidth Allocation Awareness Greedy Path selection algorithm (BAGP). The goal of our solutions is to maximize the throughput under the considerations of the distinguished features about the path selection. In order to achieve high system throughput, BAGP first picks up the connection that can transmission packet on the path with the best average transmission rate in the network topology, and then BAGP chooses this path as the packet transmission path for the connection. The path selection for the remaining connections follows the same manner. In addition, the selected path will be modified according to the available bandwidth of each link to avoid the congestion and starvation of the relay packets on the relay link.

The organization of this paper is as follows. Section 2 describes the background and Section 3 formally describes the detailed algorithm of BAGP. In Section 4, the effectiveness of the proposed algorithms compared with Round Robin (RR) without of support RS, BFH, and DPS is demonstrated by simulation. Finally, some conclusions are given in Section 5.

2. Background
The protocol stack in a cellular network consists of two layers, physical layer and MAC layer. The former provides the means to transfer raw data, and the latter is designed to support the physical layer to manage radio resource efficiently. With regard to the physical layer adopting OFDMA, three modulations, quadrature phase shift keying (QPSK), 16 quadrature amplitude modulation (16QAM), and 64 quadrature amplitude modulation (64QAM) with different coding rate are used according to the channel quality, i.e. carrier-to-interference-plus-noise ratio (CINR). Three duplex modes are used in OFDMA including TDD (Time Division Duplex), FDD (Frequency Division Duplex), and H-FDD (Half-duplex Frequency Division Duplex). TDD is usually the more attractive duplex mode because of its flexibility.

![Multi-hop relay model](image)

**Figure 1.** Multi-hop relay model.

To improve the robustness of the network, an amendment of introducing multi-hop technology and a Relay Station (RS), is developed [2]. RS is also regarded as a mobile station in D2D communication. By adopting multi-hop technology, the RS can enhance scalability and coverage of different
deployment scenarios according to the characteristics and the requirements of the network environment.

Figure 1. shows the usage models of the RS that can be categorized as the following applications: (1) the RS can reduce the network constructions cost by deploying in stationary areas to improve the SNR and transmission rate of the SS; (2) the RS can fill the coverage hole shadowed by the building, tunnel, or subway; (3) the RS can be rapid deployed on the place for temporary or emergency events where a large group of people are densely packed into a small area.

3. Proposed algorithm

In this section, we first elaborate the notations and formal problem definition on the multi-hop relay path selection problem. Then, a Bandwidth Allocation Awareness Greedy Path selection algorithm (BAGP) that considering the channel quality of overall path and coordinating the bandwidth allocation is proposed.

Table 1. The notations for the Path Selection Problem and the proposed algorithm.

| Notation Name | Explanation |
|---------------|-------------|
| F             | The frame structure |
| DLC          | The sets of all DL connections where |DLC| = n |
| R_{m,n}      | The matrix of each connection’s modulation coding schemes where R_{m,n} specifies the transmission data size (bytes/slot) from node m to node n |
| B_{i}        | The data size of i-th connection requested for downlink transmission |
| BWR          | The set containing all B_{i} |
| P_{i}^{j}    | The diverse path between BS and SS that selects one path to send the data |
| W_{p_{i}}^{h} | The number of pre-allocation slots of each hop that connection i transmits packets on path j by the certain bandwidth allocation algorithm Round Robin (RR) |
| BWA          | The set containing all W_{p_{i}}^{h} |
| FPS          | Stands for the number of frames the BS sends per one second |
| Th(F)        | Throughput of F which denotes the set A = \{(P_{i}^{j}, W_{p_{i}}^{h}) | i \in DLC\} allocates the minimum number of slots to gain the maximum throughput |

3.1. The problem definition

As mentioned above, the multi-hop relay path selection algorithm has to decide the route between BS and SS and the amount of bandwidth to allocate for each connection in order to maximize the overall throughput, where the former is called the path selection and the latter is bandwidth allocation. As the notations shown in table 1, the formal definition of the path selection problem is that given a Frame F, a DLC set, a modulation coding scheme matrix R, a BWR set, and a BWA set allocated by the certain bandwidth allocation algorithm, find a set of path and allocate bandwidth A = \{(P_{i}^{j}, W_{p_{i}}^{h}) | i \in DLC\} that the total throughput Th(F) is maximized.

3.2. Bandwidth Allocation Awareness Greedy Path selection algorithm (BAGP)

The detailed algorithm of BAGP is presented in Figure 2 and explained as follows:

Intutionally, each connection should transmit packet on the path with best transmission rate to promote the throughput. Thus, in the first step, we list all possible transmission paths of each connection and calculate the average transmission rate respectively.
$R_{m,n}$: the modulation coding scheme of each hop from node $m$ to node $n$
$B_i$: the bandwidth requirement of $i$-th connection
BWR: the set of connections
for each connection $i$ arrives

//Step1: Decide the suitable path form the path set
for each diverse path
{
    calculate $A_{i'} = \frac{1}{\hat{A}_{i'} R_{m,n}}$
}
Sort($A_{i'}$) in descending order
//Step2: Pre-Allocation the minimum number of slots
for each $A_{i'}$ to allocation bandwidth
{
    if ($P'_i$ = Relay)
    {
        $\hat{\mu}\ W_{i'} = require\_slot(B_i, R_{m,n}, FPS)$
        saving = $\hat{\mu}\ W_{i'}$
        $N_{\text{prio,con}} = N_{\text{prio,con}} - \text{saving}$
    } //Step 3: Modify the selected path to avoid the congestion
    if (the remaining bandwidth of relay is exhausted or less than the require slot of connection)
    {
        Mark the $P'_i$ and do not assign it to the connection
        Find next $P'_i$
        if ($P'_i$ fulfills require slot)
        {
            Assign $P'_i$ to this connection and allocate the suitable bandwidth to the connection
            $W_{i'} = require\_slot(B_i, R_{m,n}, FPS)$
        }
    }
}
while(all connections of BWR have been satisfied)
Terminate the execution of BAGP

Figure 2. The BAGP algorithm.

The average transmission rate of the path $j$ for the connection $i$ is calculated by:

$$A_{i'} = \frac{1}{\hat{A}_{i'} R_{m,n}}$$  (1)
In (1), $\frac{1}{R_{m,n}}$ is the number of slot to transmit one bit per hop, $\frac{1}{R_{m,n}} / R_{m,n}$ means the number of slot to transmit one bit on the path $P_{m,n}^j$, therefore $A_{m,n}^j$ is the average transmission rate that connection $i$ transmits packets on path $j$. Then, BAGP selects the connection that owns the path with best average transmission rate among the topology, and this path is set as the packet transmission path for the selected connection.

In the second step, BAGP uses Round Robin (RR) as the bandwidth allocation algorithm to allocate suitable number of slots to this chose connection according to its requested bandwidth and the modulation coding scheme of the first hop of the selected path.

$$\frac{1}{B_{m,n}^j} W_{m,n}^j = \text{require_slot}(B, R_{m,n}, FPS)$$

In (2), require_slot($B$, $R_{m,n}$, FPS) is the overall number of slots necessary to ensure the bandwidth requirements then divide it by the number of frames, therefore, $\frac{1}{B_{m,n}^j} W_{m,n}^j$ aggregates the number of pre-allocation slots of each hop that connection $i$ transmits packets on path $j$ we have to allocate in current and following frame.

In addition, BAGP will reserve the bandwidth saving for the remaining hops of the selected path to avoid that packets are congested and starved in the relay path. Furthermore, if the selected path does not have enough bandwidth of the each hop for the requested bandwidth of this connection, BAGP will not assign this path to the connection, and the bandwidth scheduling for this connection will be detained until being picked up by BAGP in the same fashion described above.

For the other connections, the path selection follows the same manner depicted above.

4. Simulations

In this section, we compare the proposed algorithm BAGP with the Round Robin (RR) without supports of RS, BFH, and DPS in terms of downlink throughput, where the downlink throughput is the summation of throughput of each downlink connection. Because BFH and DPS only depict the path selection algorithm, we use RR as the bandwidth allocation algorithm to combine with BFH and DPS.

![Network topology](image)

**Figure 3.** Network topology.

4.1. Simulation model

For the simulation environment, an OFDMA system with 20MHz bandwidth is used. The number of sub channels and symbols for a downlink sub frame are set to 60 and 36, which is 18 downlink slot width where one downlink slot occupies two symbols. Figure 3 shows the network topology that
includes one BS and fifteen SSs. In order to prevent bandwidth allocation in the SSs from influencing the simulation results, each SS owns only one connection. The packet interarrival time of the connections follows the Exponential distribution. Different modulation coding schemes of each connection are adopted according to the received Carrier to Interference-plus-Noise Ratio (CINR) as shown in 2 [1]. In addition, the received CINR follows the Normal distribution with different means and standard deviations according to each simulation scenario.

| Modulation | Coding Rate | Receiver CINR (dB) | Bytes Per Slot |
|------------|-------------|--------------------|----------------|
| QPSK       | 1/2         | 6.0                | 6              |
|            | 3/4         | 8.5                | 9              |
| 16QAM      | 1/2         | 11.5               | 12             |
|            | 3/4         | 15                 | 16             |
| 64-QAM     | 2/3         | 19                 | 24             |
|            | 3/4         | 21                 | 27             |

### 4.2. Traffic load

To observe the influence of different traffic load on downlink throughput, 15 downlink connections with different data transmission rate from 100kbps to 800kbps are measured. The mean CINR between each SS and RS and between RS and BS are 15dB, and the standard deviation is 5dB. The mean CINR between each SS and BS is 8dB and the standard deviation is 1dB.

Observing from Figure 4, the downlink throughput improved by BAGP increases as the requested bandwidth increases. The reason is that BFH selects the path by considering the channel quality of the first hop, leading that the relay packet will congest on the relay link if the channel quality of relay link is worse. On the other hand, although DPS selects the path according to the SNR value, transmission rate of the link, and the number of hops, but it does not consider the available bandwidth of each link in the following frame, causing that the packets congest and starve on the relay link. With regard to RR without supports of RS, it suffers worst performance because the connection cannot relay the packets by RS if the channel quality of the access link is bad.

![Figure 4. Total throughput vs. requested bandwidth.](image1)

![Figure 5. Total throughput vs. CINR.](image2)

![Figure 6. Total throughput vs. standard deviation.](image3)

### 4.3. Channel quality

We investigate the effects of the channel quality for BAGP on the downlink throughput. In this simulation, 15 downlink connections with 800kbps transmission rate are measured. The mean CINR of the subcarriers received by each SS is varied from 10dB to 20dB, and the standard deviation is 5dB.
From Figure 5, the downlink throughput BAGP still outperforms other algorithms, as the channel quality is better. However, the improve of BAGP on downlink throughput is small while the mean CINR is between 10 dB to 12 dB, this is because packets have extra bandwidth to relay RS and the influence to relay packet through RS will begin to shrink if the channel quality of the relay link is close to the access link.

4.4. The variation of channel quality
We observe the effects of different variation of the channel quality on the total throughput in this section. In this simulation, the mean CINR of the subcarriers received by the SS is 15dB, and the standard deviation is varied from 0dB to 10dB. Figure 6 shows that all algorithms have the same performance when standard deviation is 0, this is because each algorithm decides to transmit each packet directly to each SS from BS without any help of RS, since the channel quality of access link and relay link are the same and transmitting packet through the relay path costs extra bandwidth for the relay link. Furthermore, the improvement of BAGP increases as the standard variation increase, the reason is as the same as above. On the other hand, the downlink throughput of all algorithms decreases as the standard deviation of the CINR increases, this is because the more the channel condition of overall path is varied, the more chance that the connection will adopt worse modulation coding scheme, leading that the downlink throughput suffers worse performance.

5. Conclusion
In this paper, the design issues and current works with regard to the multi-hop relay path selection in the wireless network are investigated and analyzed. We also propose a path selection algorithm, Bandwidth Allocation Awareness Greedy Path selection algorithm (BAGP), which considers the channel quality, the number of hop, and available bandwidth of the path for the lacks of the current studies. The simulation results show that BAGP provides higher throughput comparing with the previous works, BFH and DPS.

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