

Path Selection for Mobile Stations in IEEE 802.16 Multihop Relay Networks*

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Abstract

Multimedia applications over wireless mobile networks become more popular with the increasing deployment of wireless infrastructures. IEEE 802.16 standard has become an emerging technology to support broadband access and Quality of Service (QoS) for real-time multimedia applications over wireless networks. This paper discusses the path selection problem in IEEE 802.16 mobile multihop relay (MMR) networks where relay stations are used to extend network coverage and enhance network capacity. For real-time applications that have explicit rate and delay requirements, choosing an appropriate path between any mobile station and the base station becomes essential. In this paper, we propose a path selection metric, named Normalized Number of Minislots (NNM), which enables a mobile station to choose a path that satisfies its application rate and delay requirements. Simulation results show that NNM outperforms existing path selection metrics, especially when network has high traffic load.

1 Introduction

Wireless mesh networks based on IEEE 802.11 [1] have difficulties to support QoS for wireless multimedia applications such as VoIP and video streaming. The major factors are the random backoff and packet collision incurred by the IEEE 802.11 MAC protocol. Recently, wireless mesh networks based on IEEE 802.16 [2] (also known as WiMAX) have become popular both in academia and in industry. IEEE 802.16 mesh networks use Time Division Duplex (TDD) or Frequency Division Duplex (FDD) to support collision-free communications. IEEE 802.16 MAC's centralized bandwidth allocation and scheduling mechanism provide

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guaranteed QoS for real-time applications.

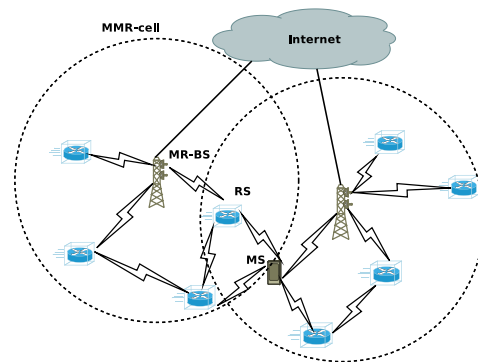


Figure 1. IEEE 802.16 mobile multihop relay network

IEEE 802.16 supports two modes of operations: Point-to-Multipoint (PMP) mode and mesh mode. In this paper, we focus on IEEE 802.16 networks that support mobility in the mesh mode. The discussed scenarios in this paper are consistent with the Mobile Multihop Relay (MMR) networks proposed in the IEEE 802.16j [3] standard, which is still a work in progress.

Figure 1 shows a typical IEEE 802.16 MMR network consisting of base stations (MR-BS), relay stations (RS) and mobile stations (MS). We denote MMR cell as the radio coverage area of a base station and all its subordinate relay stations where mobile stations are serviced [15]. In Figure 1, only the coverage areas of base stations are shown. The base station is the gateway for data traffic of mobile stations from or to the Internet. Communication resources within a cell are managed by the base station through routing and scheduling. The relay stations are used to extend the coverage of the cell and to enhance the throughput of mobile stations. They may be static, nomadic or mobile. In this paper, we only consider fixed relay stations.

The base station is responsible for constructing the

downlink and uplink routing tree [7]. For simplicity, we only consider the downlink traffic from the base station to various mobile stations. Our discussion on path selection only concerns the downlink routing tree. However, our work can also be applied to path selection in the uplink routing tree.

When roaming around the network, the mobile station should perform handover to maintain connectivity and a good QoS. The most important task of handover is to select an appropriate path between the mobile station and the base station. In this paper, we assume that the routing tree consisting of the base station and relay stations are already constructed. Algorithms for establishing routes between relay stations and the base station are discussed in several contributed documents [16, 12] to the IEEE 802.16's relay task group. With the above assumption, the path selection problem for mobile stations is equivalent to the access station (AS) selection problem. The access station is the parent node of the mobile station in the downlink routing tree and it could be either a base station or a relay station. We denote the access link as the link between the mobile station and its access station. Note that the potential access stations of a mobile station can be in different cells. In the rest of the paper, we will use path selection and access station selection interchangeably.

The paper is organized as follows: In Section 2 we review the related work. Section 3 introduces some preliminary concepts related to the path selection problem in IEEE 802.16 MMR networks. Section 4 gives a detailed introduction to several path selection metrics. We provide a simulation evaluation of our proposed path selection metric and compare its performance with other proposed metrics in Section 5. Conclusions and future work are given in Section 6.

2 Related Work

Relay networking has been a research topic in wireless cellular networks. Sreng, et al. [17] investigated the relay node selection strategies in cellular networks with peer-to-peer relaying. The authors proposed relay node selection strategies based on distance and pathloss for two-hop relaying networks.

The path selection problem for mobile stations has been discussed in several contributed documents to the IEEE 802.16's relay task group. Oyman, et al. [14] proposed two end-to-end path selection metrics for mobile stations: a capacity-based metric and a throughput-based metric. The capacity-based metric computes the harmonic mean of the capacities over individual links.

The capacity of each link is calculated based on the Signal to Interference and Noise Ratio (SINR). The throughput-based metric computes the harmonic mean of maximum throughputs over individual wireless links. Per-link throughput estimation accounts for link errors, modulation and coding schemes.

The path capacity or the maximum end-to-end throughput is a good metric to measure the quality of a path, however, it fails to reflect the achievable end-to-end throughput and delay of mobile stations in IEEE 802.16 MMR networks. In addition to path capacity, the achievable throughput of a mobile station in MMR network also depends on the available communication resources of a cell and the scheduling algorithm used in the base station (the detailed discussion is in Section 3 and Section 4). In this paper, we propose a path selection metric that takes both path capacity, resource availability and scheduling algorithms into consideration. Our proposed path selection metric enables mobile stations to choose a path that yields high achievable end-to-end throughput and low delay.

3 Preliminaries

3.1 Frame Structure

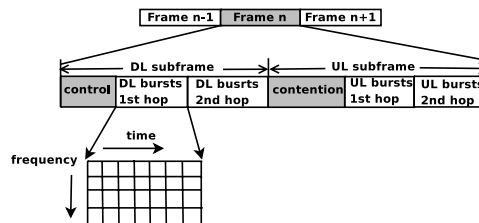


Figure 2. IEEE 802.16 MAC frame structure

According to the IEEE 802.16j standard draft, the MAC frame structure is based on the Orthogonal Frequency Division Multiple Access (OFDMA) transmission technique [5]. Under the TDD scheme, a MAC frame consists of a Downlink (DL) sub-frame period and an Uplink (UL) sub-frame period. Figure 2 shows the frame structure of a two-hop relay network. Some time intervals in the frame are reserved for control messages and contention-based communications.

OFDMA is a multi-carrier transmission scheme. Under OFDMA, the whole frequency band is segmented into a set of sub-carriers. Sub-carriers are grouped into logical entities called sub-channels. Sub-channels can

be constructed in two different ways: grouping contiguous sub-carriers or grouping sub-carriers scattered over the entire frequency band. The second method is considered now by WiMAX vendors as the most relevant solution for practical wireless access systems [6]. Under OFDMA, the time domain is segmented into constant symbol durations, thus the communication resources of a cell can be represented as a two-dimensional matrix. Each resource element is a combination of the symbol duration and the sub-channel. Resource elements are allocated in repeated frame period to different links of the network.

In this paper, we only consider the resource allocation in the time domain, i.e, the symbols are carried on all available sub-channels. In addition, symbol durations are grouped into minislots. A minislot contains a fixed number of symbol durations and is considered as the basic resource allocation unit in this paper. Note that the above choice is made for the ease of presentation and it is consistent with the Orthogonal Frequency Division Multiplexing (OFDM) transmission technique [5]. Our work can be easily extended to accommodate OFDMA transmission technique by changing the resource allocation granularity from minislot to the element of the two-dimensional matrix mentioned above.

3.2 Scheduling

The base station needs to translate the traffic rate requirements of mobile stations into the number of minislots that are needed for each link in the routing tree. The number and the order of the minislots assigned to each link is determined by the scheduling algorithm. Several scheduling algorithms have been proposed [7, 9] for IEEE 802.16 networks. In this paper, we consider a scheduling algorithm that is proposed as an example in the IEEE 802.16 standard [7].

The algorithm assigns minislots to links following a breadth-first traversal of the routing tree. Links that are visited first are assigned minislots earlier in the frame. When the total number of minislots assigned to links exceeds the number of available minislots in a frame, the algorithm scales down the number of minislots assigned to each link. The scheduling algorithm is performed at the beginning of each frame period at the base station. We will discuss the scheduling algorithm in more detail in Section 4.

3.3 Fast Access Station Switching

In this paper, we assume that the fast access station switching [19] method is used. Using this method, a

mobile station can change its access station from frame to frame depending on the access station selection mechanism [15]. Thus, the path selection is performed before the scheduling algorithm at each frame by different base stations. In order to use this method, mobile stations and relay stations should periodically monitor the quality of its uplink and downlink, and report them to the associated base station. The link quality measurement and report mechanisms have been discussed in several contributed documents [18] to the IEEE 802.16's relay task group.

4 Path Selection Metric

In this section, we introduce three path selection metrics. The first one, "number of hops", is very easy to implement. However it does not take the path capacity into consideration, which is one of the important factors that affect the achievable throughput and delay of the mobile stations. The second one, "maximum end-to-end throughput", is based on the previous work in [14]. This metric reflects the path capacity. However, it does not consider the achievable throughput of a mobile station. Finally we discuss our proposed path selection metric, "normalized number of minislots", which enables mobile stations to achieve high end-to-end throughput and low delay. The path selection metric can be used by the base station in a centralized manner or by mobile stations in a distributed manner.

Before discussing these path selection metrics, we introduce notation that will be used in this section. Denote the set of cells as $Q = \{q_1, \dots, q_M\}$, the set of mobile stations as $V = \{v_1, \dots, v_N\}$ and the set of links as $E = \{e_1, \dots, e_L\}$. Assume that the link rate, in bits per second, of link e_l is r_l . The link rate depends on the modulation and coding scheme used for the link, which is determined by the Signal to Noise Ratio (SNR) at the receiver side of the link. Table 1 shows the type of modulation and link rate (represented as bits/symbol) in relation to the received SNR [7, 13].

Table 1. Link rate vs. SNR

Modulation	Bits/Symbol	Received SNR (dB)
BPSK 1/2	96	3
QPSK 1/2	192	6
QPSK 3/4	288	8.5
16QAM 1/2	384	11.5
16QAM 3/4	576	15
64QAM 2/3	768	19
64QAM 3/4	864	21

4.1 Number of Hops (NOH)

The simplest path selection metric is the number of hops between the mobile station and the base station. Mobile stations choose the path with the smallest number of hops. This metric is widely used in several routing protocols for mobile ad hoc networks. The major drawback of this metric is that it usually results in long hops that have poor link rates.

4.2 Maximum End-to-End Throughput (MET)

In [14], the authors propose that the maximum end-to-end throughput of a given multi-hop path p_n may be expressed as

$$MET = \frac{b}{ETT} \quad (1)$$

where b is the number of bits per packet, ETT is the expected transmission time of a packet on path p_n . ETT has originally been proposed and discussed in [8] for IEEE 802.11 mesh networks. ETT can be calculated as

$$ETT = \sum_{l:e_l \in p_n} ETT_l$$

where ETT_l is the expected transmission time of a packet on link e_l . For simplicity, we don't consider packet retransmissions caused by link errors. So ETT_l can be calculated as

$$ETT_l = \frac{b}{r_l}$$

To get the optimal throughput, a mobile station should choose a path with the maximum MET value.

4.3 Normalized Number of Minislots (NNM)

Equation (1) calculates the maximum throughput of a path, however, it does not correctly reflect the achievable end-to-end throughput of a mobile station when the IEEE 802.16 MAC frame structure and scheduling algorithms are taken into consideration. In the following, we calculate the end-to-end throughput of a mobile station v_n . Assume that the mobile station uses path p_n , which belongs to cell q_m . Denote the traffic rate of mobile node v_n , in bits per second, as g_n . Denote the throughput of the mobile node, in bits per second, as \hat{g}_n .

The throughput of mobile station v_n can be calculated as [7]

$$\hat{g}_n = \min_{l:e_l \in p_n} \frac{\hat{s}_l}{s_l} g_n$$

where s_l is the number of required minislots on link e_l . \hat{s}_l is the number of assigned minislots on link e_l . As explained in [7], the achievable end-to-end throughput is the minimum bandwidth the mobile station gets on all the links on the path.

In fact,

$$s_l = \sum_{n:p_n \ni e_l} \lceil \frac{g_n}{r_l t} \rceil$$

where t is the duration of a minislot. Here is a brief explanation of the above equation. Link e_l carries traffic of several mobile stations whose path contains the link. For every mobile station, the required transmission time on link e_l equals to its traffic rate divided by the link rate. Thus, for every mobile station, the number of required minislots on link e_l equals to the required transmission time divided by the duration of a minislot. Finally, the total number of required minislots on link e_l is the sum of required minislots of all mobile stations which uses path that contains the link.

The number of assigned minislots on link e_l depends on the number of available minislots in a frame for downlink traffic in the cell and the scheduling algorithm used in the base station. For the scheduling algorithm discussed in Section 3,

$$\frac{\hat{s}_l}{s_l} = \min \left\{ 1, \frac{S_m}{\sum_{l:e_l \in q_m} s_l} \right\}$$

where S_m is the number of available minislots in a frame for downlink traffic in the cell q_m to which the path p_n belongs. $\sum_{l:e_l \in q_m} s_l$ represents the total number of minislots required for all links in the cell q_m .

Similar to [11], we denote \hat{s}_l/s_l as the *downlink satisfaction index* of link e_l . In fact, the satisfaction index represents the proportion of the number of assigned minislots over the number of required minislots. According to the scheduling algorithm, all links that belongs to the same cell have the same downlink satisfaction index, so we can define the *downlink satisfaction index* of the cell q_m as

$$SI_m = \min \left\{ 1, \frac{S_m}{\sum_{l:e_l \in q_m} s_l} \right\}$$

We also define the *downlink load ratio* of the cell q_m as

$$LR_m = \frac{\sum_{l:e_l \in q_m} s_l}{S_m}$$

Thus the end-to-end throughput of mobile station v_n can be expressed as

$$\hat{g}_n = SI_m \cdot g_n$$

When the number of available minislots is larger than the total number of required minislots, the cell is underloaded. In this case, all links are assigned the number of minislots according to their requirements, and mobile station's throughput equal to its traffic rate since the downlink satisfaction index is 1. In addition, the delay of a packet is within the length of a frame. When the number of available minislots is smaller than the total number of required minislots, the cell is overloaded. In this case, all links are assigned a number of minislots that is scaled down according to the downlink load ratio in order to make sure that all assigned minislots fit into a single frame. In this case, a mobile station's throughput will be smaller than its traffic rate since the downlink satisfaction index is smaller than 1. More importantly, some packets that sent out in a frame can only be delivered to the destination in subsequent frames. This makes the delay of packets to be of several frame durations. From the above discussion we can see that the overloading of cells reduces the performance of mobile stations. The increased delay has especially detrimental effects on real-time multimedia applications.

In order to reduce the chances that cells get overloaded, we define the following minimization problem,

$$\min \sum_{m=1}^M LR_m \quad (2)$$

The solution to this minimization problem, which will be shown in the following, can be translated into a path selection metric. In fact,

$$\begin{aligned} \sum_{m=1}^M LR_m &= \sum_{m=1}^M \frac{\sum_{l:e_l \in q_m} s_l}{S_m} \\ &= \sum_{n=1}^N \frac{\sum_{l:e_l \in p_n} \lceil \frac{q_n}{r_l t} \rceil}{S_{p_n}} \end{aligned}$$

where S_{p_n} is the number of available minislots in the cell to which path p_n belongs. The last equality is based on the fact that the number of required minislots on all links in a cell equals to the number of required minislots to support traffic of mobile stations in this cell. Based on the above analysis, we define a metric named NNM of a path p_n as follows,

$$NNM = \frac{\sum_{l:e_l \in p_n} \lceil \frac{q_n}{r_l t} \rceil}{S_{p_n}}$$

NNM equals to the number of minislots that will be used by mobile node v_n using path p_n divided by the total number of available minislots for downlink traffic in

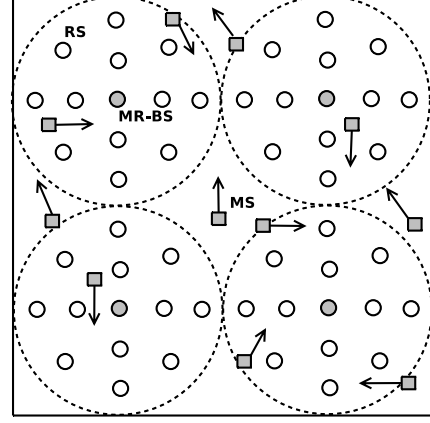


Figure 3. Simulation topology

the cell to which p_n belongs. In order to solve the minimization problem defined in (2), mobile stations should use a path that has the minimum NNM value.

Note that the number of available minislots in a frame for downlink traffic is a configurable and adaptive parameter of a cell. It depends on the number of minislots needed for control messages and contention-based communications in a frame and the downlink-to-uplink-subframe ratio [5], which can be dynamically adjusted based on the network traffic profile.

5 Performance Evaluation

5.1 Simulation Setup

We use the ns-2 [4] simulator for the performance evaluation. The simulated network topology is shown in Figure 3. It is a 4000m by 4000m flat area with four cells. The radio coverage areas of base stations are shown in dotted circles. The shaded circles represent base stations; unshaded circles represents relay stations; shaded square represents mobile stations. Each cell has one base station and 12 associated relay stations. In each cell, the distance between the base station and the relay stations located near the center of the cell is 250m. The distance between the base station and the relay stations located near the edge of the cell is 700m. The base station establishes a one-hop path with all associated relay stations. We assume that different cells use different frequency bands, so there is no inter-cell interference in our simulation. Other detailed simulation parameters are given in Table 2.

The number of mobile stations is varied from 20 to 60 in different simulation scenarios. Mobile stations'

Table 2. Simulation parameters

Parameter	Value
Frequency band (GHz)	5
Channel bandwidth (MHz)	20
Frame duration (ms)	20
Minislots in a frame	200
Minislots for downlink	[40,160]
MAC PDU (bytes)	96
RS queue size (packets)	100
BS transmit power (dBm)	30
RS transmit power (dBm)	25
Path Loss Model	$28.3 \log(d) + 41.9$, d is the distance
Noise Level (dBm)	$\text{bandwidth} * \frac{4 * 10^{-12}}{10^9}$, according to [10]

positions are randomly generated. We use the random way-point mobility model. Each mobile station picks a direction and a speed randomly. After reaching the destination, the mobile station pauses for some time and moves to a new direction with a new speed. In our simulation, the speeds of mobile stations are uniformly distributed in the range [1m/s, 30m/s]. The pause times are uniformly distributed in the range [0s, 10s].

All base stations are connected to a fixed node, denoted as the content station, through a wired link. One CBR connection is established between the content station and each mobile station. The CBR traffic rate is varied from 200Kbps to 600Kbps in different simulation scenarios. The packet size is set to be 96 bytes. We use the average throughput and average delay of all mobile stations as the metrics to evaluate the performance of different path selection metrics. We also present the average downlink satisfaction index and the average downlink load ratio of the cells over all frames during the simulation.

5.2 Simulation Results

We first vary the CBR traffic rate from 200Kbps to 600Kbps. In this set of simulations, we fix the number of mobile stations in the network to be 40. For every traffic rate, we conducted 10 simulation runs with different mobility scenarios and different numbers of available downlink minislots for cells. The throughput and delay value presented in Figures 4 and 5 are average values of all mobile stations in 10 simulation runs. Each simulation run lasts for 60 seconds.

Figure 4 shows the average throughput of mobile stations using three path selection metrics under different

traffic rates. We observe that for all traffic rates, NNM achieves the highest throughput while NOH gives the lowest throughput. Figure 5 shows the average delay of mobile stations using three path selection metrics under different traffic rates. NNM achieves lowest delay for all traffic rates.

When the traffic rate is low, the throughput equals to the traffic rate and the delay is within a single frame duration. From Figure 6, we can see that the average satisfaction index equals 1 when the traffic rate is low, which means no cell is overloaded. When the traffic rate increases, the performance gain of using NNM becomes more obvious. With NOH and MET, some cells become severely overloaded, which results in degraded throughput and delay. On the other hand, even with a very high traffic rate, NNM enable cells to maintain high downlink satisfaction index, which result in better throughput and delay performance for mobile stations compared with NOH and MET. We also observe that the performance gain of using NNM in terms of delay is much higher than throughput. This shows that the overloading of the cell has a much higher impact on delay than on throughput. From Figure 7 we can see that NNM yields minimum average downlink load ratio of cells for all traffic rates.

We also conduct simulations by varying the number of mobile stations (the density of mobile stations) in the network while fixing the traffic rate at 400Kbps. For each density, we conducted 5 simulation runs with different mobility scenarios and different numbers of available downlink minislots for cells. The throughput and delay value presented in Figures 8 and 9 are average values of all mobile stations in 5 simulation runs. Each simulation run lasts for 60 seconds.

Figures 8 and 9 show the average throughput and delay of mobile stations using three path selection metrics under different mobile station densities. Figures 10 and 11 show the average downlink satisfaction index and downlink load ratio of cells. We observe that for all densities, NNM gives the best performance while NOH always gives the worst performance. Increasing the number of mobile stations in the network has the same effect of increasing the traffic rate: the downlink traffic load of the network increases. So we observe similar performance gain of NNM compared to NOH and MET as in the simulation set while the traffic rate is varied.

6 Conclusion and Future Work

We have proposed a path selection metric for mobile stations in IEEE 802.16 MMR networks to select appropriate paths to the base station. Based on the calculation

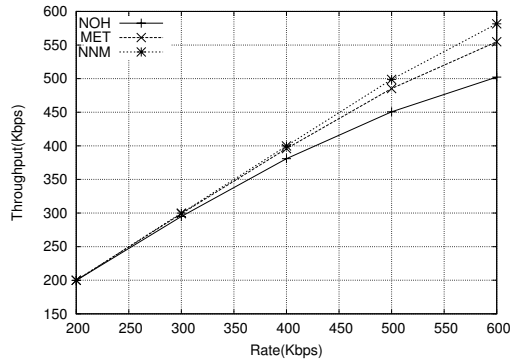


Figure 4. Throughput vs. CBR traffic rate

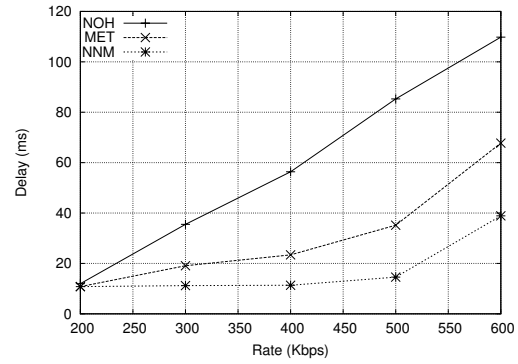


Figure 5. Delay vs. CBR traffic rate

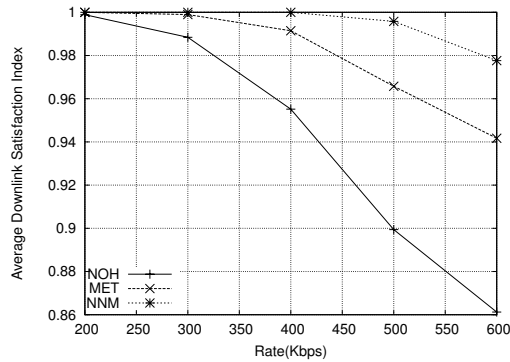


Figure 6. Downlink satisfaction index vs. CBR traffic rate

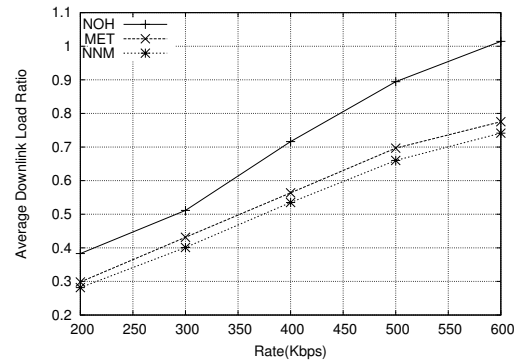


Figure 7. Downlink load ratio vs. CBR traffic rate

of the end-to-end throughput of mobile stations, we observed that the overloading of the cells has detrimental effects on the QoS of mobile stations, especially for real-time multimedia applications. Based on the above observation, we designed the path selection metric NNM, which enables the minimization of the sum of downlink load ratios of cells in the networks. Our proposed path metric effectively takes all the factors that affect end-to-end achievable throughput into consideration. Simulation results demonstrated that our metric yields better performance in terms of throughput and delay compared to existing path selection metrics, especially when network has high traffic load.

When the scheduling algorithm becomes more complex, for example, spatial reuse and channel diversities are taken into consideration, a simple path selection metric may not be sufficient to enable the mobile station to find a path that yields optimal end-to-end throughput and delay. We plan to investigate the joint design of scheduling algorithm and path selection method in case of more

sophisticated scheduling algorithms in the near future.

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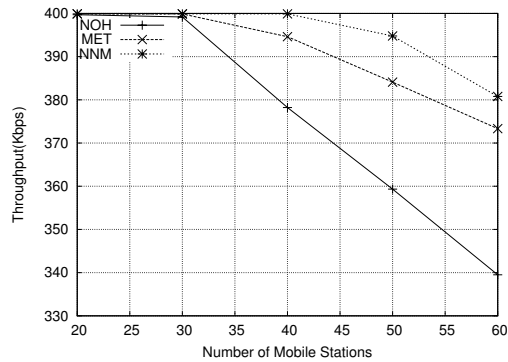


Figure 8. Throughput vs. Number of mobile stations

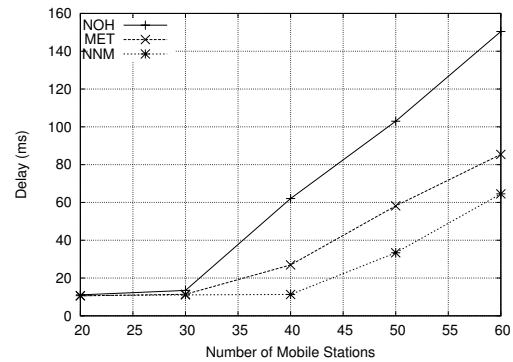


Figure 9. Delay vs. Number of mobile stations

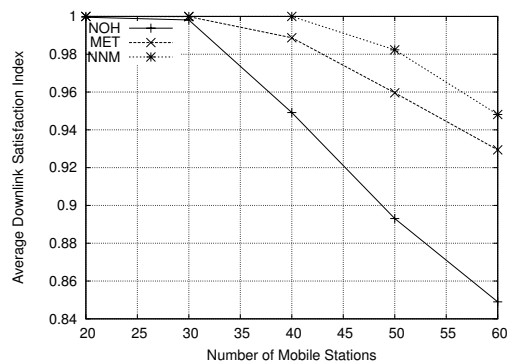


Figure 10. Downlink satisfaction index vs. Number of mobile stations

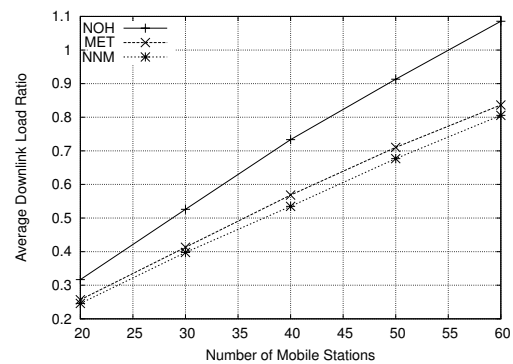


Figure 11. Downlink load ratio vs. Number of mobile stations

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