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Routing Scheme for Bandwidth Guaranteed Traffic in AMC-Enabled Wireless Mesh Networks*

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SUMMARY Backbone network of the mobile networks, i.e. mobile backhaul networks, is an important part of mobile network system. With the decreasing size of mobile network system cells, it is considered next-generation mobile backhaul networks will form mesh topology. Most mobile backhaul networks are formed with microwave radios. To increase data rate, Adaptive Modulation and Coding (AMC) is used for wireless links. However, the data rate of each wireless link changes over time and leads to unexpected packet loss or traffic degradation. This paper proposes a routing scheme and methods for estimating the transmission parameters or modes of wireless links to route bandwidth guaranteed flows over mobile backhaul networks. Proposed routing scheme can reduce degradation of flows caused by unexpected changes of the data rate of wireless links. We evaluate our routing scheme when mode distribution of links follows normal, uniform and Poisson distributions. This paper shows mode estimation using mode history of link to estimate the link quality can route bandwidth guaranteed flows efficiently by choosing more stable links for the path.

key words: *Adaptive Modulation and Coding, mobile backhaul, routing*

1. Introduction

With the recent deployment of 3G and high bandwidth services like High Speed Downlink Packet Access (HSDPA), the amount of traffic needed to be supported by mobile networks has been increasing. In addition, because of the technological issues involving 4G mobile systems such as higher transmission speed, the number of base stations needed to cover a given range will increase [2]. Thus, it is considered that the next-generation mobile backhaul networks which transfer traffic between mobile base stations and core networks will form mesh topologies [3]. Two things need to be addressed to accommodate this trend: provide network architecture suited for mesh topologies and increase overall bandwidth of the network.

In order for mobile backhaul networks, especially with mesh topologies, to support bandwidth-consuming data traffic while keeping the cost of network operation low, mobile operators are considering to shift their circuit-switched networks to packet-switched networks. Even though packet-switched networks are widely used in the Internet, existing packet-switched networks lack some of the features that the carriers need, such as path control of flows. Hence, new connection-oriented packet switching technologies such as Provider Backbone Bridging Traffic Engineering (PBB-TE) [4] and MPLS Transport Profile (MPLS-TP) [5] have been proposed as a replacement for the current SDH and ATM networks used by the carriers. Both PBB-TE and MPLS-TP provide the capabilities necessary to perform Traffic Engineering (TE) and Operation Administration and Maintenance (OAM). Existing TDM services, e.g. E1/T1 lines, are carried using the pseudo-wire emulation technique [6]. Efficient TE technique is necessary to optimize the use of network resources.

In mobile backhaul networks, high-frequency microwave radio is often used as links. Due to the space constraints, the number of transceivers which cell site can use for the microwave radio links is limited. With the increasing demand for high bandwidth services, Adaptive Modulation and Coding (AMC) which selects appropriate modulation and coding to achieve better spectrum efficiency, has attracted attention for mobile backhaul networks. Effective data rates in wireless links are determined by channel conditions and transmission parameters such as modulation and coding level, power level and signaling bandwidth. A set of transmission parameters is referred to as a transmission mode or simply as a mode. Channel condition of wireless links are affected mostly by the weather conditions, i.e., rain, wind and humidity. These weather conditions affect the quality of wireless links, e.g., Signal-to-Noise Ratio (SNR), and may triggers AMC-enabled wireless links to change their mode. Other than the weather conditions, when wireless links are used in the urban area, other factor such as interference from electronic devices may affect the channel condition.

Since the capacity of wireless links depends on the conditions of wireless channel, by adjusting the mode dynamically to the time varying channel conditions, spectrum efficiency can be improved compared to that of wireless links using only single mode [7].

However, when AMC is employed in mobile backhaul networks, it introduces a new problem that needs to be addressed. Because of its nature, AMC makes it harder to route bandwidth guaranteed traffic since the data rate of wireless links may change abruptly in order to adapt to the channel conditions. If the data rate is decreased, as a result, all the traffic using that same link will be affected, which may leads to congestion. This is not acceptable for bandwidth guaranteed traffic. The problem further exacerbates when wireless links use mode with higher-order modulation

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which are more prone to deteriorated channel conditions.

In this paper, we present a routing scheme along with mode estimation methods for AMC-enabled point-to-point microwave radio links to route bandwidth guaranteed traffic. We will show that it is necessary to estimate the link quality in the future as well. Since data rate of AMC-enabled microwave radio links are subjected to change, current data rate of the link do not represents the quality of link in the future. By using the historical usage data of modes or mode distribution of the link, link quality can be estimated.

The remainder of this paper is structured as follows. Section 2 explains the related work. In Sect. 3, a routing scheme and mode estimation methods which alleviate the problem associated with routing over the AMC-enabled microwave radio links are introduced. Proposed routing scheme and estimation methods are evaluated through simulation in Sect. 4. Different mode distributions are used to evaluate our scheme in Sect. 5. Further evaluations are performed in Sect. 6. Section 7 conclude this paper.

2. Related Work

Number of routing protocols have been proposed for Mobile Adhoc Network (MANET) such as AODV [8] and OLSR [9]. In QoS aware ad hoc routing protocols, study such as [10] evaluate the stability of links when choosing the path. QoS aware routing protocol which incorporates bandwidth estimation and admission control is also studied in [11].

Studies such as [8]–[10] do not consider capacity fluctuation associated with AMC. Although [11] estimates the bandwidth of the links, it assumes 802.11 like channel access mechanism which channel interferences among neighboring nodes are concern. However, channel interference is not the problem in the mobile backhaul networks where point-to-point wireless links are used. Our study is focused on the mobile backhaul networks and studies [10] and [11] are not suited for the wireless mesh networks with AMC-enabled point-to-pint links.

For more stable static wireless mesh network, routing metrics such as ETX [12], ETT [13] and WCETT [13] have been proposed. These routing metrics are used to represent the current quality of wireless links and the quality of wireless links are not guaranteed to remain in the future.

To perform traffic engineering, QoS routing algorithms have been proposed to route bandwidth guaranteed traffic such as MIRA [14], LMIR [15] and LCPF [16]. PBR [17] uses traffic profiles known in advance to perform optimal routing. Although these algorithms achieve optimal routing to increase overall network usage, they can only be applied to the networks where the data rate of each link in the network is constant and these algorithms can not simply be applied to the networks where the data rate of each wireless link may change.

In wireless optical networks, SMIRA [18] integrates both topology control and routing to optimize the network usage when the number of transceivers at a node is limited. This too assumes the data rate of wireless links to be static and does not consider any data rate change of the links.

In terms of routing over AMC enabled wireless links, the work presented in [19] is the closest to this work. In [19], the most suitable mode for a flow at each wireless link is determined based on the QoS requirement of the flow, e.g. Bit Error Rate (BER). The path is then computed afterwards. The algorithm proposed in [19] differs from our work since it needs to control the mode of all the wireless links and routes are computed based on the current BER of wireless links.

3. Routing Scheme for Mobile Backhaul Networks

In this section, a routing scheme and three mode estimation methods for AMC-enabled wireless links are presented. After the problem illustration, the basic concept of proposed routing scheme is first explained, followed by the description of steps taken by the routing scheme.

3.1 Problem Illustration

Here is a simple example which conventional QoS routing algorithm did not consider. As shown in Fig. 1, when routing a flow from node a to node c, flow can be routed either $a - b - c$ or $a - c$. Suppose available bandwidth of wireless link $a-b$, $b-c$ and $a-c$ are 15 Mbps, 15 Mbps and 20 Mbps respectively. If 10 Mbps of bandwidth is necessary for the flow, route $a - c$ will be chosen as a route since it has more available bandwidth and is shorter hop than $a - b - c$. However, if the bandwidth of route $a - c$ decreases to 5 Mbps, after the flow is routed, as a result of deteriorated channel condition, the flow will be affected. If route $a - b - c$ is constant at 15 Mbps throughout the flow's duration, then the flow would not have been affected if it had used the route $a - b - c$. Therefore, it is important to estimate the capacity of wireless link in the future when routing flows.

3.2 Basic Concept

Two ideas form the basis of the routing scheme: mode estimation of wireless links and prioritization of flows.

The effective data rate of a wireless link changes as its channel conditions change. Hence, simply routing traffic based on the current data rate information of wireless links is insufficient. There needs to be a way to reduce the number of flows affected by data rate changes in wireless links. In order to route bandwidth guaranteed flows efficiently while

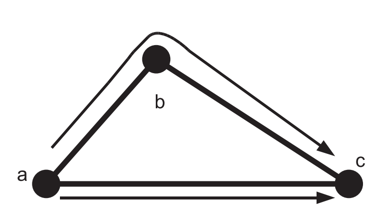


Fig. 1 Example of route selection.

avoiding the disruption of flows caused by AMC, it is necessary to estimate the mode that each wireless link will use in foreseeable future. If wireless links do not use the lower-order mode than the estimated mode, none of the flow will experience any degradation. Thus, accuracy of mode estimation is crucial in routing traffic, since network resources can be used more efficiently.

As for the prioritization of flows, some traffic like VoIP requires stringent QoS, while data traffic are usually best effort. In other words, different levels of estimation accuracy and assurance are required for the traffic. Therefore, several traffic classes are introduced and flows will be classified and treated differently depending on their assigned priorities.

Proposed routing scheme takes following steps.

- Classification of the flow.
- Estimate the mode of wireless links.
- Perform routing of the flows.

3.3 Mode Estimation Method

Here, we present three mode estimation methods, Lowest Mode Estimation, Statistical Estimation and Link Stability Estimation. The first method is the most conservative method which considers that the modes which wireless links use are unpredictable. The second method is based on an ideal condition which statistical properties of wireless links, i.e., mode distribution, are known in advance. The third method is more realistic method which assumes that the modes wireless links use follow the same pattern as in the past.

3.3.1 Lowest Mode Estimation (LM)

The most conservative way to estimate the future mode of wireless links is to assume that all the wireless links will eventually use their lowest mode. In other words, this method ignores the AMC and uses the lowest possible mode.

Estimated mode of link l, $M_E(l)$, is expressed as follows:

$$M_E(l) = \min(M). \tag{1}$$

Here, M is the set of transmission modes that the link can use.

3.3.2 Statistical Estimation (ST)

If there is information known in advance regarding the modes which wireless links use, such as mode distribution of the link, then it can be used to find the lowest modes that the wireless links will use in the future.

Suppose the distribution of the modes which wireless link l uses follows the normal distribution with the average of $\mu(l)$ and the deviation of $\sigma(l)$. If these are known in advance, then the mode which the wireless link will use can be estimated with certain probability. For 99.74% confidence interval, the mode falls within the range of $\mu(l) \pm 3 \times \sigma(l)$.

Therefore, $M_E(l)$ is derived as:

$$M_E(l) = \lfloor \mu(l) - \delta \times \sigma(l) \rfloor. \tag{2}$$

For different confidence interval, different value of δ is used.

3.3.3 Link Stability Estimation (LS)

In more realistic environment, it would be difficult to obtain statistical property of mode usage. Assuming that the modes wireless links use have some time-varying pattern, the mode usage in the past can be used to find the lowest mode that wireless links will use in the foreseeable future.

By using the time spent at each mode, how stable each mode had been can be evaluated. Stability of the mode c is calculated using the following equation:

$$S_t[c] = \frac{\sum_{m=c}^{\max(M)} T_m}{T_{Interval}} \quad (c \in M). \tag{3}$$

Here, $S_t[c]$ represents the fraction of time that the wireless link have used mode c or higher at t-th interval. $T_{Interval}$ represents the time of each interval time while T_m represents the time spent at mode m during that interval.

Since $S_t[c]$ is computed for every interval, Exponentially Weighted Moving Average (EWMA) is used to reflect the previous interval values. Total stability of mode c at the t-th interval $FS_t[c]$ is derived as follows:

$$FS_t[c] = \begin{cases} S_t[c] & t = 0 \\ S_t[c] \times \gamma + (1-\gamma) \times FS_{t-1}[c] & t \geq 1. \end{cases} \tag{4}$$

Here, γ is the smoothing factor used to smooth out the value where $0 < \gamma < 1$.

Since channel condition of wireless links are affected by the weather, these channel conditions correlate to the recent channel condition of the past. We use EWMA instead of Simple Moving Average (SMA), which is the unweighted mean of the previous data and Linear Weighted Moving Average (LWMA) which weights previous data linearly. Unlike SMA and LWMA, EWMA decreases the weighting of each older data exponentially. As a result, EWMA can put more importance to recent data while still not eliminating the older data entirely.

A threshold value of total stability, f_{th}, is assigned to a flow. The highest mode m having the higher total stability $FS_t[m]$ than or equal to the threshold f_{th} is chosen as $M_E(l)$.

$$M_E(l) = \max_{\forall m \in M}(m \mid FS_t[m] \geq f_{th}). \tag{5}$$

Different $T_{Interval}$ can be used to calculate $FS_t[c]$ depending on the duration of flows.

3.4 Routing Algorithm

Different routing algorithm can be used in our routing scheme. Here, we use a routing algorithm which we call Link Estimation Routing (LER) in proposed routing scheme. LER use inverse of the difference between the estimated data rate and the bandwidth usage as a link cost.

Weight of each link, $W(l)$, in LER is calculated as follows:

$$W(l) = \begin{cases} \dfrac{1}{R(e) - D_P(l)} & \text{if } R(e) \geq D_P(l) + D \\ \infty & \text{otherwise.} \end{cases} \tag{6}$$

Here, e is the derived estimated mode of link l, i.e. $e = M_E(l)$. The estimation methods described in 3.3 are used to derive e. $R(e)$ is the data rate of given mode e. $D_P(l)$ is the total bandwidth consumed by the flows on the link l with the priority higher than or equal to P. D is the bandwidth demand of the flow.

After the weight of each link $W(l)$ is assigned, Dijkstra's algorithm is used to find the path which minimizes $\sum W(l)$. If the path can not be found, admission request of the flow is rejected.

The routing scheme using LER for routing algorithm is summarized in Fig. 2.

3.5 Routing of Flows

Although proposed routing scheme can be applied to the distributed controlled networks, we assume network to be centralized controlled networks, namely PBB-TE and MPLS-TP. In these networks, routing decisions are performed by the controller node, i.e., Network Management System (NMS) or Path Computing Element (PCE) [20]. The controller knows all the nodes in the network either through static configuration or bootstrapping mechanism such as creating a spanning tree rooted from the controller. The controller collects all the link information including mode usage data through periodical report by the nodes or routing protocols such as OSPF-TE [21].

Admission requests are handled by the controller. The controller calculates the path of the flow and decide whether to admit the flow. When the flow is admitted to the network, the controller or the requesting node sets up the path for the flow either manually through management interface such as SNMP [22] or through signaling protocol, e.g., RSVP-TE [23].

INPUT:
A graph $G(V, E)$ and a set D_{ALL} of all bandwidth usage of the link. Demand of a bi-directional flow between node a and node b having a priority P with the bandwidth of D Mbps in each direction.
OUTPUT:
A bi-directional route between a and b having a capacity of D Mbps of bandwidth with the priority P.
ALGORITHM:

1. Estimate the mode of each wireless link, $M_E(l)\ \forall l \in E$, using one of the methods described in 3.3.
2. Assign weights to all wireless links, $W(l)\ \forall l \in E$, using Eq. (6).
3. Eliminate all links which have residual bandwidth less than D and form a reduced network.
4. Use Dijkstra's algorithm to find the least-cost path in the reduced network.
5. Route the demand of D units between a and b in both directions along this least cost path and update the D_{ALL}.

Fig. 2 Proposed routing scheme using Link Estimation Routing (LER).

4. Simulation

Simulation was performed to evaluate the effectiveness of proposed routing scheme and mode estimation methods. In this section, we describe a simulation study we performed on proposed routing scheme.

4.1 Simulation Conditions

Simulation was performed on following conditions which are summarized in Table 1.

4.1.1 Network Model

Topologies are generated using Waxman model [24] with values of $\alpha = 0.3$ and $\beta = 0.2$ to form mesh topologies. Current mobile backhaul networks are usually tree based topologies. Due to the economical and technological reasons, future mobile backhaul networks, which are expected to form mesh topologies, will form sparse mesh topologies with short distanced links [25]. Therefore, we use the values, $\alpha = 0.3$ and $\beta = 0.2$, to create sparse network topology with short distanced links.

Different topologies are generated for each simulation trial. Priority Queueing is enforced in all nodes.

4.1.2 Traffic Pattern

We set each source-destination pair to request total of 60 Mbps of the bandwidth. We assume requested bandwidth is the sum of 16 E1 lines or 32 Mbps for 2G/3G traffic and 28 Mbps for multiple HSDPA or HSDPA+ traffic.

Here, we set flow to be the aggregated traffic of same source-destination pair and consume 1 Mbps of link bandwidth. The duration of flows are exponentially distributed with the average of 6 hours. Since we set the average duration of aggregated flows to 6 hours, each source-destination pair constantly generates 10 flows per hour in order to generate traffic of 60 Mbps. Since there are 10 source-destination

Table 1 Simulation conditions.

Property	Value
Simulation Time	72 hours
Number of Nodes	50
Source Destination Pair Sets	10
Flows Generated	100 req/h
Proportion of High Priority Flows	20, 40, 60, 80, 100%
Bitrate of Flows	1 Mbps
Average Duration of Flows	6 hours
Deviation of Highly Unstable Link	0.8
Deviation of Unstable Link	0.4

pairs in the network, flows are generated at the rate of 100 requests per hour.

Two priority classes, high and low, are assigned to the flows. The proportion of high priority flows among all requests are varied between 20%, 40%, 60%, 80% and 100% to see how the performance of proposed routing scheme changes when the traffic profile has been changed.

As stated in Sect. 3.5, there are several ways to apply proposed routing scheme in the actual network. We did not consider the traffic caused by the control messages, i.e., signaling and routing protocol messages in the simulation as our motive is to evaluate proposed routing scheme independently from the control scheme.

4.1.3 Link Condition

Of all the wireless links in the network, 50% of the links are highly unstable links while rest of the links are unstable links. Highly unstable links change their mode frequently and the distribution of the mode used by the link follows normal distribution with the deviation of $\sigma(l) = 0.8$. Unstable links, on the other hand, have the mode distribution with the deviation of $\sigma(l) = 0.4$ which follows normal distribution. Average mode of wireless links are given at a random between the lowest mode, QPSK, to the highest mode, 128 QAM. Corresponding data rates of each mode are shown in Table 2.

Since channel condition is affected by the weather, we use the past statistical data provided by Japan Meteorological Agency [26] to set the average interval time between mode fluctuations. The average interval time between weather changes, i.e., duration of rain and time between rains, of Isesaki-shi, Gunma Prefecture in August of 2008 was about 5 hours and that distribution is, though not a exact match, similar to the exponential distribution. For this reason, we set the average interval time between mode fluctuations to exponentially distributed with average of 5 hours.

4.2 Routing Algorithms Used in Simulation

Three existing routing algorithms, Minimum Hop routing (MH), Least Cost Path (LCP) and Minimum Interference Routing Algorithm (MIRA) [14], which do not use any estimation methods, are used as comparisons. MH simply finds the shortest hop path, while LCP finds the least-cost path, in which the cost of a link is the inverse of the available bandwidth. MIRA is a routing algorithm that avoids using the bottleneck links, i.e. *critical links*, of other source destination pairs.

Proposed routing schemes using three different estimation methods are used in the simulation. LER is used as the routing algorithm. The first, LER-LM, uses LM estimation when routing a high priority flow and the current mode of wireless links are used to route low priority flows. The second, LER-ST, uses ST estimation with different confidence intervals for high and low priority flows. The third, LER-LS, uses LS estimation for both high and low priority flows with different threshold values. In LER-LS, γ is set to 0.2 and different time intervals, i.e. one hour, three hours, six hours and 12 hours, are used, depending on the duration of flow. Table 3 summarizes the proposed schemes used in the simulation.

Table 2 Data rate of each mode.

Mode	QPSK	16 QAM	32 QAM	128 QAM
Data Rate	40 Mbps	80 Mbps	108 Mbps	155 Mbps

4.3 Overall Simulation Result

Simulations were performed on different proportions of high priority flows. The results reflect a total of 10 simulations. All the proposed schemes and the routing algorithms are performed on the same network topology, using the same traffic pattern and link condition.

4.4 Performance of Routing Scheme

First, reliability is evaluated by comparing the number of degraded flows. Here, degraded means that the flow was not able to achieve requested bitrate at some point in its duration. Figure 3 shows the number of degraded flows. The results show that proposed schemes were able to reduce the number of degraded flows for both high and low priority flows. Among proposed schemes, LER-LM and LER-ST had no degraded flows among high priority flows. LER-LS, on the other hand, can not eliminate the degraded flows completely, but was able to reduce the number of degraded flows to less than one-third for the high priority flows when compared to the existing routing algorithms in most cases. LCP had fewer degraded flows than LER-LS with the proportion of high priority flows of 40%. This is due to the estimation error of LS estimation which overestimated the data rate of

Table 3 Estimation methods used in proposed schemes.

Name	High Priority Flows	Low Priority Flows
LER-LM	LM	Non
LER-ST	ST ($\delta = 3$)	ST ($\delta = 1$)
LER-LS	LS ($f_{th} = 0.9999$)	LS ($f_{th} = 0.9$)

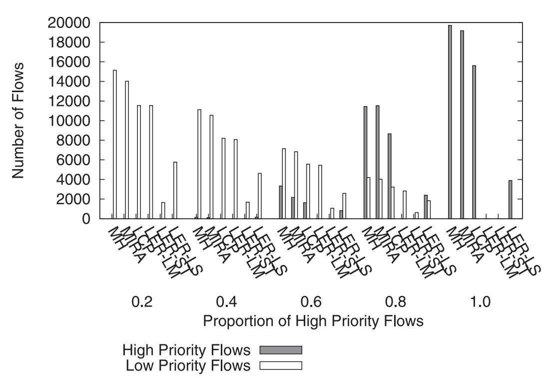


Fig. 3 Number of degraded flows.

wireless links.

Second, efficiency is evaluated by comparing the number of successful flows which did not experience any degradation. The number of successful flows is shown in Fig. 4. The results show that LER-ST and LER-LS can route more bandwidth guaranteed flows than the existing algorithms by 5 to 30%, depending on the proportion of high priority flows. As for LER-LM, since LER-LM restricts the number of high priority flows entering the network, LER-LM performed similarly to LCP when the proportion of high priority flows were 20, 40 and 60%.

Finally, accuracy is compared. Successful admission rate of flows are shown in Fig. 5. Successful admission rate is the ratio of successful flows among all admitted flows. This figure shows how much of the admitted flows avoided degradation. LER-LM and LER-ST performed better than the existing algorithms for both high priority and low priority flows. For high priority flows, LER-LM and LER-ST achieved 100% successful admission rate whereas LER-LS achieved more than 94% successful admission rate. By contrast, successful admission rate of high priority flows in existing routing algorithms dropped to 70 to 76% as the proportion of high priority flows increased to 100%.

These results show that proposed routing scheme is effective when routing bandwidth guaranteed flows over the network which data rate of its wireless links change. From Fig. 4 and Fig. 5 we can see that proposed schemes were able to route more successful flows while maintaining high successful admission rate for both high and low priority flows. From the results of LER-LS we can also see that using past information to estimate the future mode of wireless links is useful.

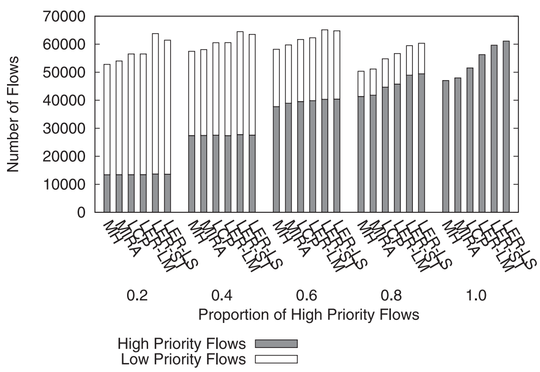


Fig. 4 Number of successful flows.

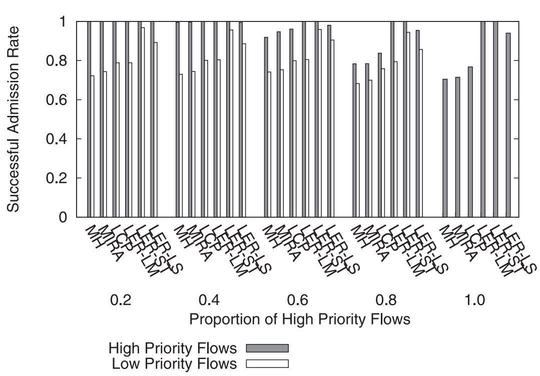


Fig. 5 Successful admission rate.

4.4.1 Impact of Routing Algorithm

In our proposed routing scheme, other routing algorithm can be used instead of LER. Here we studied how the performance of proposed routing scheme changes when MH and LCP are used as the routing algorithm. For mode estimation method, LS is used.

Figure 6 shows the results of proposed schemes with different routing algorithms. Since LER allows more high priority flows to be routed, LER routed more successful high priority flows by 2 to 6%. However, the results also show little difference among routing algorithms which indicates accuracy of mode estimation has more impact on the performance of proposed routing scheme.

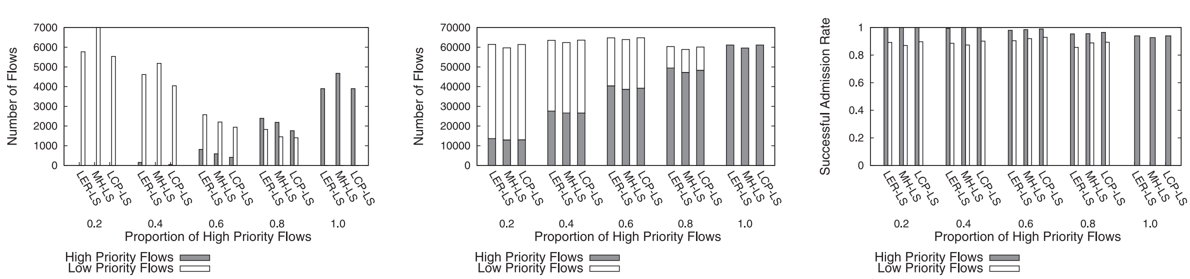
4.5 Detailed Observation

For detailed observation, we observed the impact of flow's duration on successful admission rate of flows and behavior of proposed routing scheme in the simulation.

Results are from the previous simulation study with the proportion of high priority flows of 80%.

4.5.1 Duration of Flows

We studied how the duration of flows affect the successful



(a) The Number of Degraded Flows. (b) The Number of Successful Flows. (c) Successful Admission Rate of Flows.

Fig. 6 Simulation results using different routing algorithm.

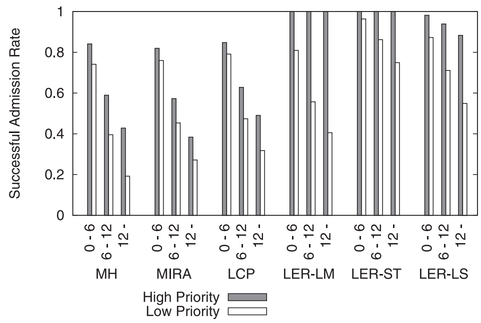


Fig. 7 Successful admission rate with different flow duration.

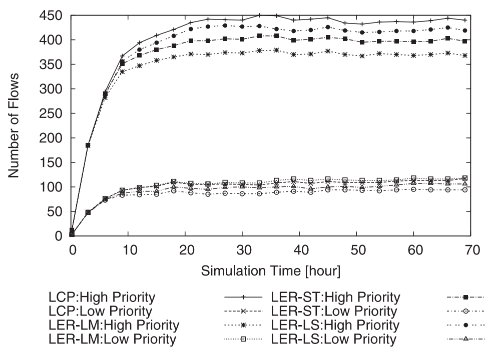


Fig. 8 Number of flows in the network.

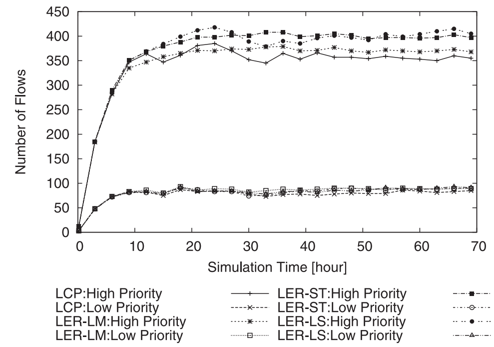


Fig. 9 Number of bandwidth guaranteed flows in the network.

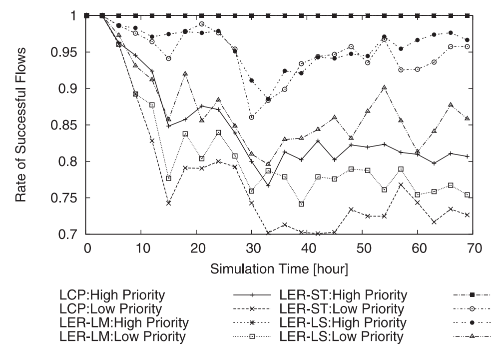


Fig. 10 Rate of bandwidth guaranteed flows in the network.

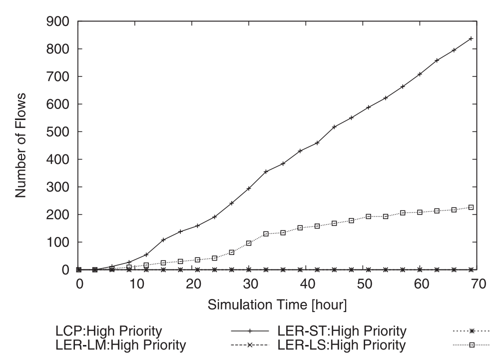


Fig. 11 Accumulated number of degraded high priority flows.

admission rate. Flows are categorized into three groups: flow with duration of less than 6 hours, flow with duration of between 6 and 12 hours and flow with duration of more than 12 hours.

Figure 7 shows the successful admission rate of each group. The figure shows that as the duration of a flow increases, successful admission rate tends to decrease. This is clearly shown in the results of existing algorithms. Although long duration flows are more likely to suffer degradation, proposed routing scheme can alleviate these degradations as proposed schemes were able to maintain high successful admission rate even for the long duration flows.

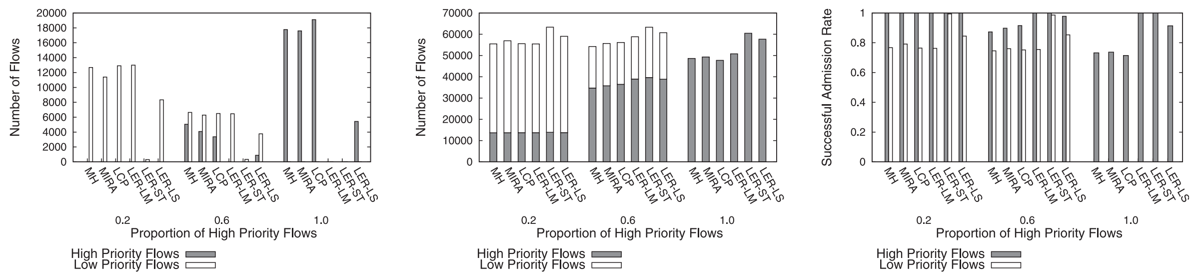
4.5.2 Routing Performance During Simulation

To see how proposed routing scheme would perform during the simulation, we compared the behavior of LCP, LER-LM, LER-ST and LER-LS. The results are the average of 10 simulations. The main motive of this study is to see whether the behavior of proposed schemes were consistent throughout the simulation.

Figure 8 shows the number of active flows in the network. LCP and proposed schemes showed similar performance for the first 10 hours of simulation time since network is still under utilized. However, as the simulation progress, they started to perform differently. From this figure we can see that LCP admitted, on average, 4 to 10% more high priority flows and 8 to 20% more low priority flows into the network than LER-ST and LER-LS. LER-LM admitted least high priority flows but admitted most low priority flows.

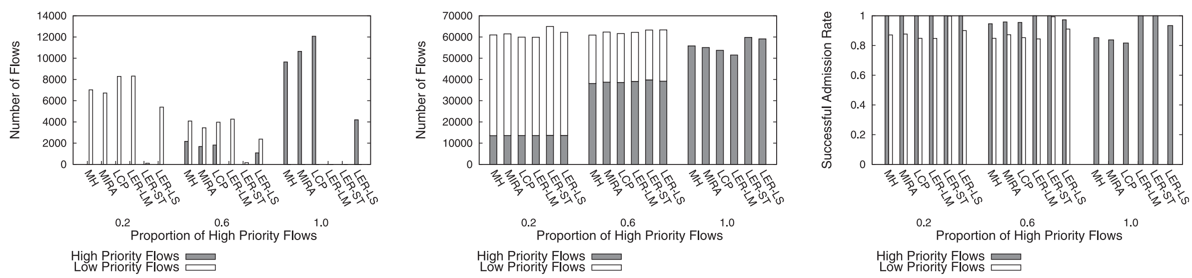
Figure 9 shows the number of bandwidth guaranteed flows in the network which have not yet experienced any degradation. As in Fig. 8, LCP and proposed schemes performed similarly for the first 10 hours of simulation. However, contrary to Fig. 8, on average, LER-ST and LER-LS both had more bandwidth guaranteed high priority flows by 11% and low priority flows by 6%. LER-LM had more bandwidth guaranteed flows than LCP by 3% for high priority flows and 9% for low priority flows.

Figure 10 shows the rate of bandwidth guaranteed flows in the network. After 10 hours, the rate of bandwidth guaranteed flows of high priority flows in LCP started to decrease and dropped to 77%. The rate of bandwidth guaranteed flows of high priority flows in LER-LM and LER-ST



(a) The Number of Degraded Flows. (b) The Number of Successful Flows. (c) Successful Admission Rate of Flows.

Fig. 12 Uniform distribution.



(a) The Number of Degraded Flows. (b) The Number of Successful Flows. (c) Successful Admission Rate of Flows.

Fig. 13 Poisson distribution.

were 100% throughout the simulation. In LER-LS, the rate of bandwidth guaranteed high priority flows was maintained above 89%. From this figure we can see that with proposed schemes, admission control works more properly.

Figure 11 shows the accumulated number of degraded high priority flows. The figure shows when degradation of high priority flows had occurred during the simulation. In the simulation, none of the high priority flows experienced degradation in LER-LM and LER-ST. A few number of high priority flows experienced degradation in LER-LS. In LCP, the accumulated number of degraded high priority flows had increased linearly and the gap between LER-LS and LCP widens as the simulation progressed.

The results show that proposed schemes have consistently outperformed existing routing algorithms.

5. Performance under Different Mode Distribution

In the previous simulation studies, normal distribution with given average and deviation is used as the mode distribution of the links. Here, we evaluate the performance of proposed routing scheme under two different mode distributions, uniform and Poisson distribution. These distributions are used to produce more unstable condition where wireless links change their mode more frequently. In uniform distribution, all the modes have the equal probability of being used by the wireless link. In Poisson distribution, wireless link change its mode at random and independently from the mode which wireless link is currently using.

For both uniform and Poisson distribution, half of the links change its mode with given distribution while rest of the links are stable. The mode of stable links are constant throughout the simulation. Other than the mode distribution of the links, simulation conditions shown in Table 1 are used. In LER-LM, we assume that whether the links are stable or not known in the simulation.

Simulation results are shown in Fig. 12 and Fig. 13 with different proportion of high priority flows, 20%, 60% and 100%. Figure 12 and Fig. 13 show the number of degraded flows, the number of successful flows and successful admission rate when mode distribution is uniform and Poisson, respectively.

From Fig. 12 and Fig. 13, we can see that LER-ST and LER-LS routed more successful flows and decreased the number of degraded flows compared to the existing algorithms. Unlike in the previous simulation study, LER-LS outperformed LCP in all cases. As with the previous simulation study, LER-LM had fewer successful flows than LCP in some cases, e.g., when all the flows were high priority flows under Poisson distribution. These results show that proposed routing scheme is also effective under different mode distributions.

It is notable that LER-LS performed well in terms of reducing the number of degraded flows and routing more bandwidth guaranteed flows. These show that using past information to estimate the future mode of wireless link is also effective in other mode distribution as well.

6. Further Evaluation of Proposed Scheme

In this section we perform further simulation studies to evaluate the effectiveness of proposed routing scheme and LS estimation.

6.1 Share of Highly Unstable Links in the Network

We now investigate how the share of highly unstable links in the network affects the proposed routing scheme.

In the simulation, the share of highly unstable links is increased from 60 to 100%. Other than the share of highly unstable links in the network, simulation conditions shown in Table 1 are used. The simulation results are the total of 10 simulation tests. Different network topologies are generated for each simulation test.

Figure 14 shows the simulation results with the proportion of high priority flows of 80%. The number of degraded flows, the number of successful flows and the successful admission rate are shown in Fig. 14 (a), Fig. 14 (b) and Fig. 14 (c), respectively.

We focus on the performance of LER-LS as it is most affected by the share of highly unstable links among proposed schemes. As the share of highly unstable links increased to 100%, the successful admission rate of low priority flows dropped to 86% from the successful admission rate of 90% with the share of 60%. For high priority flows, the successful admission rate dropped to 94% from the 96% with the share of 60%.

Although more flows experienced degradation as the share of highly unstable links increased, LER-LS routed most successful flows and had less degraded flows than existing routing algorithms.

As for LER-LM and LER-ST, more low priority flows experience degradation as the share of highly unstable links increases. However, high priority flows were unaffected by the increased share of highly unstable links.

We can also see that proposed schemes outperform existing routing algorithms even when all the links become highly unstable links which shows the effectiveness of proposed routing scheme.

6.2 Evaluation of LS Estimation

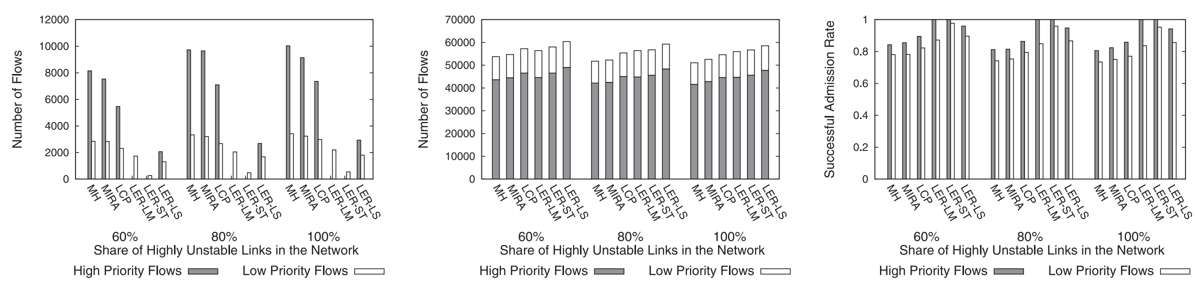
We also evaluated LS estimation further. First we evaluate how the value of γ used in LS affects its performance. Then we compared LS estimation with other mode estimation methods which also use past mode usage.

The following simulation results are obtained from the simulation study performed in Sect. 4.

6.2.1 LER-LS with Different γ Values

We have evaluated how the value of γ used in Eq. (4) affects the performance of LER-LS by comparing LER-LS with different γ values, 0.1, 0.2, and 0.5.

Table 4 and Table 5 show the results of LER-LS with different γ with the proportion of high priority flows of 20% and 80% respectively. The results show that the larger γ value tends to yield higher successful admission rate for both high and low priority flows in both cases. However, Table 5 shows that LS with $\gamma = 0.2$ has the most successful high priority flows. From these results we can expect optimal γ value to vary accordingly with the network conditions, e.g., the proportion of high priority flows and the



(a) The Number of Degraded Flows. (b) The Number of Successful Flows. (c) Successful Admission Rate of Flows.

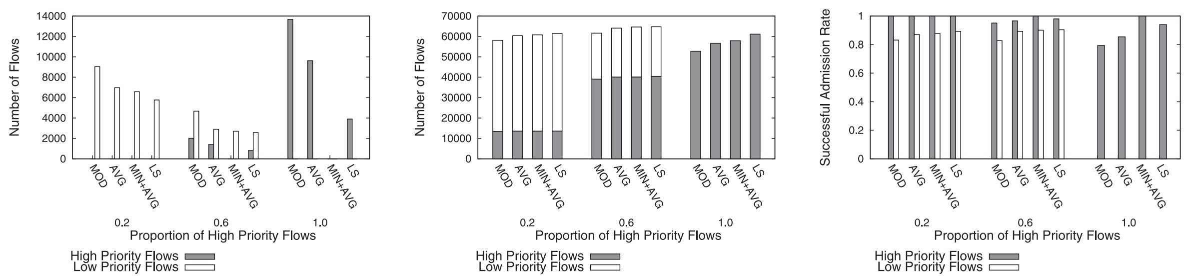
Fig. 14 Different share of highly unstable links.

Table 4 LER-LS with different γ: Proportion of high priority flow = 20%.

γ	Number of Degraded Flows		Number of Successful Flows		Successful Admission Rate	
	High Priority	Low Priority	High Priority	Low Priority	High Priority	Low Priority
0.5	0	4861	13603	48359	100.00%	90.87%
0.2	0	5769	13597	47839	100.00%	89.24%
0.1	0	5880	13582	47919	100.00%	89.07%

Table 5 LER-LS with different γ: Proportion of high priority flow = 80%.

γ	Number of Degraded Flows		Number of Successful Flows		Successful Admission Rate	
	High Priority	Low Priority	High Priority	Low Priority	High Priority	Low Priority
0.5	2191	1563	49309	10922	95.75%	87.48%
0.2	2393	1826	49455	10899	95.38%	85.65%
0.1	2942	1831	49051	11016	94.34%	85.75%



(a) The Number of Degraded Flows. (b) The Number of Successful Flows. (c) Successful Admission Rate of Flows.

Fig. 15 Simulation results comparing LS, AVG, MOD and MIN+AVG.

link model, or the objective, e.g., increase the number of successful flows or achieve high successful admission rate.

6.2.2 Comparison with Other Estimation Methods

To further evaluate the effectiveness of LS, we have compared LS estimation with different estimation methods, AVG, MOD and MIN which are also based on mode usage.

AVG estimate the mode of wireless links by calculating the average mode. When the time which wireless link has used the mode m is represented with T_m, estimated mode in AVG is obtained as follows:

$$M_E(l) = \sum_{m \in M} Q(m) \times \frac{T_m}{T_{Total}} , \tag{7}$$

where

$$T_{Total} = \sum_{m \in M} T_m . \tag{8}$$

Here, M is the set of transmission modes and $Q(m)$ is the numerical value assigned to mode m where each mode is assigned as QPSK = 0, 16 QAM = 1, 32 QAM = 2, 128 QAM = 3.

MOD, by contrast, select the most used mode as the estimate mode. Therefore, estimated mode is given as:

$$M_E(l) = \underset{m \in M}{\operatorname{argmax}}(T_m). \tag{9}$$

MIN selects the least mode used in the past as the estimated mode.

$$M_E(l) = \min_{m \in M}(m \mid T_m > 0). \tag{10}$$

Note that LS estimation in Eq. (5) can act as MIN by using the threshold value of 1.0 and very small γ value. In AVG, MOD and MIN, T_m is recorded throughout the simulation.

LS is compared with different mode estimation, MOD, AVG and MIN+AVG. Same routing algorithm LER is used for all the compared mode estimations. LS uses LS estimation with the same parameter in the previous simulation studies. As for MIN+AVG, high priority flows use MIN estimation whereas AVG estimation is used for low priority flows.

Figure 15 shows the performance of LS, AVG, MOD and MIN+AVG with different proportion of high priority flows, 20, 60, and 100%. From the figures in Fig. 15, we can see that the LS performs better than AVG and MOD in all accounts; less degraded flows, having more successful flows and higher successful admission rate. However, MIN+AVG is better at avoiding the degradation of high priority flows but with less successful flows. When compared to MIN+AVG, LS have more successful flows by 1% with the proportion of high priority flows of 20% and by 6% with the proportion of high of 100%.

Although AVG and MOD estimate the most likely mode of wireless links, unlike MIN, these estimations do not estimate the lowest possible mode used by the wireless links. Hence, AVG and MOD suffer more degradation of admitted flows.

From this comparison, we can see that LS estimation is in fact effective mode estimation method for routing bandwidth guaranteed flows.

7. Conclusion

This paper presented a routing scheme and three mode estimation methods for AMC-enabled wireless mesh network. When link capacity of the network changes, simply using existing routing algorithm with admission control based on traffic information would result in degradation of admitted flows. Effectiveness of proposed routing scheme and mode estimation methods were evaluated through simulations. From the simulation results, we found that proposed routing scheme using mode estimation method can reduce the number of degraded flows to less than one-third and increased the number of successful flows by 5 to 30%. It was shown that mode estimation is important factor in performing accurate admission control and especially important for long-duration flows. Simulation study showed that proposed routing scheme with different estimation methods have consistently outperformed LCP throughout the simulation.

Proposed routing scheme was evaluated when mode distribution is uniform and Poisson distribution and showed proposed routing scheme is also effective under these mode distributions. More detail evaluation was performed on proposed routing scheme by increasing the share of highly unstable links in the network. The simulation results showed that proposed routing scheme is effective even when all the links are highly unstable. Finally, LS estimation was examined by changing its parameter and through comparison with similar mode estimation methods which rely on the mode usage.

Our future work will be to evaluate the performance of our mode estimation methods under actual deployment conditions.

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