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Adaptive Zone-based Bandwidth Management in the IEEE 802.16j Multi-hop Relay Network

Chun-Chuan Yang [1], Yi-Ting Mai [2], and I-Wei Lin [1]

***Abstract*–By comparing with the characteristics of the traditional mobile Quality-of-Service mechanisms, the idea of zone-based bandwidth allocation for mobile users in the IEEE 802.16j multi-hop relay network (IEEE 802.16-MR) is proposed in the paper. The zone of a mobile user includes the current relay station and its neighboring relay stations within the zone size in hop count. Bandwidth allocation is made for the mobile user roaming within the zone, and calculation of the required bandwidth is presented in the paper. Adaptive selection of the zone size fit for user mobility is the main focus of the paper. Markovian analysis is used to determine the proper zone size. Simulation study has demonstrated the effectiveness of the adaptive zone scheme.**

***Index Terms*— IEEE 802.16, Multi-hop Relay Network, Mobile QoS, Bandwidth Management**

I. Introduction

The IEEE 802.16 Standard [1]-[4], first published in 2001, defines a means for wireless broadband access as a replacement for current cable and DSL "last mile" services to home and business. The adoption of this standard is currently in progress through the use of WiMAX Forum certified networking equipment and widespread adoption should appear over the next few years. A series of specifications have been published in the history of IEEE 802.16. *IEEE 802.16d* (802.16-2004) [1] focuses on fixed location wireless access and can support up to 134 Mbps bit rate. *IEEE 802.16e* [2]-[3], completed in 2009, was proposed to support wireless access with high user mobility. The latest version of the standard, *IEEE 802.16j-2009* [4] was proposed for mobile multi-hop relay networks, which is denoted by *IEEE 802.16-MR* in the paper. Differing from the single-hop wireless connectivity of IEEE 802.16e, IEEE 802.16-MR allows the mobile stations to route through intermediate relay stations (RS) to reach the base station (BS). By adopting the idea of relay stations, IEEE 802.16-MR enables fast network deployment in a large area at a lower cost than the traditional wired counterpart.

Mobile users equipped with the IEEE 802.16 interface can directly access the IEEE 802.16-MR network while roaming in the network area. The IEEE 802.11 access point connected to the Relay Station is required for WiFi users to gain access of the network. In either case, an appropriate bandwidth allocation scheme in the IEEE 802.16-MR network is expected in order to guarantee QoS transmission. The issue of QoS supporting for mobile users (also referred as *Mobile QoS*, denoted by *MQoS*), has been addressed in the literature for many years. The typical strategy for MQoS is to reserve necessary bandwidth at neighboring nodes before the mobile user handoff to the new node, which inevitably results in low bandwidth utilization. Extension of RSVP (Resource Reservation Protocol) was adopted in traditional MQoS mechanisms, such as *Mobile RSVP* [5] and *Hierarchical Mobile RSVP* [6]. Most of the QoS-related researches in IEEE 802.16 [7]-[10] focused on bandwidth allocation, scheduling, and architecture design with associated mechanisms, yet the issue of MQoS in IEEE 802.16-MR has not been widely addressed. Some researchers [11]-[12] proposed the idea of adopting RSVP for end-to-end bandwidth reservation in the IEEE 802.16 Mesh network, but the core of MQoS bandwidth management in the IEEE 802.16-MR network has not been addressed.

Two important factors make traditional MQoS mechanisms inappropriate for MQoS support in the IEEE 802.16-MR network. Firstly, all relay stations in the network share the same medium (channel), and the bandwidth requirement for a traffic flow depends on (more specifically, is proportional to) its path length (the number of relay stations en route). Therefore, the bandwidth requirement of a mobile user at current relay station is correlated with the bandwidth requirement at neighboring or nearby relay stations. Secondly, the medium in the IEEE 802.16-MR network is managed by the base station in a centralized control manner, which provides the feasibility of more sophisticated bandwidth management in the network. The correlation of required bandwidth at nearby relay stations leads to the idea of *zone-based bandwidth allocation* in the paper. The zone of bandwidth allocation for a mobile user includes the user's current relay station and the nearby relay stations. The number of relay stations in a zone is determined by the zone size in hop count. Adaptive selection of the zone size is the main focus of the paper. Mobility level of the mobile user presents an impact on the zone size. For example, a higher-mobility user deserves a larger zone in order to maintain a certain level of zone stability. Markovian analysis of user mobility in the network is used to determine the proper zone size. Simulation study has shown the flexibility as well as the effectiveness of the proposed scheme.

The remainder of the paper is organized as follows. Zone-based bandwidth allocation is presented in section II. Markovian modeling and analysis for adaptively selecting the zone size is presented in section III. Simulation study is presented in section IV. Finally, section V concludes the paper.

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II. Zone-based Bandwidth Allocation

A. Basic idea

The motivation of zone-based bandwidth allocation is to reserve appropriate amount of bandwidth used for a mobile user at all relay stations within the zone such that bandwidth re-allocation is not necessary for handoffs of the user among the relay stations of the same zone. The size of a zone (denoted by Z_{size}) is defined to be the hop count of the most distant relay station from the initial (center) relay station as displayed Fig. 1. Following assumptions are made for better understanding zone-based bandwidth management.

(1) All relay stations in the network share the same medium without *spatial reuse* in medium access, i.e. two or more relay stations cannot access the medium at the same time.

(2) BS is fully in charge of medium access control and is responsible for bandwidth allocation by using fields like *UL-MAP* and *DL-MAP* in the control sub-frame. Details of the signaling procedure and the exchange of control messages are not presented in the paper.

(3) Although the proposed scheme can be applied to other types of network topology, a chessboard like topology as displayed in Fig. 1 is used for modeling the IEEE 802.16-MR network, in which BS is located at the upper-left corner, and the correspondent node (CN) outside the network. The proposed scheme only considers bandwidth allocation within the network.

(4) The visiting probability of the mobile user at each relay station is assumed to be obtainable either by the user profile data or network modeling techniques. The visiting probability of the mobile user at relay station $RS_{i,j}$ is denoted by $P_{RS_{i,j}}$.

(5) The applications are assumed to be adaptable to bandwidth adjustment. The satisfaction rate for the required bandwidth, denoted by S, is defined as the ratio of the allocated bandwidth over the required value. The mobile user provides the flow data rate (denoted by BW) as well as the threshold of the satisfaction rate (denoted by S_TH) for bandwidth allocation.

B. Bandwidth allocation

Given the flow data rate BW, the satisfaction threshold S_TH, the zone size Z_{size}, and the initial location of the mobile user $RS_{initial}$, we are showing the calculation of the allocated bandwidth. First of all, all relay stations in the zone must be identified according to the value of Z_{size} as follows.

$$RS_{i,j} \in Zone \text{ if the hop count } (RS_{i,j}, RS_{initial}) \le Z_{size}$$

Secondly, by normalization of the visiting probability at all relay stations in the network, the visiting probability for each relay station in the zone (denoted by $P_{RS_{i,j}}^{Zone}$) can be obtained.

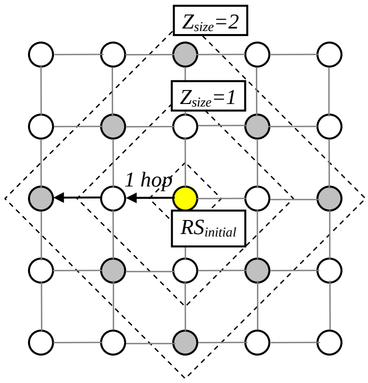

Fig. 1. Zone with different Z_{size}

$$P_{RS_{i,j}}^{Zone} = \frac{P_{RS_{i,j}}}{\sum_{\forall \text{ RS in the } Zone} P_{RS}}$$

If we assume the bandwidth allocated in the zone is $N*BW$, the satisfaction rate S for the allocation can be calculated as follows.

$$S = \sum_{\forall \text{ RS in the } Zone} \left[Min\left(1, \frac{N*BW}{HC_{RS_{i,j}} * BW}\right) \right] * P_{RS_{i,j}}^{Zone}, \qquad (Eq\text{-}1)$$

where $HC_{RS_{i,j}}$ is the hop count between BS and $RS_{i,j}$.

Note that the satisfaction rate at each relay station should be no larger than 1. This is the reason why the *Min* operator is placed in the above equation.

Finally, the allocated bandwidth is determined by the minimum value of N which makes the value of S in *Eq-1* larger than (or equal to) the threshold of the satisfaction rate S_TH.

Admission control for a new mobile user is simply by checking if current available bandwidth is enough for the calculated value of bandwidth allocation. Moreover, by introduction the idea of zone, two types of handoff between relay stations are defined, *intra-zone handoff* and *inter-zone handoff*. Bandwidth re-allocation is only triggered by inter-zone handoffs, and the relay station triggering bandwidth re-allocation becomes the initial relay station of the new zone. Notations used in zone-based bandwidth management are summarized in Table I.

TABLE I.
Summary of Notations

Notation	Description	Remark
S_TH	Threshold of the satisfaction rate	User parameters
BW	Flow data rate	
$RS_{initial}$	Initial relay station for bandwidth allocation	
Z_{size}	Zone size	System parameters
S	Satisfaction rate for the required bandwidth	
$P_{RS_{i,j}}$	Visiting probability at the relay station	
$P_{RS_{i,j}}^{Zone}$	Normalized visiting probability at the relay station in the zone	
$HC_{RS_{i,j}}$	Hop count between BS and $RS_{i,j}$	

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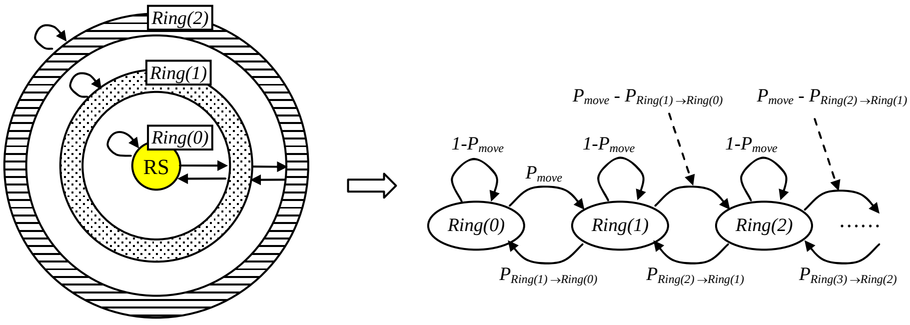


(a) The idea of *Ring* (b) New Markov chain of *Ring* states

Fig. 3. Reducing the number of states by the idea of *Ring*

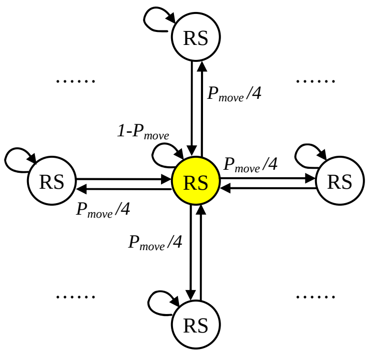
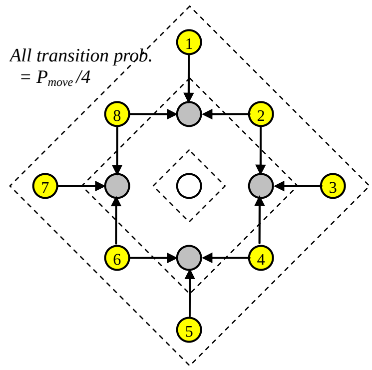


Fig. 2. Modeling user mobility



$$P_{Ring(2)\rightarrow Ring(1)} = (P_{move}/4)*12*(1/8) = (3*P_{move})/8$$

Fig. 4. Calculation of $P_{Ring(2)\rightarrow Ring(1)}$

III. Adaptive Selection of Zone Size

As mentioned in section I, the mobility level of the user imposes some impact on selecting a proper zone size. In this paper, user mobility in the network is modeled by the probability moving out of the current RS, denoted by P_{move}, and moving into any of the neighboring RS with equal probability. The discrete-time Markov chain modeling user mobility in the chessboard-like network is displayed in Fig. 2. Our goal is to find a large enough zone to make the stay probability of the mobile user in the zone larger than the pre-defined threshold (denoted by $P_{stay}TH$, 0.8 is used in the simulation). Two factors must be considered in the calculation of the stay probability in the zone. First, the stay probability should not include the case that the mobile user moving out of the zone and into the zone again, since a new zone should be initiated when the user moving out of the zone. Second, in the practical sense, the stay probability should be associated with a certain number of transitions. Therefore, the stay probability, denoted by $P_{stay}(k)$, is defined as the probability of the mobile user never leaving the zone within *k* transitions.

In order to reduce the number of states in the discrete-time Markov chain, RSs with the same hop count from the initial RS are treated as a single state, denoted by *Ring*(*L*) as displayed in Fig. 3-(a), in which *L* indicates the hop count. The new Markov chain of *Ring* states is displayed in Fig. 3-(b). The approximation of modeling is reasonable since the transition probability from the initial RS to each of its neighboring nodes is the same. Transition probability from *Ring*(*L*) to *Ring*(*L-1*) is calculated by the following equation. An example of calculating $P_{Ring(2)\rightarrow Ring(1)}$ is given in Fig. 4.

$$P_{Ring(L)\rightarrow Ring(L-1)} = \frac{\text{Summation of all transition prob. from } Ring(L) \text{ to } Ring(L-1)}{\text{Total number of nodes in } Ring(L)} \quad (Eq\text{-}2)$$

Expansion of the states is used to compute the probability of each *Ring* state after *k* transitions. An example of the *Ring* states after 5 transitions is displayed in Fig. 5, in which the transition probability between Ring states can be obtained by *Eq-2* (Note that $P_{Ring(L)\rightarrow Ring(L+1)} = P_{move} - P_{Ring(L)\rightarrow Ring(L-1)}$ for L > 0). The probability of the mobile user staying in states *Ring(0)* ~ *Ring(5)* is calculated from the root state *Ring(0)* (the initial state with probability 1) following all possible paths until the 5th transition. For a given zone size, e.g. $Z_{size} = 2$, the staying probability of the mobile user in the zone within 5 transitions, $P_{stay}(k{=}5)$, is the summation of the staying probability of *Ring(0)*, *Ring(1)*, and *Ring(2)* at the 5th transitions in Fig. 5. Unfortunately, a computer program is required to calculate $P_{stay}(k)$ since the closed form for the probability is difficult to find. Simulation programs were conducted to evaluate the accuracy of the calculation of $P_{stay}(k)$. Fig. 6 displays the simulation result as well as the analytical result in the case of $Z_{size} = 2$ and $P_{move} = 0.5$. Closeness of the two curves in the Fig. demonstrates the feasibility of the above Markovian analysis. Finally, for a given value of *k*, the proper zone size for the mobile user is set as the smallest value of Z_{size} to make $P_{stay}(k) \geq P_{stay}TH$.

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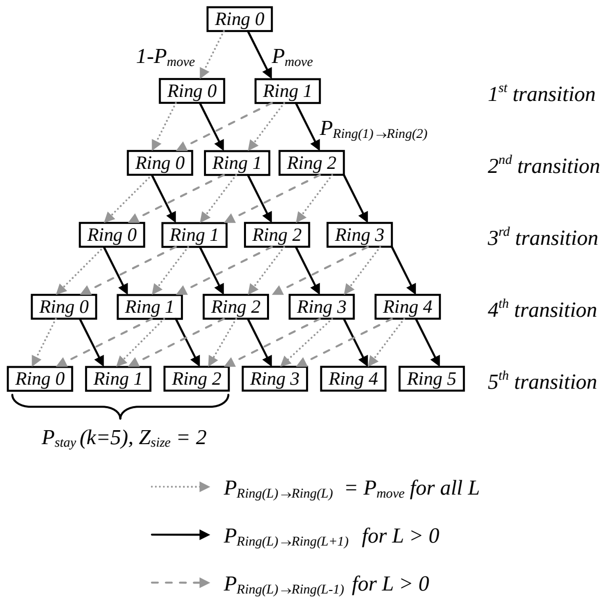

Fig. 5. Expansion of *Ring* state for 5 transitions

IV. Performance Evaluation

Simulation study has been conducted to evaluate the performance of the adaptive zone scheme. An 11x11 chessboard-like network is used to simulate the IEEE 802.16-MR network, in which the BS is located at the upper-left corner and the CN is located outside the network. A discrete-time model is used to simulate user mobility. The initial position of a mobile user is randomly selected from the RSs in the network. Each mobile user leaves its current RS and moves to one of its neighboring RSs with probability P_{move} at each transition time. Considering the regular service range of an RS is about 1 km and the highest speed of the mobile user is 90 km per hour, the average staying time at an RS is about 1 minute, which maps to one transition time unit in the Markovian analysis in section III. Simulation parameters are listed in Table II.

Table II.
Summary of Simulation Parameters

Parameter	Value
Topology size	11x11
Link capacity	70Mbps
Value of *k* for $P_{stay}(k)$	5 transitions
$P_{stay}TH$	0.8
P_{move}	0.1 ~ 0.9
S_TH	1.0
Flow data rate (*BW*)	14Kbps
Flow type	UGS
# of mobile users	100 ~ 700

Simulation results of some performance criteria are presented in the paper. (1) *Handoff call degradation ratio* is defined as the ratio of the case that the required bandwidth cannot be met after handoff. A lower *Handoff call degradation ratio* implies better service quality for handoff calls. (2) *New call blocking ratio* is defined as the ratio of which new calls are rejected due to the failure of meeting the required bandwidth in admission control. (3) *Bandwidth allocation* is defined as the amount of allocated bandwidth for each flow in the IEEE 802.16-MR network.

Fig. 7 displays the result of *Handoff call degradation ratio* in the case of $P_{move} = 0.5$. The curve of $Z_{size} = 0$ in the figure presents the case of no pre-reservation of bandwidth for handoff, which inevitably increases the likelihood of failing to meet the bandwidth requirement as the load (# of flows) increases. The result of *New call blocking ratio* is shown in Fig. 8, indicating that larger zone size results in higher new calling blocking ratio, since a larger zone requires more bandwidth allocation as displayed in Fig. 9. Fig. 7~9 has demonstrated the goal of the proposed adaptive zone scheme in seeking for a good balance between the service quality of handoff calls and new calls, and bandwidth allocation in the adaptive zone scheme is moderate in comparison with other schemes.

In order to investigate the effectiveness of the zone size, one more performance criterion namely *Zone effectiveness* is defined as $\frac{Assigned\_Z_{size}+1}{Ideal\_Z_{size}+1}$, where the assigned zone size is the actual zone size in the schemes (fixed or adaptively selected), and the ideal zone size is defined as the average distance of the mobile user for 5 consecutive transitions. Closeness of *Zone effectiveness* to 100% implies the zone size is more effective. *Zone effectiveness* higher than 100% implies the waste of bandwidth allocation, while *Zone effectiveness* under 100% implies lower quality of service. As shown in Fig. 10, the adaptive scheme is more effective in zone size selection for different move probabilities.

V. Conclusion

The standard of IEEE 802.16j-2009 defines the architecture of a multi-hop relay network, denoted by IEEE 802.16-MR in the paper. To support QoS for mobile users in the IEEE 802.16-MR network, mobile QoS mechanisms should be properly designed. By comparing the characteristics of the traditional Internet-based network environment with IEEE 802.16-MR, the authors concluded that traditional mechanisms for mobile QoS cannot fit well in IEEE 802.16-MR, and the idea of zone-based bandwidth management is proposed. Bandwidth allocation is made for the mobile user roaming within the zone, which is defined to include the current relay station and its neighboring relay stations within the zone size in hop count. The required bandwidth and the service level provided are affected by the size of the zone. A larger zone requires more bandwidth but can provide better quality of service for handoff. Markovian analysis for adaptively selecting the zone size based on user mobility is proposed in the paper. Simulation study has demonstrated the effectiveness of the adaptive zone scheme. The mobility model in the paper assumes equal probability to neighbors for movement. The future work of the research is to target on a more general model for user mobility such as directional mobility.

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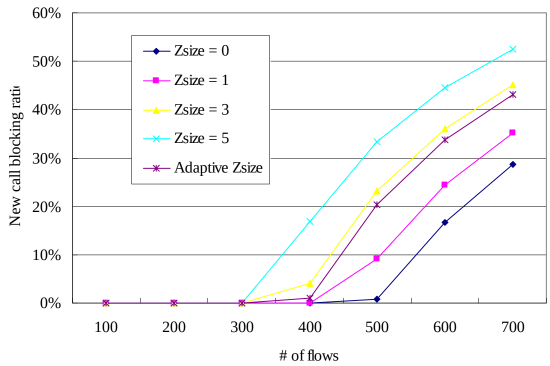
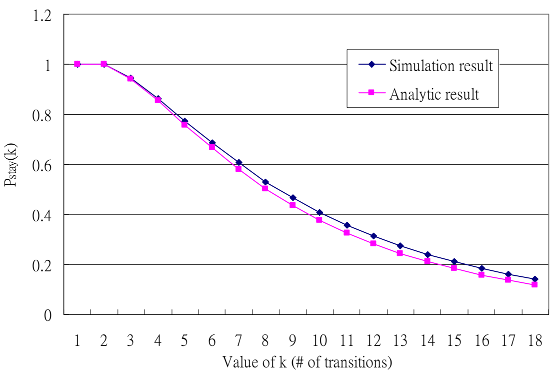


Fig. 8. New call blocking ratio, $P_{move} = 0.5$



$Z_{size} = 2, P_{move} = 0.5$

Fig. 6. Analytic vs. Simulation for $P_{stay}(k)$

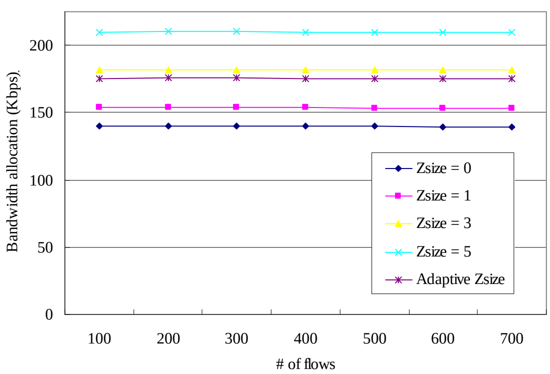


Fig. 9. Bandwidth allocation, $P_{move} = 0.5$

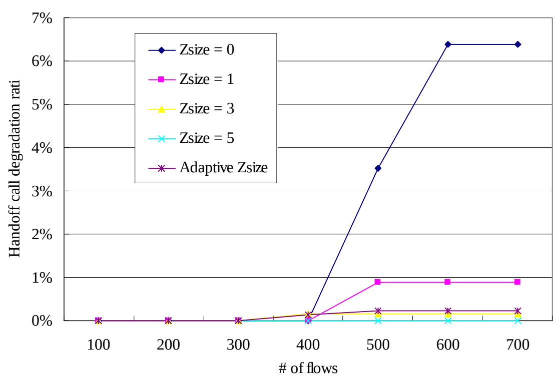


Fig. 7. Handoff call degradation ratio, $P_{move} = 0.5$

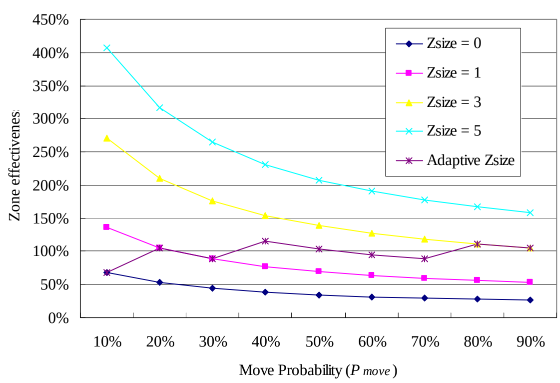


Fig. 10. Zone effectiveness

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