Project	**IEEE 802.16 Broadband Wireless Access Working Group <http://ieee802.org/16>**
Title	**End-to-End Throughput Metrics for QoS Management 802.16j MR Systems**
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Re:	Response to a call for contributions on 2006-12-12 for the Relay TG, see IEEE 802.16j-06/034
Abstract	This document proposes metrics to quantify end-to-end throughput of a routing path over multi-hop relay (MR) systems. These metrics capture the instantaneous physical layer channel quality over each hop and enable the MR BS to keep track of route qualities and end-to-end link quality of service (QoS) over multi-hop routes under varying physical channel conditions. Their computation is performed during uplink and downlink message exchanges among terminals (BS, RS, MS) in the MR network.
Purpose	To propose throughput metrics for end-to-end QoS management
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Procedures	use of patent(s), including patent applications, provided the IEEE receives assurance from the patent holder or applicant with respect to patents essential for compliance with both mandatory and optional portions of the standard." Early disclosure to the Working Group of patent information that might be relevant to the standard is essential to reduce the possibility for delays in the development process and increase the likelihood that the draft publication will be approved for publication. Please notify the Chair <mailto:chair@wirelessman.org> as early as possible, in written or electronic form, if patented technology (or technology under patent application) might be incorporated into a draft standard being developed within the IEEE 802.16 Working Group. The Chair will disclose this notification via the IEEE 802.16 web site <http://ieee802.org/16/ipr/patents/notices>.

End-to-End Throughput Metrics for QoS Management in 802.16j MR Systems

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1.   Summary of Contribution

The goal of this contribution is to propose end-to-end path metrics in 802.16j multi-hop relay (MR) systems. In particular, a mechanism to compute an end-to-end metric and convey it across multiple hops is provided. The contribution while recommending the standardization of a basic end-to-end path metric, permits the use of any other vendor specific path metrics also.

In order to facilitate the incorporation of this proposal in to IEEE 802.16j standard, specific changes to the baseline working document IEEE 802.16j-06/026 are listed in Section 6.

2.   General Description

In a multihop IEEE 802.16 network that employs relay stations (RS) for the purpose of coverage extension or capacity improvement, it is important for the RSs entering the network or performing handover in the network, to consider the routing characteristics of the access RS and the path from the access RS to its MR-BS, before associating with the access RS.

Elements of Routing Announcements

There are several parameters that are of interest and should be considered.

Path Metric to the MR-BS

Consider the exemplary network shown in Figure 1. BS is a MR-BS. RS1 and RS2 are already in the network and are associated to BS as per the topology shown. The end-to-end (ETE) path metric between RS1 and BS is m_{br1} and between RS2 and BS is m_{br2}.
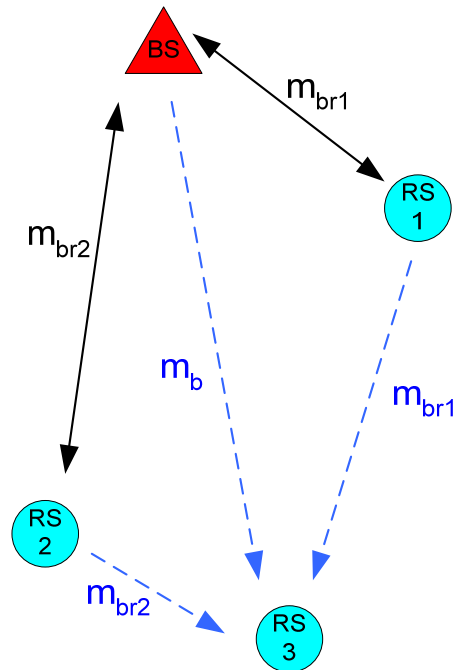
Figure 1 – Path metric announcement

When RS3 enters the MR network or performs handover into an MR cell, it should be made aware of the ETE path metric from each access station to the MR-BS, so that RS3 may use this information in its network entry decisions. Each MR-BS and RS should transmit this information on the downlink using the mechanism described in Section 3. The MR-BS should also transmit a metric value (m_b, in this example).

In the example above, based on the ETE path metrics provided by the RS1 and RS2, RS3 selects the path corresponding to the lowest ETE metric to the MR-BS and completes the network entry or handover process. Once in the MR network, RS3 begins to transmit announcements of its current ETE metric.

Number of Hops to the BS

Each RS should transmit on the downlink, its number of hops to the MR-BS that they are associated to. The mechanism used to transmit this information is described in Section 3.

BSID

Each RS should transmit on the downlink, the BSID of the MR-BS it is associated to. The mechanism used to transmit this information is described in Section 3.

Next Hop towards the BS

Each RS should transmit on the downlink, the node ID of the device that is their next hop towards the MR-BS. The mechanism used to transmit this information is described in Section 3.

3.   Data Encapsulation

The above information should be encapsulated in to a structure (Routing_Advertisement_IE), and may be carried in the DL-MAP transmitted by the MR-BS and the RSs, as an extended IE.

4.   Derivation of the end-to-end path metrics

The following PHY abstraction relationship is the key formula for quantifying the end-to-end quality of an N-hop routing path in terms of throughput in an MR network:

$$End\_to\_End\_Throughput = \left(\sum_{n=1}^{N} \frac{1}{Per\_Link\_Throughput\_over\_Hop\_n} \right)^{-1}.$$

In other words, based on this PHY abstraction, MR BS obtains an estimate of the end-to-end throughput by computing the harmonic mean of the per-link throughputs over the individual hops. This equation provides one incarnation of the end-to-end metric, referred to as m_{br1} and m_{br2} in the example figure above.

To motivate the quantification of end-to-end throughput as the harmonic mean of the throughputs over the individual wireless links, consider an N-hop routing path with time-division relaying such that the transmission rate at hop n is R_n bits/second/Hertz and all hops operate over the common bandwidth W but orthogonally time-share the channel. If the transmitted packet contains B bits of information, then the required transmission time at hop n is $t_n = B/WR_n$ seconds (ignoring retransmissions and channel overheads for now). Thus, the end-to-end latency T (i.e., the total time required to transmit this packet in multiple hops over the routing path), and the resulting end-to-end throughput (in bits/second/Hertz) can be calculated as

$$T = \sum_{n=1}^{N} t_n = \sum_{n=1}^{N} \frac{B}{WR_n} \qquad \rightarrow \qquad Throughput = \frac{B}{WT} = \left(\sum_{n=1}^{N} \frac{1}{R_n} \right)^{-1},$$

which validates the harmonic mean relationship. Alternatively, we can consider an N-hop routing path with frequency-division relaying such that the transmission rate at hop n is R_n bits/second/Hertz, all transmissions simultaneously occur over the time duration of T seconds and the bandwidth is allocated orthogonally among hops. Hence the channel over hop n should be allocated $W_n = B/TR_n$ Hertz of bandwidth, and accordingly the total required bandwidth W and the resulting end-to-end throughput can be calculated as

$$W = \sum_{n=1}^{N} W_n = \sum_{n=1}^{N} \frac{B}{TR_n} \qquad \rightarrow \qquad Throughput = \frac{B}{WT} = \left(\sum_{n=1}^{N} \frac{1}{R_n} \right)^{-1},$$

yielding the identical harmonic mean relationship, which therefore holds for any orthogonal sharing of resources (in time or frequency) among hops over a given routing path.

The harmonic mean formula assumes that optimizing time/frequency allocations among different hops over a given routing path in a channel-dependent manner is possible such that different rates can be transmitted over different hops; i.e., separate rate-adaptations can be performed across multiple hops so that each link can be operated at its best supportable rate chosen with respect to the instantaneous physical layer channel conditions. If the time duration and bandwidth of transmissions have to be fixed across multiple hops regardless of the channel qualities, fixed-rate transmissions over multiple hops will be necessary and therefore the rate supportable over the worst link will be a limitation on the rates chosen over the remaining links, which leads to the end-to-end throughput given by the scaled minimum relationship (applicable to both time-division and frequency-division relaying)

$$Throughput = \frac{1}{N} \min_{n=1,...N} R_n.$$

The discussion in the remaining part of the contribution will focus on the end-to-end PHY abstraction methodology based on the harmonic mean metric, while it should be understood that these techniques can be easily applied to address the scaled minimum metric in the special case of fixed time slot and bandwidth allocation.

In the following, we shall provide two approaches for designing per-link metrics to allow the MR BS estimate the end-to-end throughput over a multi-hop link. It must be emphasized that **other per-link metrics for quantifying throughput over the individual hops can be designed as well; and one can still estimate end-to-end throughput in terms of per-link throughputs through the harmonic mean and scaled minimum formulas**.

A. Capacity-based Approach:

The capacity-based approach computes the harmonic mean of the capacities (only depends on the signal-to-interference-and-noise ratio (SINR)) over individual wireless links and obtains an end-to-end PHY abstraction given as follows:

$$SINR_{eff} = 2^C - 1, \quad where \quad C = \frac{1}{\displaystyle\sum_{n=1}^{N} \frac{1}{C_n}} = \frac{1}{\displaystyle\sum_{n=1}^{N} \frac{1}{\log_2(1 + SINR_{eff,n})}}$$

Where:

- $SINR_{eff}$: Effective SINR for the multi-hop route

- C : Effective end-to-end capacity for the multi-hop route

- C_n : Effective capacity over hop n , $n = 1,...,N$

- $SINR_{eff,n}$: Effective SINR over hop n

- N : Number of hops over the established route between MR BS and MS

Further analysis on this capacity-based end-to-end PHY abstraction metric can be found in [1]-[4]. The effective SINR parameter, $SINR_{eff,n}$, is determined on a per-hop basis over each individual OFDMA PHY link, using any PHY abstraction methodology. In this respect, for an OFDMA system with K subcarriers, denoting the SINR over the k -th subcarrier and n -th hop by $SINR_{n,k}$, $n = 1,...,N$, $k = 1,...,K$, example PHY abstraction metrics could be

- the mean-capacity metric proposed by [5]-[7], where

$$\log_2(1 + SINR_{eff,n}) = \frac{1}{K}\sum_{k=1}^{K}\log_2(1 + SINR_{n,k}) \qquad \Rightarrow SINR_{eff,n} = 2^{\frac{1}{K}\sum_{k=1}^{K}\log_2(1+SINR_{n,k})} - 1,$$

- or the exponential effective SNR mapping (EESM) metric proposed by [8]-[11], where, for a given choice of parameter β ,

$$SINR_{eff,n} = -\beta \log\left(\frac{1}{K}\sum_{k=1}^{K}\exp\left(-\frac{SINR_{n,k}}{\beta}\right)\right).$$

B. Throughput-based Approach:

This PHY abstraction approach involves more computation but is also more accurate than the capacity-based approach in terms of quantifying the end-to-end throughput performance. Unlike the capacity-based approach, the per-link throughput estimation accounts for losses in data rate due to link errors, finite modulation and coding schemes (MCSs) and overheads associated with channel access and protocols. In this setting, the end-to-end throughput estimation is based on computing the harmonic mean of achievable throughputs over individual wireless links.

We denote the expected transmission time (ETT) (first proposed by [12] for 802.11s mesh standard) over hop n as ETT_n , which represents the overall airtime cost in terms of the amount of channel resources consumed by transmitting the packet over the particular link and includes the cost of data transmission as well as cost of necessary retransmissions to recover from packet decoding errors and cost of overhead. Accordingly, the end-to-end throughput for a given multi-hop route of length N can be expressed as

$$Throughput = \frac{B}{T} = \frac{B}{\sum\limits_{n=1}^{N} ETT_n} \quad where \quad ETT_n = \left[T_{overhead} + \frac{B}{R_n} \right] ETX_n .$$

Where:

ETX_n : Expected number of packet transmissions until successful reception over hop n subject to instantaneous channel conditions

R_n : Aggregate data rate per packet over hop n based on the MCS chosen by the link adaptation algorithm while satisfying a certain target packet error rate (PER) subject to instantaneous channel conditions

B : Number of bits per packet

$T_{overhead}$: Latency cost per link due to fixed channel access and protocol overheads

Note that the total sum of ETTs has a physical meaning as well; it is an estimate of the total end-to-end latency $T = \sum\limits_{n=1}^{N} ETT_n$ experienced by a packet traveling along that path.

In the ETT formula, R_n and ETX_n both depend on the instantaneous channel realizations over hop n; in particular they depend on the vector of received SINRs over the K OFDMA subcarriers given by $\left\{ SINR_{n,k} \right\}_{k=1}^{K}$ or effectively they depend on a single measure $SINR_{eff,n}$ computed using the per-link PHY abstractions.

To compute ETX_n more explicitly, we consider a hybrid automatic repeat request (HARQ) mechanism over each link, which requires packet retransmissions upon decoding failure, continued until successful reception of each packet. Thus, the definition of ETT also incorporates the impact of retransmissions upon erroneous reception of transmitted frames/packets and hence takes into account the additional transmission time necessary until successful delivery to the destination. Now,

- If the HARQ protocol discards erroneous packets completely, we have

$$ETX_n = \frac{1}{1 - PER_n} ,$$

where PER_n denotes the packet error rate over hop n determined based on the chosen MCS and channel conditions over the physical layer given by the vector of SINRs in the set $\left\{ SINR_{n,k} \right\}_{k=1}^{K}$.

- If the HARQ protocol stores previously received erroneous packets and uses them during later decoding attempts (e.g. as in chase combining), the PER will improve upon retransmissions, which leads to

$$ETX_n = 1 + \sum_{m=1}^{M} \prod_{j=1}^{m} PER_{n,j},$$

where $PER_{n,j}$ denotes the conditional PER over hop n during transmission j provided that the transmissions for the first $j-1$ trials were unsuccessful, and M is the maximum number of allowed transmissions ($M-1$ retransmissions allowed).

Due to the stationarity of the terminals over the wireless backhaul (i.e. MR BS and RSs), we expect that the channels experienced over the hops will be slow-fading (except for the last hop involving the MS) and each node will be able to track its transmit/receive channels to perform link adaptation and estimate supportable throughput.

Considering the cost of each link to be equal to ETT_n, the throughput-maximizing path (i.e., the path that maximizes end-to-end throughput or minimizes end-to-end latency T) is the path that minimizes total end-to-end routing cost given by $T = \sum_{n=1}^{N} ETT_n$ for a path of length of N hops. The use of such end-to-end link QoS metrics toward designing centralized scheduling algorithms for MR systems have been studied in [13].

5.   Computation of End-to-End Metrics Based on UL/DL Control Information
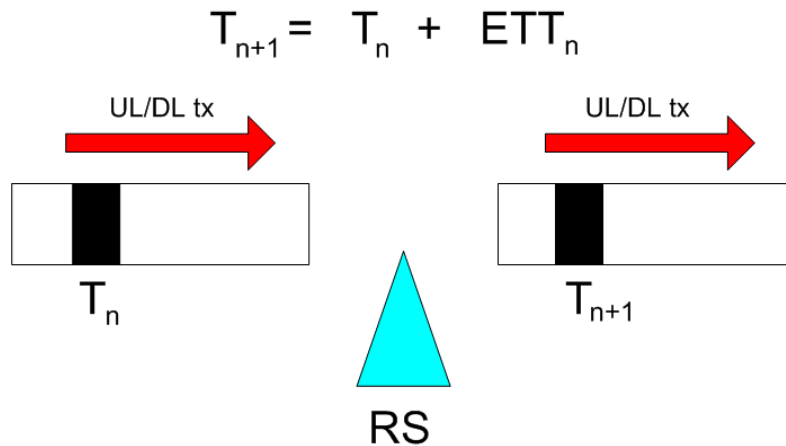
In general, the computation of the end-to-end path cost metric $\sum_{n=1}^{N} \dfrac{1}{C_n}$ in the capacity-based approach or $\sum_{n=1}^{N} ETT_n$ in the throughput-based approach requires a field in the uplink (UL) and/or downlink (DL) control

messages to carry the end-to-end accumulated route costs, i.e. the summation of the reciprocal capacities or ETTs over various hops. This cost metric is to be propagated and updated based on the uplink (UL) and/or downlink (DL) control information transmissions, as depicted below for the throughput-based approach.

Specifically in this contribution, it is proposed to carry the ETE routing information in the Routing_Advertisement_IE transmitted as part of the DL MAP. As the Routing_Advertisement_IEs are received and processed at an RS, the RS will generate its own Routing_Advertisement_IE with the ETE field specifying the end-to-end path cost from itself to its associated MR-BS, taking into account the throughput/latency of transmissions over the current hop.

6.   Proposed Text Changes

[Insert text in sub clause 6.3.9.16]

[Insert a new sub clause 6.3.9.16.1]

6.3.9.16.1 Network Entry Procedure for RS

This section describes the network entry procedure for relay stations entering an MR network.

[Insert a new sub clause 6.3.9.16.1.1]

6.3.9.16.1.1 Routing Announcements for network Entry Support

The MR-BS and the RS shall transmit the Routing_Advertisement_IE in the form of a DL-MAP extended IE in the DL-MAP message transmitted in the MMR-BS-to-MS and RS-to-MS control zones. [These zones are defined in C80216j-06_155].

The MR-BS and the RS shall also transmit the Routing_Advertisement_IE in the MAP message transmitted in the MMR-BS-to-RS and RS-to-RS control zones. [These zones are defined in C80216j-06_155].

Routing_Advertisement_IE is defined in section 8.4.5.3.28.

The RS entering the MR network shall decode the Routing_Advertisement_IE and use its contents to select the access station to enter the MR network through it. The RS shall then proceed to complete the rest of the network entry procedure with the selected access station.

[Change section 8.4.5.3.2.1]

[Insert new row in Table 277a]

Extended DIUC (hexadecimal)	Usage
0A	**Routing_Advertisement _IE**

[Insert a new sub clause 8.4.5.3.28]

8.4.5.3.28 Routing Advertisement IE

[Insert the following text in section 8.4.5.3.28]

In the DL-MAP the MR-BS and the RS may transmit DIUC = 15 with the Routing_Advertisement _IE() to facilitate RS network entering.

Syntax	Size	Notes
Routing_Advertisement_IE(){	-	-
Extended DIUC	4 bits	RANN = 0x0A
Length	4 bits	Length = 0x06 or 0x13
ETE Metric	16 bits	The metric of the path from the access station to its MR-BS
Metric Identifier	32 bits	Identifies the ETE metric being used. Most significant 3 octets represent the OUI. Least significant 1 octet represents specific metric. See table (below) for metric identifier encoding.
BSID	48 bits	The BSID of the MR-BS to which the access station is associated
Next Hop Node ID	48 bits	The ID of the node next hop towards the MR-BS.
Number of Hops	8 bits	Number of hops from the access station to its MR-BS
}	-	-

The "Length" field of the Routing_Advertisement_IE() could take either of the two values, 0x06 and 0x13. This enables MR-BSs to transmit a shorter version of the Routing_Advertisement_IE().

The following table lists values for the Metric Identifier field and the method to generate vendor specific metric identifiers.

Metric Identifier		Value
OUI	**Metric #**	
00-0F-AC	01	TBD (Simple Standardized Metric)
Vendor OUI	Vendor Metric #	Vendor Specific Metric

7.   References

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