MAC-Aware Routing Metric for 802.11 Wireless Mesh Networks

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Abstract—**We develop a new wireless link quality metric, ECOT (Estimated Channel Occupancy Time) that enables a high throughput route setup in wireless mesh networks. The key feature of ECOT is being applicable to diverse mesh network environments where IEEE 802.11 MAC (Medium Access Control) variants are used. We take into account the detailed operational features of various 802.11 MAC protocols, such as 802.11 DCF (Distributed Coordination Function), 802.11e EDCA (Enhanced Distributed Channel Access) with BACK (Block Acknowledgment), and 802.11n A-MPDU (Aggregate MAC Protocol Data Unit), and derive an integrated link metric that enables finding maximum throughput end-to-end routes. Through simulations in randomized topological environments, we evaluate the performance of the proposed link metric and routing strategy to demonstrate that our proposed schemes can achieve up to 354.4% throughput gain over existing ones.**

I. INTRODUCTION

Recently, the wireless backhaul networks has been gaining considerable attention due to their potential for self configuring, instantly deployable, low-cost networking system. Gaining momentum and receiving more interests from research, standardization, and deployment sectors, the backhaul networks, or wireless mesh networks has become a popular research topic.

As a backhaul, the main goal of wireless mesh networks is to provide reliable high throughput network connectivity to wireless users. Many link quality metrics have been proposed to improve the end-to-end throughput performance [1]–[9].

IEEE 802.11 technology has been preferred as for the radio device in wireless mesh networking because of its advantages such as widely deployed and cost-effective. Rare attention however, has been given to its evolutions (e.g., IEEE 802.11e/n) when designing a wireless mesh architecture so far.

We introduce a unified framework of link quality metrics called ECOT (Estimated Channel Occupancy Time) that is modeled on the frame[1] exchange sequences of the advanced 802.11 MAC protocols. Unlike existing link metric designs that typically assume the original 802.11 MAC, ECOT precisely estimates the time duration occupied by a unit frame exchange along with different MACs such as 802.11 DCF (Distributed Coordination Function), 802.11e EDCA (Enhanced Distributed Channel Access) with BACK (Block Acknowledgment), and 802.11n A-MPDU (Aggregate MAC Protocol Data Unit) [10]. Accordingly, ECOT is capable of searching for a high throughput path by making a MAC-aware routing decision. To the best of our knowledge, this is the first work to design a wireless mesh link metric dealing with advanced 802.11 MAC features. We evaluate the effectiveness of the proposed link metric with ns-2 simulator in random (generalized) topological environments.

The rest of the paper is organized as follows. Sections II and III review the related work and the 802.11 MAC/PHY details that are considered for the ECOT design. The formulation of ECOT is presented in Section IV. Section V describes several route decision criteria that are applicable to wireless mesh routing. ECOT is evaluated in Section VI and the paper concludes with Section VII.

II. RELATED WORK

ETX (Expected Transmission Count) [1] is an early generation of mesh link metric that represents the expected number of transmissions for a successful reception over an 802.11 link with a homogeneous PHY transmission rate. ETT (Expected Transmission Time) [2] was designed to enhance ETX for the multiple rates in the 802.11 PHY. In addition, the authors of [2] proposed a weighted form of end-to-end metric, i.e., WCETT to give priority to the least-congested-channel path when selecting a path in a multi-radio, multi-channel mesh environment. While ETT and WCETT employ the rate information to represent the wireless link quality, they do not accommodate the protocol overhead of the 802.11 such as MAC/PHY headers, control frames, and backoff. Moreover, it is obviously based on ETX; the way to measure ETX using the lowest rate hello messages does not change for ETT calculation, while a data packet can be sent at any.

Similar approaches to WCETT have been proposed in the literature such as MCR (Multi-Channel Routing) [3] and AETD (Adjusted Expected Transfer Delay) [4]; the former additionally considers the channel switching delay when calculating link metrics and the latter utilizes spatial reuse distance for the least-congested-channel search. The authors of [5], [6] addressed the asymmetric link quality of wireless links and proposed one-way link metrics that originate from ETX and ETT, yet reflect the link asymmetry. Presenting the importance of short-term time variation of wireless link quality, the authors of [7] enhanced ETX. The impact of protocol overhead in the 802.11 MAC on link metric design was investigated in [8], [9].

III. IEEE 802.11 MAC/PHY SPECIFICATIONS

A. IEEE 802.11 DCF

In DCF [10], when a data frame is successfully received, the receiver responds with an ACK (Acknowledgment) frame, after a SIFS (Short Inter-Frame Space) time interval. It is only

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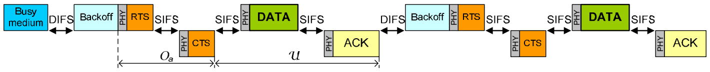
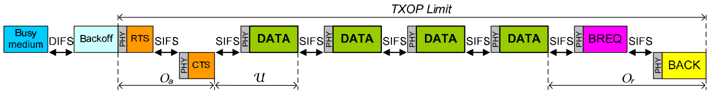
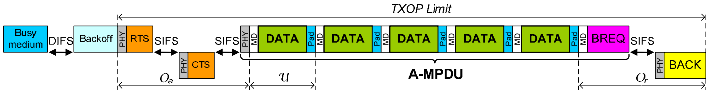
[1] In this paper, an 802.11 MPDU (MAC Protocol Data Unit) is referred to as a *frame*, whereas a *packet* represents a network layer protocol data unit.



(a) 802.11 DCF.



(b) 802.11e EDCA with BACK.



(c) 802.11n A-MPDU.

Fig. 1. Medium access illustrations of IEEE 802.11-based MAC protocols: (a) 802.11 DCF; (b) 802.11e EDCA with BACK; and (c) the 802.11n A-MPDU. DATA, PHY, MD, and Pad represent MPDU, PHY preamble/header, MAC delimiter, and padding octets, respectively.

after receiving an ACK frame correctly that the transmitter confirms a successful delivery of the corresponding data frame. Fig. 1(a) illustrates frame exchange sequences of DCF. Note that all considered MACs utilize four-way handshake to mitigate the hidden/exposed node problems in multi-hop environments.

B. IEEE 802.11e EDCA

EDCA provides a channel access method called *TXOP* (Transmission Opportunity). TXOP is a time interval during which a particular transmitter has the right to occupy the wireless medium to transmit multiple frames without interruptions from other competing uses. *BACK* (Block ACK) in the 802.11e is a selective ARQ (Automatic Repeat reQuest) to improve MAC efficiency. During a TXOP, a transmitter can send a number of frames without receiving corresponding ACK frames immediately. Right after finishing a batch of data frame transmissions within the predetermined TXOP limit, the TXOP initiator generates a *BREQ* (Block ACK Request) frame after waiting for a SIFS duration. The BREQ recipient replies with a BACK before the expiration of the TXOP limit.

In order to protect the burst transmission during a TXOP from possible collisions, BACK should incorporate either an RTS/CTS exchange or an immediate ACK reply for the very first MPDU transmission within a TXOP [11]. We use the RTS/CTS-protected burst transmission in this paper.

Fig. 1(b) shows the frame exchange sequence of the BACK-enabled 802.11e EDCA. Thanks to the reduced channel access overhead, the BACK-enabled EDCA spends less time sending the same number of data frames compared with DCF.

C. IEEE 802.11n A-MPDU

Using IEEE 802.11n A-MPDU [10], a node transmits a group of data frames within a TXOP, similar to EDCA with BACK. One main difference here is that multiple MPDUs are transmitted within a single PHY frame via A-MPDU, as illustrated in Fig. 1(c). A-MPDU and BACK are mandatory in the current 802.11n draft to constitute a high-efficient MAC protocol.

When a transmitter with A-MPDU obtains a medium access, it searches MSDUs (MAC Service Data Units) that are expected to be transmitted to the same receiver and have the same QoS requirement from its MAC hardware queue. An *MD* (MPDU Delimiter) and a *Pad* (padding octets) are attached in front and rear of an MPDU, respectively, when an A-MPDU is generated to delimit the MPDUs within the aggregate.

By reducing SIFS time intervals and PHY preamble/header uses between sequentially transmitted data frames within a TXOP, A-MPDU achieves even more efficient channel use compared with BACK-enabled EDCA.

D. IEEE 802.11a PHY

Even though the current 802.11n draft specifies high-speed transmission rates with newly added modulation and coding schemes, we employ a common PHY model (i.e., the 802.11a). The 802.11a PHY is based on OFDM (Orthogonal Frequency Division Multiplexing) and provides eight transmission rates utilized at the 5 GHz band [10].

IV. METRIC FORMULATION

The design of ECOT aims to estimate the required medium occupancy time to successfully transmit a unit data frame, while being aware of the underlying medium access protocols. We define the concept of ECOT, keeping in mind the frame exchange sequence illustrated in Fig. 1:

$$\mathrm{ECOT} \triangleq \frac{E[\mathcal{T}]}{E[n]}, \tag{1}$$

where $E[\mathcal{T}]$ is the expected time occupancy during which a data frame or a group of data frames is transmitted and $E[n]$ is the expected number of successfully transmitted data frames at a unit transmission attempt.

In order to obtain $E[\mathcal{T}]$ and $E[n]$, we decompose a unit frame exchange sequence into three temporal elements: $\mathcal{O}_a$ (channel access overhead), $\mathcal{O}_r$ (channel release overhead), and $\mathcal{U}$ (unit transmission time for an MPDU transmission) as notated in Fig. 1.

Before deriving $E[\mathcal{T}]$ and $E[n]$ by means of the decomposed temporal elements, we first denote parameters and probabilities that are used to calculate $E[\mathcal{T}]$ and $E[n]$. Table I lists notations of parameters considered in this paper.

During $tTXOP$, $E[n]$ is bounded by the maximum number of successfully transmitted data frames: $\mathcal{N} = \left\lfloor \frac{tTXOP - \mathcal{O}_a - \mathcal{O}_r}{\mathcal{U}} \right\rfloor$.

TABLE I
LIST OF NOTATIONS REPRESENTING MAC/PHY CHARACTERISTICS

Notations	Definitions
$\mathcal{O}_{phy}$	transmission duration for PHY header and preamble
$CW_{\min}$	the minimum contention window
$CW_{\max}$	the maximum contention window
$tFrame$	transmission duration for that *Frame* type
$tDIFS$	time interval of DIFS (DCF Inter-Frame Space)
$tSIFS$	time interval of SIFS (Short Inter-Frame Space)
tMD	transmission duration for an MPDU delimiter
$tPad$	transmission duration for padding bytes
tBO	backoff interval
$tTimeslot$	a slot time
$tTXOP$	time interval specified by the TXOP Limit
τ	wireless propagation delay

Note that, in the case of DCF, $\mathcal{N}$ should be always one. $E[n]$ can be calculated as follows:

$$E[n] = \sum_{n=0}^{\mathcal{N}} nP_s(n), \tag{2}$$

where $P_s(n)$ is the probability that n consecutive data frames are successfully transmitted during $tTXOP$ and also varies over MAC protocols, which will be discussed in the next subsection.

Let p_e^{Frame} be FER (Frame Error Rate) of a specific *Frame* type. We deal with an orthogonal channel assignment to adjacent wireless link so as to investigate the maximum achievable capacity of IEEE 802.11/11e/11n-based wireless mesh networks. Then, we can simplify the success probabilities of RTS/CTS, data/ACK, and BREQ/BACK exchanges without considering collision losses, thus having

$$\left\{\begin{array}{lcl} p_s^{rts} & = & \left(1-p_e^{rts}\right)\left(1-p_e^{cts}\right), \\ p_s^{data} & = & \left(1-p_e^{data}\right)\left(1-p_e^{ack}\right), \\ p_s^{breq} & = & \left(1-p_e^{breq}\right)\left(1-p_e^{back}\right). \end{array}\right. \tag{3}$$

As the calculation of Eq. (3) is based on the knowledge of FER that depends on the frame size and transmission rate, an FER estimation method must precede. If we have a predetermined FER vs. SNR information in advance, the problem becomes simple. Such table can be obtained either from measurement, or from the vendor's datasheet.

$E[\mathcal{T}]$ is expressed by the sum of decomposed temporal elements and channel access time (deferring + average backoff time):

$$E[\mathcal{T}] = tDIFS + E[tBO] + E\left[Y\right], \tag{4}$$

where $E[tBO]$ is the average backoff interval and Y is a MAC-specific time spent during the corresponding frame exchange sequence, which varies over MAC protocols. We will derive such MAC-dependent components in the next subsection.

In the case of a transmission failure, the backoff procedure updates CW (Contention Window) and the backoff interval of the i^{th} transmission attempt is denoted by $tBO_i = \mathsf{rand}\left[0, CW_i\right],$ where CW_i is the size of contention window at the i^{th} transmission and is: $CW_i = \mathsf{min}\left[2^{i-1}\left(CW_{\min}+1\right)-1, CW_{\max}\right]$. We can approximate that $tBO_i \approx CW_i/2$ on average. Accordingly, the average backoff interval per unit transmission, $E[tBO]$ is derived as follows:

$$E[tBO] = \sum_{i=1}^{\gamma} s(i)\frac{CW_i}{2} \cdot tTimeslot, \tag{5}$$

where γ is the retry limit (including the initial transmission) and $s(i)$ is the probability that a data frame is successfully transmitted after the i^{th} transmission attempt. $s(i)$ varies with the backoff procedure of a particular MAC protocols.

The calculation of $E[\mathcal{T}]$, $E[n]$, and ECOT hinges on the operational details of the selected MAC protocol. All related notations are specified with the considered MAC protocol: for example, $E[\mathcal{T}_{dcf}]$ stands for the expected time occupancy during which a data frame is transmitted in DCF.

1) The 802.11 DCF: As illustrated in Fig. 1(a), $\mathcal{O}_a$, $\mathcal{U}$, and $\mathcal{O}_r$ for DCF can be described as:

$$\left\{\begin{array}{lcl} \mathcal{O}_a & = & 2\mathcal{O}_{phy} + tRTS + tSIFS + tCTS + 2\tau, \\ \mathcal{U} & = & 2\mathcal{O}_{phy} + tDATA + 2tSIFS + tACK + 2\tau, \\ \mathcal{O}_r & = & 0. \end{array}\right. \tag{6}$$

$\mathcal{O}_r$ is designed for selective repeat ARQ-based MAC protocols; therefore, it becomes zero for a stop-and-wait ARQ. Accordingly,

$$E\left[Y_{dcf}\right] = E\left[\mathcal{O}_a + \mathcal{U}\right] = \mathcal{O}_a + \mathcal{U}, \tag{7}$$

as both $\mathcal{O}_a$ and $\mathcal{U}$ are constant given the transmission rate and the size of data frame.

An exponential backoff is invoked from the failure of either an RTS/CTS or data/ACK exchange in DCF. Therefore, p_{bo}, the probability that an exponential backoff is initiated is expressed as:

$$p_{bo,dcf} = 1 - p_s^{rts}p_s^{data}. \tag{8}$$

We then have

$$s_{dcf}(k) = \left(p_{bo,dcf}\right)^{k-1}\left(1-p_{bo,dcf}\right). \tag{9}$$

Note that $s(k)$ for different MACs uses the same equation except the condition of a backoff activation, i.e., p_{bo}. By inserting Eq. (9) into Eq. (5), we can calculate $E\left[tBO\right]$ for DCF. $E[\mathcal{T}_{dcf}]$ is calculated by inserting Eqs. (5) and (7) into Eq. (4).

The number n of data frames successfully transmitted during $tTXOP$ is a simple binary value (i.e., 0 or 1); hence, $P_{s,dcf}(n)$ becomes

$$P_{s,dcf}(n) = \left\{\begin{array}{ll} 1 - p_s^{rts}p_s^{data}, & \text{if } n = 0, \\ p_s^{rts}p_s^{data}, & \text{if } n = 1 = \mathcal{N}, \end{array}\right. \tag{10}$$

which is inserted into Eq. (2) to obtain $E[n]$.

2) The 802.11e EDCA with BACK: Considering the selective repeat ARQ-based EDCA with BACK operation illustrated in Fig. 1(b), $\mathcal{O}_a$, $\mathcal{U}$, and $\mathcal{O}_r$ are expressed as follows:

$$\left\{\begin{array}{lcl} \mathcal{O}_a & = & 2\mathcal{O}_{phy} + tRTS + tSIFS + tCTS + 2\tau, \\ \mathcal{U} & = & \mathcal{O}_{phy} + tDATA + tSIFS + \tau, \\ \mathcal{O}_r & = & 2\mathcal{O}_{phy} + tBREQ + 2tSIFS + tBACK + 2\tau. \end{array}\right. \tag{11}$$

For EDCA with BACK,

$$E\left[Y_{edca}\right] = E\left[\mathcal{O}_a + \mathcal{U} + \mathcal{O}_r\right] = \mathcal{O}_a + \mathcal{N}\mathcal{U} + \mathcal{O}_r, \tag{12}$$

since $\mathcal{N}$ data frames are transmitted irrespective of any failure occurring during $tTXOP$, if a RTS/CTS exchange succeeds.

The exponential backoff for EDCA with BACK is invoked from either an RTS/CTS failure, or a BREQ/BACK failure. The probability that an exponential backoff is activated is expressed as:

$$p_{bo,edca} = 1 - p_s^{rts}p_s^{breq}. \tag{13}$$

$P_{s,edca}(n)$ is derived as:

$$P_{s,edca}(n) = \left\{\begin{array}{ll} p_s^{rts}\left(p_e^{data}\right)^{\mathcal{N}} + \left(1-p_s^{rts}\right), & \text{if } n = 0, \\ \binom{\mathcal{N}}{n}\left(1-p_e^{data}\right)^{n}\left(p_e^{data}\right)^{\mathcal{N}-n}p_s^{rts}, & \\ & \text{if } 0 < n \le \mathcal{N}. \end{array}\right. \tag{14}$$

3) The 802.11n A-MPDU: $\mathcal{O}_a$, $\mathcal{U}$, and $\mathcal{O}_r$ for A-MPDU is expressed as

$$\begin{cases} \mathcal{O}_a &= 3\mathcal{O}_{phy} + tRTS + 2tSIFSTime + tCTS + 3\tau, \\ \mathcal{U} &= tDATA + tMD + tPad, \\ \mathcal{O}_r &= \mathcal{O}_{phy} + tBREQ + tSIFSTime + tBACK \\ & \quad +tMD + \tau. \end{cases} \tag{15}$$

The calculation of $E[Y]$, p_{bo}, and $P_s(n)$ for the 802.11n A-MPDU is identical to that addressed in EDCA with BACK.

V. END-TO-END ROUTE SELECTION ALGORITHM

A. ECOT Estimator

We assume that each node calculates the FER of a given length and type of frame using a predetermined SNR vs. FER information. A node, say $\mathcal{A}$ keeps estimating wireless link qualities toward its one-hop neighbors by running the following algorithm:

Algorithm 1: **ECOT estimator**

1) For a selected MAC and a given wireless link, $\mathcal{A}$ estimates the required FER information; for example, $\mathcal{A}$ calculates p_s^{rts} and p_s^{data} in the case of DCF.
2) Using the FER information, $\mathcal{A}$ determines MAC-specific values, i.e., $E[Y]$, p_{bo}, $s(k)$, and $P_s(n)$.
3) $\mathcal{A}$ inserts these values into Eqs. (5) and (4) to get $E[\mathcal{T}]$, and into Eq. (2) to obtains $E[n]$.
4) ECOT for the given link and MAC is calculated using Eq. (1).

B. Channel Allocation and Routing Strategies

We consider a multi-channel/-radio mesh network in this paper. Although ECOT is applicable to any types of wireless mesh network, it has been revealed that interference-limited single-channel mesh has its limitation to show a performance enhancement even with an intelligent link metric [12]. An ideal channel assignment that eliminates interference from neighboring links is assumed to show the upper bound performance of the considered routing strategies.

We consider two routing strategies. We first define $\mathbb{P}$ that is the set of all feasible end-to-end paths from the source node to the destination node. Path j in set $\mathbb{P}$ is composed of a set of links represented by set $\mathbb{H}_j$. The estimated ECOT value for link k in path j is represented by $\text{ECOT}_{j,k}$. The first routing strategy is formally defined by

$$\arg\min_{j\in\mathbb{P}} \text{CECOT}_j, \tag{16}$$

where

$$\text{CECOT}_j = \sum_{k\in\mathbb{H}_j} \text{ECOT}_{j,k}. \tag{17}$$

Note that CECOT_j is a summed value obtained by adding all ECOT values along path j. Accordingly, this strategy selects the route that achieves the minimum CECOT (Cumulative ECOT) value, i.e., minimum-sum-metric path selection. We refer to this strategy as CECOT. Many existing end-to-end mesh route metrics adopt a cumulative form to estimate the end-to-end routing cost, e.g., ETX and ETT.

The second routing strategy is formally defined by

$$\arg\min_{j\in\mathbb{P}} \max_{k\in\mathbb{H}_j} \text{ECOT}_{j,k}. \tag{18}$$

This strategy selects the route with the "least-congested link" using the estimated ECOT values. In multi-hop communications, the end-to-end throughput hinges on the achievable maximum throughput at the bottleneck link. Since the inverse of the ECOT value of a given link should be proportional to the achievable link throughput, we expect that this strategy selects the maximum end-to-end throughput route, and refer to it as mMECOT (min-Max ECOT).

VI. PERFORMANCE EVALUATION

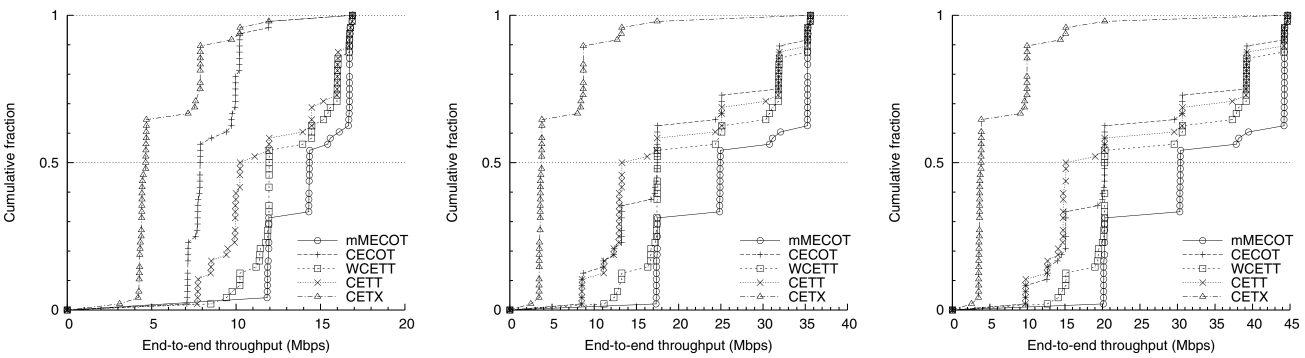
We have enhanced the relevant modules of ns-2 to evaluate all addressed features of ECOT. The TXOP limit is fixed with 3008 μs. We adopt RBAR (Receiver-Based Auto Rate) [13] for the optimal PHY rate selection over links: the transmitter and receiver use modified RTS/CTS for exchanging the length of subsequent data frame and estimating the highest transmission rate. The estimation is done by looking up a predetermined SNR vs. transmission rate table. All control frames are transmitted at the lowest rate, 6 Mbps to help a designated receiver successfully decode required information such as length and rate conveyed in RTS/CTS frames.

We implement and compare ETX and ETT with ECOT. The route selection strategies of ETX and ETT follow the minimum-sum-metric selection and they are referred to as CETX (Cumulative ETX) and CETT, respectively. WCETT (Weighted Cumulative ETT) is also considered with the weighting factor (β) of 0.5. Therefore, the considered comparative evaluation includes five routing strategies, i.e., mMECOT, CECOT, WCETT, CETT, and CETX. We built and use an offline routing scheme based on Dijkstra's algorithm, whose path selection always follows the considered routing strategy.

We assume that a mesh access point forwards traffic from and to client devices, thus working as a source or a destination node of the traffic. Each mesh node transmits with 20 dBm transmission power and all nodes are stationary. The background noise level is set to -93 dBm. We use a log-distance path-loss model with the path-loss exponent of four [14] in AWGN (Additive White Gaussian Noise) channel to simulate an indoor mesh environment. We use LLC/IP/UDP as the upper layer protocol suite. The source nodes continuously generate and transmit 960-byte UDP packets.

We consider a 90 $m \times 90$ m square topology where mesh nodes are deployed; 49 mesh nodes are arbitrarily scattered inside the square with different random seeds. A gateway is located at the right upper corner of the square. UDP packets generated by one randomly selected node is destined to the gateway. We measure and compare end-to-end throughput of five routing strategies. Fig. 2 shows the cumulative fraction of end-to-end throughput performance of five routing schemes on top of DCF, EDCA with BACK, and A-MPDU. Each sample point represents the measured value for a randomly selected source.

We observe that mMECOT achieves the best throughput performance for all MAC protocols. As for the MAC, A-MPDU



(a) 802.11 DCF.   (b) 802.11e EDCA with BACK.   (c) 802.11n A-MPDU.

Fig. 2. End-to-end throughput comparison of five routing strategies in multi-channel/-radio, random-topology networks.

achieves the highest throughput, followed by EDCA with BACK and then DCF. We investigate the measured hop count of all strategies and observe that mMECOT finds *larger-hop* path than those based on other strategies, when searching for the least-congested path. A source node may have multiple available paths toward the gateway. For a given source and destination pair, the smaller number of hop count, the lower transmission rate links are likely over the end-to-end path, which means that a bottleneck due to the long transmission time happens to exist. Since the routing strategy of mMECOT searches for the min-max ECOT path, the chosen route typically is composed of fast rate links (i.e., small ECOT links). As a result, a higher throughput path selected by mMECOT has longer paths than other routing schemes.

CETT and WCETT show worse performances than mMECOT. It should be noted that MAC-unaware routing strategies, i.e., CETX, CETT, and WCETT select identical path irrespective of the employed MAC protocols. Note that hop count distribution is not included in this version. It is interesting to observe that CECOT yields less throughput than CETT and WCETT for many cases. This result indicates that the minimum-sum-metric path is not the highest throughput path even if a MAC-aware link metric is employed.

Table II summarizes the average throughput gain of mMECOT over other schemes. In the case of A-MPDU, mMECOT outperforms CETX with 354.4 % throughput improvement on average. The most comparable strategy is WCETT, which shows 8.5, 16.1, and 17.6 % differences in throughput (14.1 % on average), compared with mMECOT. The reason why WCETT shows the second best performance is because WCETT considers link congestion and gives priority to the least-congested-channel path. We also observe that higher throughput gain is achieved with mMECOT than other routing strategies as the MAC improves its efficiency: the average throughput gains for DCF, EDCA with BACK, and A-MPDU are 52.2, 98.4, and 112.2 %, respectively. It demonstrates that mMECOT successfully utilizes the features of underlying MACs, thus achieving higher throughput gain over existing strategies for enhanced MACs.

TABLE II
AVERAGE THROUGHPUT GAIN OF mMECOT OVER OTHER SCHEMES.

(in %)	CETX	CETT	CECOT	WCETT	avg.
DCF	128.0	17.4	55.0	8.5	52.2
EDCA w/ BACK	309.0	34.0	34.5	16.1	98.4
A-MPDU	354.4	37.2	39.5	17.6	112.2

VII. CONCLUSION AND FUTURE WORK

We proposed a new design of wireless link quality metric, ECOT (Estimated Channel Occupancy Time). The key feature of ECOT is that it is MAC-aware. We investigated the underlying protocol features of 802.11 MAC protocols based on which ECOT is developed. We proposed a routing strategy, mMECOT (min-Max ECOT) that selects the maximum end-to-end throughput path. Through simulation studies, the effectiveness of the proposed routing strategy has been evaluated, and it was demonstrated that mMECOT outperformed state-of-the-art link metrics and routing strategies.

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