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IEEE 802.11 MAC 특성을 고려한 무선 메쉬 네트워크용 링크 품질 인자 개발

(Design of Link Cost Metric for IEEE 802.11-based Mesh Routing)

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요 약 본 논문에서 ECOT(Estimated Channel Occupancy Time)이라는 새로운 무선 링크 성능 지표를 제시하며, 이를 기반으로 멀티 홉 무선 메쉬 네트워크 환경에서 종간간 높은 수율을 얻고자 한다. ECOT의 핵심적인 특징은 다양한 형태의 IEEE 802.11 MAC(Medium Access Control) 환경에서 적용이 가능하다는 점이다. 우리는 802.11 DCF(Distributed Coordination Function), 802.11e EDCA(Enhanced Distributed Channel Access) with BACK(Block Acknowledgement), 802.11n A-MPDU(Aggregate MAC Protocol Data Unit)와 같은 다양한 형태의 링크 계층 구조를 고려하며, 이와 같은 다양한 환경에서 제안하는 ECOT이 기 제안된 다른 성능 지표 방법론과 비교하여 높은 종단간 수율 성능(이득: 8.5~354.4%)을 보여줄 수 있다는 것을 확인하였다.

키워드 : 무선 메쉬 네트워크, 매체 접근 제어, 링크 성능 지표, 라우팅, 무선랜

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 to be applicable to diverse mesh network environments where IEEE 802.11 MAC(Medium Access Control) variants are used. We take into account the exact operational features of 802.11 MAC protocols, such as 802.11 DCF(Distributed Coordination Function), 802.11e EDCA(Enhanced Distributed Channel Access) with BACK (Block Acknowledgement), and 802.11n A-MPDU(Aggregate MAC Protocol Data Unit), and derive the integrated link metric based on which a high throughput end-to-end path is established. Through extensive simulation in random-topology settings, we evaluate the performance of proposed link metric and present that ECOT shows 8.5 to 354.4% throughput gain over existing link metrics.

Key words : Wireless Mesh Network, Medium Access Control, Link Quality Metric, Routing, IEEE 802.11 WLAN

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1. Introduction

Recently, the concept of 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 [1,2], standardization [3,4], and deployment [5-9] sectors, such a new concept of backhaul networks has become a solid research topic, called *wireless mesh network*.

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 [10-19]. Unlike simply searching for the shortest-hop path typically accepted in mobile ad hoc networking, the precise investigation of the underlying MAC (Medium Access Control) and PHY (Physical layer) features has been considered in metric designs.

IEEE 802.11 technology has been preferred as for the radio device in wireless mesh networking because of its incomparable advantages such as the most popularized, easily attachable, and cost-effective. Rare attention however, has been given to its evolutions (e.g., IEEE 802.11e/n) when designing a wireless mesh architecture. In this paper, we develop a new link quality metric that is based on in-depth understanding of advanced MAC features of the 802.11. 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 802.11 MACs. 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) [4]. 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, showing the superiority of ECOT in random (generalized) topological environments.

The rest of the paper is organized as follows. Sections 2 and 3 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 4. Section 5 describes several route decision criteria that are applicable for wireless mesh routing and considered routing algorithm in this paper. The proposed link quality metric is evaluated in Section 6. Finally, the paper concludes with Section 7.

2. Related Work

The efficiency of wireless mesh routing is mostly handled by designing an accurate link metric that stands for the quality of the target wireless link. A number of link quality metrics have been proposed to enhance the routing performance in wireless mesh networks [10-19].

ETX is an early generation of mesh link metric and was developed to quantify an 802.11 link quality [10]. Assuming a homogeneous PHY transmission rate, ETX stands for the expected number of transmissions for a successful transmission over an 802.11 link. The forward and reverse packet delivery ratios based on which ETX is derived are measured with hello messages transmitting at the lowest transmission rate, while a data packet can be sent at any. Hence, ETX over a multi-rate link may misdiagnose the link quality. A fixed size hello message cannot have the identical result in transmissions compared with actual data packets and 802.11 ACKs.

ETT was designed to enhance ETX in consideration of the multi-rate feature of the 802.11 PHY [11]. In addition, the authors of [11] 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 employs the rate information to represent the wireless link quality more precisely than ETX, it does not accommodate the pro-

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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.

tocol overhead of the 802.11 such as MAC/PHY headers, control frames, and backoff. Moreover, it is obviously based on ETX; how to measure ETX does not change for ETT calculation. That is, the addressed issues of ETX inherently exist in ETT.

Similar approaches to WCETT have been proposed in the literature such as MCR (Multi-Channel Routing) [12] and AETD (Adjusted Expected Transfer Delay) [13]; the former additionally considers the channel switching delay when calculating link metrics and the later utilizes spatial reuse distance for the least-congested-channel search. The authors of [14, 15] addressed the asymmetric link quality of wireless links and proposed one-way link metrics that originate in ETX and ETT, yet reflecting the link asymmetry phenomenon. Presenting the importance of short-term time variation of wireless link quality, the authors of [16] enhanced ETX. The impact of protocol overhead in the 802.11 MAC on link metric design is also investigated in [17], [18]. The authors of [19] pointed out the dynamics of estimated metrics (ETX and ETT) over time and locations, through test-bed investigation. However, those metrics only assume the original 802.11.

IEEE 802.11s standardization group has shown a vigorous activity to build a WLAN-based mesh infrastructure for small-to-large-scale regional area [4]. The default link metric specified in the 802.11s draft is *airtime* metric that basically has a similar form one-way ETT, additionally taking care of protocol overhead. It however, does not include detailed analysis of expected performances and their internal causes, which has not been either investigated thoroughly in the literature. Although there exist MAC/PHY advances, the current 802.11s draft does not deal with them.

As a preliminary study, we analyzed the impact of various MAC and transmission rate adaptation schemes on wireless mesh performance, and concluded that a new link metric design is highly required with advanced MAC usage [20]. The MAC framework and offline routing that were used in our previous study become the baseline of this paper, and those have been advanced when designing the proposed link metric and routing strategies.

3. IEEE 802.11 MAC/PHY Specifications

We first present operational details of three different 802.11 MAC protocols: 802.11 DCF, 802.11e EDCA with BACK, and 802.11n A-MPDU. We then describe the feature of 802.11a and a PHY rate selection scheme that are commonly applied for three MACs in this paper. Fig. 1 illustrates the medium access procedures of three MACs whose detailed understanding becomes the fundamentals to design ECOT.

3.1 IEEE 802.11 DCF

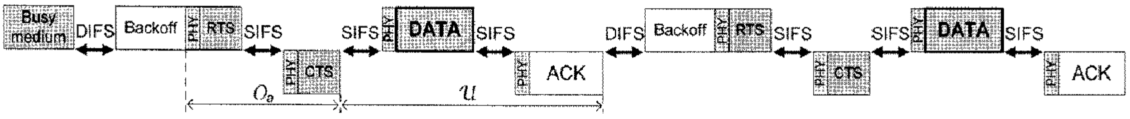
In IEEE 802.11 standard, the DCF based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) is specified as a mandatory medium access scheme [4]. If a data frame is successfully received, the receiver responds with an ACK (Acknowledgment) frame, after a SIFS (Short Inter-Frame Space) time interval. It is only after receiving an ACK frame correctly that the transmitter assumes a successful delivery of the corresponding data frame.

Fig. 1(a) illustrates frame exchange sequences of DCF. We assume that any of considered MAC protocols utilizes four-way handshake that activates an RTS/CTS (Request-to-Send/Clear-to-Send) exchange before transmitting a data frame or a group of data frames, in order to mitigate the hidden/exposed node problems in multi-hop environments. Nodes that overhear the duration field of RTS/CTS set their NAV (Network Allocation Vector) fields so that they do not interrupt the transmission of a data frame or a group of data frames following the RTS/CTS exchange.

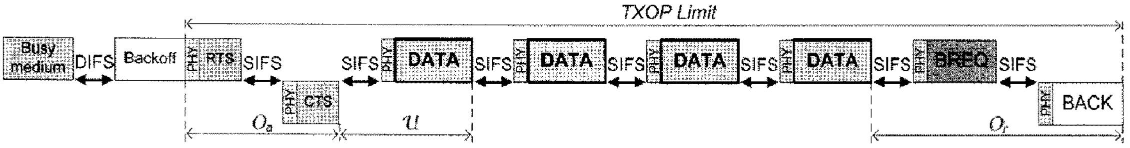
While a high-rate transmission for a control frame is possible and reduces the duration of a frame exchange sequence, RTS and CTS with high rates shrink the NAV set range that is the range within which nodes can set the NAV correctly. In order to maximize the effect of RTS/CTS exchange in terms of mitigating the hidden node problem, we fixed the transmission rate of RTS and CTS frames as the lowest (6 Mbps of the 802.11a PHY).

3.2 IEEE 802.11e EDCA

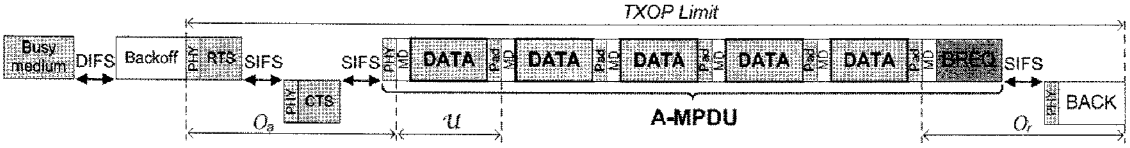
IEEE 802.11e EDCA enhances the DCF by providing differentiated and distributed channel accesses for frames with different required QoS (Quality of Service) [4]. In this paper, however, QoS is not the



(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

concern; yet, the new MAC features of 802.11e MAC for throughput enhancement is mainly considered. EDCA provides a new 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. A TXOP is defined by a starting time and a maximum duration (TXOP limit). During a TXOP, a node transmits one or more MPDUs in a burst manner taking one or more frame exchange sequences.

BACK (Block ACK) is a new selective ARQ (Automatic Repeat reQuest) scheme defined in the 802.11e standard to improve MAC efficiency. The scheme works as follows: during a TXOP, a transmitter can send a number of frames without receiving corresponding ACK frames immediately. Right after finishing a bunch 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 expiry of the TXOP limit.[2] BACK bitmap is used inside the BACK frame to inform which frames are not received correctly.

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. Otherwise, the whole bursting transmission could be corrupted [21]. As described before, we use the former, 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 amount to send the same number of data frames compared with DCF.

3.3 IEEE 802.11n A-MPDU

The main objective of the ongoing IEEE 802.11n standardization is to develop a new MAC and PHY to significantly improve the throughput performance at least 100 Mbps measured at the interface between MAC and a higher layer [4]. The 802.11n MAC is backward-compatible with the 802.11e MAC, which is in turn backward-compatible with the original 802.11 MAC.

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[2] There are two types of BACK procedures in the 802.11e, namely, *immediate BACK and delayed BACK*. The former is explained and used in this paper as it is a more efficient option [4].

Using A-MPDU, a node also transmits a group of data frames within a TXOP, similar to what EDCA with BACK does. 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. Note that BACK must be utilized in conjunction with A-MPDU in the 802.11n, while its use in the 802.11e standard is specified as optional.

A-MPDU frame aggregation is a MAC function and is architecturally done at the bottom of the MAC. 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 (Quality of Service) requirement from its MAC hardware queue. As illustrated in Fig. 1(c), an MD (MPDU Delimiter) and a Pad (padding octets) are attached in front and rear (except for a Pad field when it is the last aggregated packet) of an MPDU, respectively, when an A-MPDU is generated. The purpose of the MD is to delimit the MPDUs within the aggregate. The padding octets are appended to make each MD+MPDU a multiple of 4 octets in length. The receiver hence can easily find the next MD when transmission error occurs.

The current 802.11n draft specifies the maximum A-MPDU length as 65,535 bytes. Therefore, a number of MPDUs can be aggregated up to the limit of A-MPDU length within a TXOP limit. Since PHY has no knowledge of MPDU boundaries, such multiple MPDUs form a single PSDU as illustrated in Fig. 1(c). The receiver of an A-MPDU checks the MD for validity based on an 8-bit CRC inside the MD. If the MD is valid, the corresponding MPDU is extracted from the aggregate. The next MD is expected at the first multiple of 4 octets right after the current MPDU. This extraction process continues until the end of the entire A-MPDU is reached. If the MD is not valid, the receiver skips forward 4 octets and checks if the new location contains a valid MD.

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

3.4 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) for a fair comparison in this paper. The 802.11a PHY is based on OFDM (Orthogonal Frequency Division Multiplexing) and provides eight transmission rates utilized at the 5 GHz band [4].

There is a trade-off between transmission rate and distance in wireless communications. The eight different rates in the 802.11a PHY also have such a property that higher rates suffer from shorter transmission range, whereas the throughput limited lower rates show longer transmission range as illustrated in Fig. 2; the x-axis is SNR (Signal-to-Noise Ratio) that is inversely proportional to distance, and the left y-axis shows throughput result for a given transmission mode (rate in Mbps) labeled in the right y-axis.

Transmission Rate Selection: In order to balance the rate-distance trade-off, a transmission rate adaptation algorithm should be used for multi-rate PHY devices. In this paper, we consider a well-known receiver-based rate control approach, RBAR (Receiver-Based Auto Rate) [22], which works as follows. A transmitter modifies the RTS frame to convey the length information of the subsequent data frame. A receiver estimates the achievable highest transmission rate based on the measured SNR and the conveyed length information. The estimation is typically done by looking up a predetermined SNR vs. transmission rate table, and the corresponding rate information is fed back to the transmitter with the modified CTS frame. Such a receiver-based approach can make a more accurate rate decision in a time-varying wireless channel compared with the transmitter-based schemes such as ARF (Automatic Rate Fallback) [23, 24], SampleRate [25], and CARA (Collision-Aware Rate Adaptation) [26], at the cost of the per-frame RTS/CTS activation. Although a receiver-based rate adaptation scheme is also specified in the current 802.11n draft, we adopt RBAR for all three MACs for the sake of fair comparison.

Fig. 2 shows the throughput performance of eight transmission rates of the 802.11a when the maximum

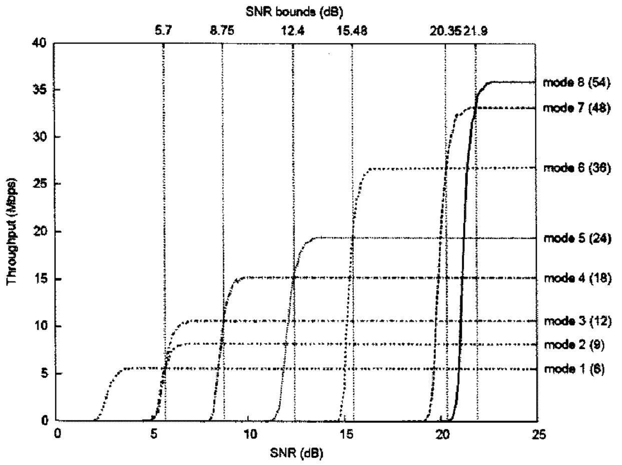

Fig. 2 Throughput performance of the 802.11a transmission rates and corresponding SNR bounds with the maximum MSDU size (2304 bytes)

MSDU size (i.e., 2304 bytes) is used. The corresponding SNR bounds are depicted where two or more throughput curves are crossed. The optimal transmission rate selection is done by adapting the rate such that the achieved throughput follows the outer envelope of the eight curves when an instantaneous SNR varies over time. Therefore, an RBAR receiver needs to maintain SNR thresholds for a given packet length.

The authors of [27], [28] discovered that the 9 Mbps rate does not show any better propagation property than the 12 Mbps rate, and it is also noticed in Fig. 2. We therefore exclude 9 Mbps rate from the candidate rate set during our evaluations in Section 6.

4. Metric Formulation

In this section, we first formulate the proposed link metric ECOT, starting with its definition. We then describe how to decompose the metric formulation into multiple components that can be separately calculated for a specific MAC protocol.

4.1 ECOT Definition

The design of ECOT aims to estimate the required medium occupancy time to successfully transmit a unit data frame, being aware of the underlying medium access protocols. In this paper, ECOT has two meanings: one is the name of proposed link quality metric, and the other means the estimated medium occupancy time for a unit data frame transfer.

We define the concept of ECOT along with the frame exchange sequence of three different 802.11 MAC protocols. As illustrated in Fig. 1, after backing off, a node accesses the wireless medium by exchanging RTS/CTS frames.[3] A data frame or a group of data frames then follow and the frame exchange completes by the ACK or BACK frame transmission. Keeping the frame exchanges in mind, we define ECOT as follows:

Definition 1: We consider two sequences of random variables, T_i and n_i: the former is the time duration spent by the node in consideration to transmit a data frame or a group of data frames (including deferring time and backoff duration as illustrated in Fig. 1) at the node's i^{th} transmission attempt; and the latter denotes the number of transmission successes out of the maximum number of transmitted data frames at the i^{th} attempt. The subscript i indexes a set of $M(t)$ transmission attempts of the node by the time t. We define ECOT as the expected medium occupancy time that is presented by the fraction of those random sequences over the total observation time t:

$$\mathrm{ECOT}(t) \triangleq \frac{\sum_{i=1}^{M(t)} T_i}{\sum_{i=1}^{M(t)} n_i}, \tag{1}$$

which is measured in the unit of second.

ECOT(t) formulated by a function of random sequences is not useful since its accuracy varies over the size of $M(t)$. Moreover, ECOT(t) does not quickly react to wireless channel variation and contention intensity. The following proposition states that ECOT(t) converges to the non-random (probabilistic) mean.

Proposition 1: Eqs. (1) and (2) are asymptotically equivalent as $t \rightarrow \infty$:

$$\mathrm{ECOT} = \frac{E[T]}{E[n]}, \tag{2}$$

where $E[T]$ 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

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[3] In this paper, we consider RTS/CTS-enabled MAC protocols in ECOT formulation. However, the usage of ECOT as a link quality metric is not limited to the RTS/CTS usage, thus being able to change the formulation to be suitable for the access without RTS/CTS exchanges.

successfully transmitted data frames at a unit transmission attempt.

Proof: The random sample (statistical) means of the *M(t)* random variables with respect to T_i and n_i are defined by:

$$\overline{T_i} = \frac{\sum_{i=1}^{M(t)} T_i}{M(t)}, \overline{n_i} = \frac{\sum_{i=1}^{M(t)} n_i}{M(t)}.$$

By the Law of Large Numbers, $\overline{T_i} \sim E[T]$ and $\overline{n_i} \sim E[n]$ as $t \rightarrow \infty$. In consequence, it follows that:

$$\mathrm{ECOT} = \frac{E[T]}{E[n]}$$

4.2 Decomposition of Frame Exchange Sequences

From Proposition 1, ECOT can be obtained by calculating *E[T]* and *E[n]*. In order to obtain *E[T]* and *E[n]*, we decompose a unit frame exchange sequence into three temporal elements:

- O_a: channel access overhead,
- O_r: channel release overhead,
- *U*: unit transmission time for an MPDU transmission.

Such temporal elements are notated in Fig. 1 showing that considered three MAC protocols have different definitions of O_a, O_r, and *U*.

Before deriving *E[T]* and *E[n]* by means of the decomposed temporal elements, we first denote parameters and probabilities that are used to calculate *E[T]* and *E[n]*. Table 1 lists notations of MAC and PHY parameters considered in this paper.

During *tTXOP*, *E[T]* is bounded by the maximum number of successfully transmitted data frames (*N*):

$$N = \left\lfloor \frac{tTXOP - O_a - O_r}{U} \right\rfloor, \tag{3}$$

Where ⌊ ⌋ is the operator that yields the maximum integer number less than or equal to the given value. Note that, in the case of DCF, there is no concept of TXOP. Therefore, *N* should be always one. The expected number of successfully transmitted data frames at a transmission attempt, E[n] can be calculated as follows:

$$E[n] = \sum_{n=0}^{N} nP_s(n), \tag{4}$$

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

Table 1 List of Notations Representing Mac/Phy Characteristics

Notations	Definitions
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

Let p_e^{Frame} be FER (Frame Error Rate) of a specific *Frame* type, such as RTS, CTS, data, BREQ, BACK, and ACK frames. In this paper, 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 (denoted by p_e^{rts}, p_e^{data}, and p_e^{breq}, respectively) without considering transmission failures due to collision losses, thus having

$$\begin{cases} p_s^{rts} = (1-p_e^{rts})(1-p_e^{cts}), \\ p_s^{data} = (1-p_e^{data})(1-p_e^{ack}), \\ p_s^{breq} = (1-p_e^{breq})(1-p_e^{back}). \end{cases} \tag{5}$$

As the calculation of Eq. (5) is based on the knowledge of FER that depends on the frame size and employed transmission rate, an FER estimation method should precede. If we have a predetermined FER vs. SNR information in advance, the problem becomes simple. Such table can be obtained either from measurement, e.g., [29], or from the vendor's datasheet, e.g., [30]. Upon the reception of packets from a neighbor, a node measures the average SNR by measuring both RSSI and the observed background noise level, and then FER is obtained from the table.

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

$$E[T] = E[tDIFS + tBO + Y] \\ = tDIFS + E[tBO] + E[Y], \quad (6)$$

where *tDIFS* is a constant (34µs in the 802.11a PHY) and *E[tBO]* is the average backoff interval. *Y* is a random variable, a MAC-specific time duration 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) to [2 × (*CW* + 1) - 1]. Once *CW* reaches CW_{max}, it remains at this value until finishing the transmission successfully or dropping the frame due to the retry limit, resetting to CW_{min}. The backoff interval of the i^{th} transmission attempt can be denoted by tBO_i = rand [0,CW_i] , where CW_i is the size of contention window at the i^{th} transmission and is written by:

$$CW_i = \min[2^{i-1}(CW_{\min}+1)-1, CW_{\max}]. \quad (7)$$

rand[x, y] is the operator that randomly draws an integer number from a uniform distribution over the interval [x,y]. Accordingly, we can approximate that $tBO_i \approx CW_i /2$ on average. The average backoff interval per unit transmission, *E[tBO]* is derived as follows:

$$E[tBO] = \sum_{i=1}^{\gamma} s(i) \frac{CW_i}{2} \cdot tTimeslot, \quad (8)$$

where γ is the retry limit and *s(i)* is the probability that a data frame is successfully transmitted after the i^{th} transmission attempt. *s(i)* varies with the rule of backoff procedure specified in a particular MAC protocol, which will be discussed with a specific MAC.

4.3 Calculation of MAC-Specific Components

As addressed before, the calculation of *E[T]*, *E[n]*, and in turn ECOT hinges on the operational details of the selected MAC protocol. We derive MAC-dependent values for each considered MAC. All related notations are specified with the considered MAC protocol: for example, $E[T_{dcf}]$ stands for the expected time occupancy during which a data frame is transmitted for DCF.

1) *The 802.11 DCF*: As illustrated in Fig. 1(a), O_a, *U*, and O_r for DCF can be described by:

$$\begin{cases} O_a = 2O_{phy} + tRTS + tSIFS + tCTS + 2\tau, \\ U = 2O_{phy} + tDATA + 2tSIFS + tACK + 2\tau, \\ O_a = 0. \end{cases} \quad (9)$$

The overhead to release wireless channel, O_r is designed for selective repeat ARQ-based MAC protocols; therefore, it becomes zero for a stop-and-wait ARQ MAC.

For DCF,

$$E[Y_{dcf}] = E[O_a + U] = O_a + U, \quad (10)$$

as both O_a and *U* are constant given the transmission rate and size of data frame.

An exponential backoff is invoked due to 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 by:

$$p_{bo,dcf} = 1 - p_s^{rts} p_s^{data}, \quad (11)$$

Then, we have

$$s_{dcf}(k) = (p_{bo,dcf})^{k-1}(1 - p_{bo,dcf}), \quad (12)$$

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. (12) into Eq. (8), we can calculate *E[tBO]* for DCF and $E[T_{dcf}]$ is calculated by inserting Eqs. (8) and (10) into Eq. (6).

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

$$p_{s,dcf}(n) = \begin{cases} 1 - p_s^{rts} p_s^{data}, & \text{if } n = 0, \\ p_s^{rts} p_s^{data}, & \text{if } n = 1 = N, \end{cases} \quad (13)$$

which then can be inserted into Eq. (4) to calculate *E[n]*.

2) *The 802.11e EDCA with BACK*: Considering the selective repeat ARQ-based EDCA with BACK operation illustrated in Fig. 1(b), O_a, *U*, and O_r are expressed as follows:

$$\begin{cases} O_a = 2O_{phy} + tRTS + tSIFS + tCTS + 2\tau, \\ U = O_{phy} + tDATA + tSIFS + \tau, \\ O_a = 2O_{phy} + tBREQ + 2tSIFS + tBACK + 2\tau. \end{cases} \quad (14)$$

For EDCA with BACK,

$$E[Y_{edca}] = E[O_a + U + O_r] = O_a + NU + O_r, \quad (15)$$

since *N* data frames should be transmitted irrespective of any failure occurring during *tTXOP*, if a RTS/CTS exchange succeeds.

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

$$p_{bo,edca} = 1 - p_s^{rts} p_s^{breq}, \tag{16}$$

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

$$p_{s,edca}(n) = \begin{cases} p_s^{rts}(p_e^{data})^N + (1 - p_s^{rts}), & \text{if } n = 0, \\ \binom{N}{n}(1 - p_e^{data})(p_e^{data})^{N-n} p_s^{rts}, & \text{if } 0 \le n \le N. \end{cases} \tag{17}$$

3) *The 802.11n A-MPDU:* O_a, U, and O_r for A-MPDU can be expressed by

$$\begin{cases} O_a = 3O_{phy} + tRTS + tSIFS + tCTS + 3\tau, \\ U = tDATA + tMD + tPad, \\ O_a = O_{phy} + tBREQ + tSIFS + tBACK + tMD + \tau. \end{cases} \tag{18}$$

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

5. End-To-End Route Selection Algorithm

In this section, we present the procedure of an end-to-end route selection considered in our mesh environment. We first present the ECOT estimator that operates at each node and describe two routing strategies that work with ECOT. Then, we introduce an offline routing algorithm that selects the optimal route in terms of the given routing strategy.

5.1 ECOT Estimator

As described in Section 4.1, 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 $\mathcal{A}$ that keeps estimating wireless link qualities toward its one-hop neighbors runs the following algorithm:

Algorithm 1: **ECOT estimator**

1) For a selected MAC and a given wireless link, A estimates required FER information; for example, A calculates p_s^{rts} s and p_s^{data} in the case of DCF.
2) Using the FER information, 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. (8) and (6) to get $E[T]$, and into Eq. (4) to obtains $E[n]$.
4) ECOT for the given link and MAC is calculated using Eq. (2).

5.2 Channel Allocation and Routing Strategies

We consider a multi-channel, multi-radio mesh network and assume an orthogonal channel assignment to adjacent wireless links. This will completely eliminate the interference from neighboring links. While this assumption could be too ideal, it will give us the upper bound performance of the considered routing strategies. The consideration of the interference due to non-ideal channel assignment will remain as our future work.

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

$$\arg\min_{j \in P} \text{CECOT}_j, \tag{19}$$

where

$$\text{CECOT}_j = \sum_{k \in H_j} \text{ECOT}_{j,k}. \tag{20}$$

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 (meaning cumulative ECOT) value, i.e., minimum-sum-metric path selection. We will refer to this strategy as CECOT for the rest of the paper. 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. CECOT simply adopts this cumulative usage of link metric values for a route selection.

The second routing strategy can be formally defined by

$$\arg\min_{j \in P} \max_{k \in H_j} \text{ECOT}_{j,k}. \tag{21}$$

This strategy selects the route with the “least-congested link” in terms of 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 will select the route achieving the maximum end-to-end throughput. We will refer to this strategy as mMECOT (meaning min-Max ECOT) for the rest of the paper.

5.3 Offline Optimal Routing

Even though the proposed metric, ECOT is possibly utilized with existing on-demand or proactive routing protocols, we built and use an offline routing scheme, whose path selection always follows the considered routing strategy. Therefore, we do not have to care about misbehavior in routing, thus expecting that the observed performance variations are dominated by the design of link metrics and considered routing strategies only. An earlier version of offline routing scheme was introduced in [20] and it has been improved by incorporating the proposed link metric and routing strategies.

The offline routing works as follows. Before starting any active data session, each mesh node collects all required link metric information and runs the Dijkstra's algorithm to find the optimal route toward all destination nodes. Then, a source node compares available paths and selects the optimal one that fulfills the corresponding routing strategy.

6. Peformance Evaluation

In this section, we evaluate the effectiveness of ECOT with various MACs in generalized multi-hop mesh networks.

6.1 Evaluation Framework

To evaluate the performance of ECOT, we have modified the ns-2 simulator. IEEE 802.11 module is enhanced to support 802.11e EDCA with BACK, 802.11n A-MPDU, and 802.11a OFDM PHY. The TXOP limit is fixed with 3008 microseconds for EDCA with BACK and A-MPDU MACs. As addressed in Section 3.4, we adopt an SNR-trigger rate adaptation, RBAR for the optimal PHY rate selection over links. All control frames are transmitted at the lowest rate, 6 Mbps to help a designated receiver successfully decodes required information such as length and rate conveyed by RTS/CTS frames.

For network layer routing, an offline routing is built, thus achieving always the optimal route setup in terms of a given routing strategy. We implement state-of-the-art link metrics, ETX and ETT so as to compare the performance of ECOT-based routing with ETX-/ETT-driven results. The route selection strategies of ETX and ETT follow the original approaches, i.e., the minimum-sum-metric selection is used for both metrics, and they are referred to as CETX (Cumulative ETX) and CETT (Cumulative ETT), respectively. For ETT, WCETT (Weighted Cumulative ETT) is additionally considered with the weighting factor (β), 0.5 [10], [11]. Therefore, the considered comparative evaluation in the following subsection includes five routing strategies, i.e., mMECOT, CECOT, WCETT, CETT, and CETX. We assume that a mesh access point forwards traffic from or to client devices, thus working like a source or destination node of such 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 [31] in AWGN (Additive White Gaussian Noise) channel to simulate the indoor mesh environment. As observed in [32], CS (Carrier Sense) range of the 802.11a PHY is completely covered by the RTS/CTS transmission range. We hence set the CS range to the same range of the RTS/CTS transmission (39.5 meters) in our simulations.

We use LLC/IP/UDP (IEEE 802.2 Logical Link Control/Internet Protocol/User Datagram Protocol) as the upper layer protocol suite. Source node also continues to generate and transmit 960-byte UDP packets, corresponding to 1024-byte MPDUs, with infinite amount of traffic. In our simulation model, each mesh node calculates the considered link metrics between its neighbors and itself based on distances and the given path-loss model, which is a ground reflection (two-ray) model [31]. The calculation of each link metric follows the formulas in Section 4.

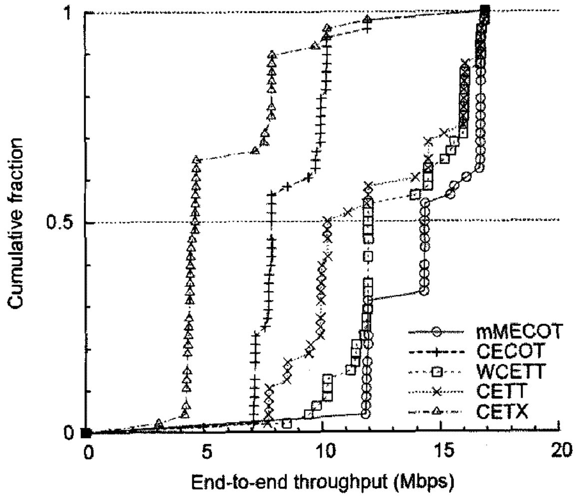
6.2 Comparative Evaluation in Random-Topology networks

We consider a 90×90 *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 and an UDP packets generated by one randomly selected node is destined to the gateway. We measure and compare end-to-end throughput and hop count of five routing strategies. Fig. 3 shows cumulative fraction of end-to-end throughput performance of DCF, EDCA with BACK, and A-MPDU, and corresponding hop counts are presented in Fig. 4. Each sample point represents the measured value for a randomly selected source. We have several observations from these figures.

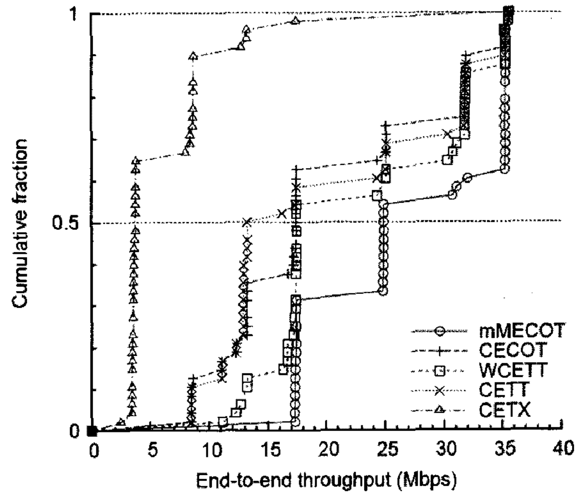
Observing that the curves of mMECOT are most right-shifted in Fig. 3(a)-(c), we find that mMECOT achieves the best throughput performance for all MAC protocols. The enhanced MAC efficiency is observed by comparing the scale of x-axes in sub-figures of Fig. 3, i.e., higher throughput values are achieved in the order of A-MPDU, EDCA with BACK, and then DCF as expected. When searching for the least-congested-link path, mMECOT tends to find a path whose hop count is larger (say, a larger-hop path) than those based on other strategies. 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. Since the routing strategy of mMECOT attempts to find a path whose worst-ECOT link has the minimum among all feasible paths, the chosen end-to-end route is likely to have fast rate links over which small values of ECOT are observed. As a result, a higher throughput path selected by mMECOT includes relatively larger number of hops.

CETT and WCETT show worse performances than mMECOT, depicting left-shifted curves compared with those of mMECOT. Note that MAC-unaware routing strategies, i.e., CETX, CETT, and WCETT show identical path building irrespective of the employed MAC protocols, thus showing the same hop count distribution in Fig. 4. It is interesting to observe that CECOT that uses ECOT measures in a cumulative manner over a given path shows worse throughput even than CETT and WCETT for many cases. It means that the end-to-end path selection policy that chooses the minimum-sum-metric path cannot select the highest throughput path even if a MAC-aware link metric is employed.

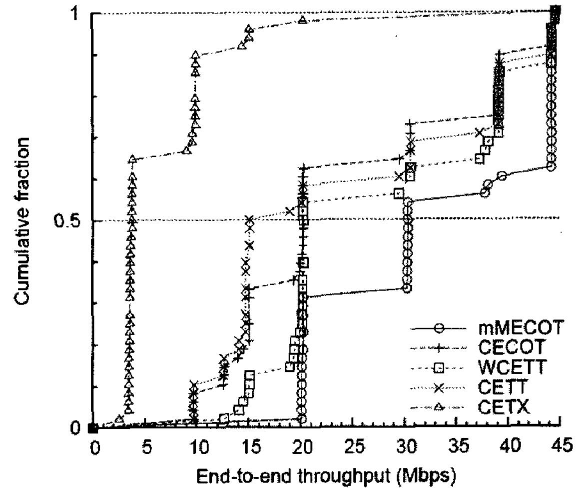
Due to the fact that EDCA with BACK and A-MPDU have a similar MAC operation, which is a



(a) 802.11 DCF.

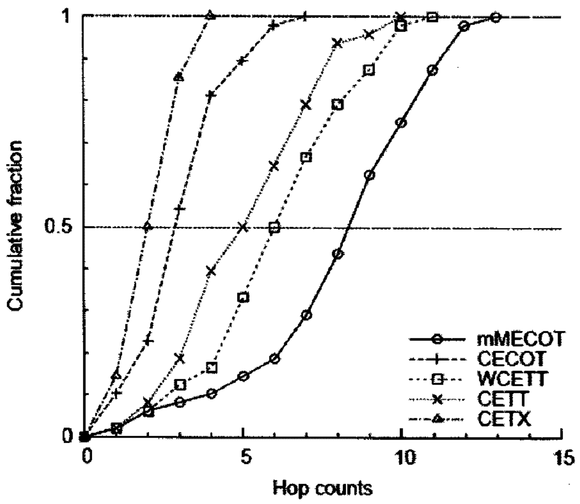


(b) 802.11e EDCA with BACK.

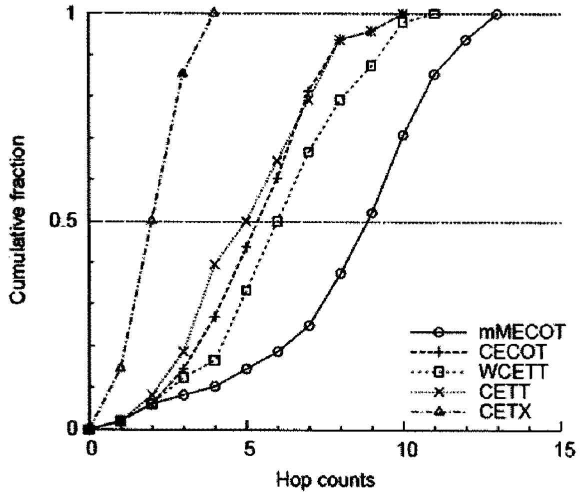


(c) 802.11n A-MPDU.

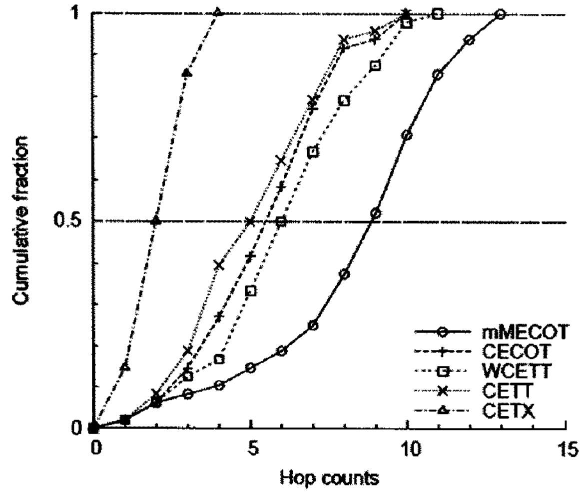
Fig. 3 End-to-end throughput comparison of five routing strategies in multi-channel/-radio, random-topology networks



(a) 802.11 DCF.



(b) 802.11e EDCA with BACK.



(c) 802.11n A-MPDU.

Fig. 4 Hop count comparison of five routing strategies in multi-channel/-radio, random-topology networks

burst data transmission using a selective repeat ARQ, the overall performance trend of both MACs seem to be identical in Figs. 3(b) and 3(c), and Figs. 4(b) and 4(c). The only differences are the enhanced throughput and increased hop counts that come from the advanced MAC protocol efficiency.

Table 2 summarizes the average throughput gain of mMECOT over other routing strategies with different MAC protocols. For all cases, positive values are observed, and it represents the superiority of mMECOT to existing strategies for various MACs. In the case of A-MPDU, mMECOT outperforms CETX with 354.4% throughput enhancement. 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. It is because WCETT considers link congestion in the metric design and gives priority to the least-congested-channel path, when selecting a high-throughput end-to-end path. We also observe that higher gain is achieved with mMECOT compared with other routing strategies for more efficient MAC: the average 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 a more enhanced MAC.

Table 2 Average Throughput Gain of Mmecot over Different Route Selection Strategies

(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

7. Conclusion and Future Work

In this paper, we propose a new design of wireless link quality metric, ECOT (Estimated Channel Occupancy Time). The key feature of the proposed metric is that ECOT works in a MAC-aware manner. We investigate the underlying protocol features of 802.11 MAC protocols such as 802.11 DCF, 802.11e EDCA with BACK, and 802.11n A-MPDU, based on which ECOT is developed. We then propose a routing strategy, referred to as mMECOT, which selects the route achieving the maximum end-to-end throughput performance. Through simulation studies, the effectiveness of mMECOT has been evaluated and it was demonstrated that mMECOT outperformed state-of-the-art link metrics and routing strategies in random-topology setups.

As future work, we plan to evaluate ECOT in comparison with other state-of-the-art link metrics and routing strategies considering more diverse traffic types such as those employing TCP. The consideration of interferences from other links and their impact in non-ideal multi-channel, multi-radio mesh network environments should be also studied. Moreover, the extension of ECOT considering other 802.11 MAC protocols (e.g., 802.11e EDCA without BACK) is also currently ongoing.

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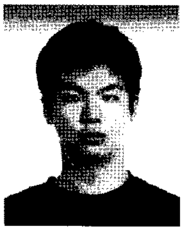

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