An Energy-Efficiency MAC-Layer Relay Method for IEEE 802.11 Infrastructure Wireless LANs *

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Abstract: In this paper, we introduce Energy-Efficiency Cut-Through (ECTP) protocol to improve energy-efficiency in infrastructure wireless LANs. We study a combined medium access and next-hop address lookup without the intervention of the host protocol stack, and introduce a proper relay node to let a pair of communication ends adopt a higher data rate according to the path loss and the channel condition at transmission time. Evaluation results show that the proposed protocol and its degraded method provide significant improvements on energy-efficiency, and remarkably enhance overall system performance.

Key–Words: Energy Efficiency, Relay-Based MAC, IEEE 802.11, Wireless LAN, Performance Analysis.

1 Introduction

In wireless local area networks (WLANs), the new high-speed IEEE 802.11a MAC/PHY provides mobile hosts (MHs) the capability to transmit packets with different data rates ranging from 6 to 54 $Mbps$. Recently, the expected data rates of IEEE 802.11a/b/g at varying distance from access point (AP) have been measured in [1]. We summarize the results of IEEE 802.11a in Table 1 along with the corresponding modes, modulation schemes, and approximate distances.

Table 1: IEEE 802.11a characteristics and expected data rates at varying distance from AP

Mode	Modulation	Data Rate	Distance
~~1~~	~~BPSK~~	~~6 $Mbps$~~	~~150 ft (46 m)~~
~~2~~	~~BPSK~~	~~9 $Mbps$~~	~~127 ft (39 m)~~
3	QPSK	12 $Mbps$	120 ft (37 m)
4	QPSK	18 $Mbps$	115 ft (35 m)
5	16-QAM	24 $Mbps$	87 ft (27 m)
6	16-QAM	36 $Mbps$	75 ft (23 m)
7	64-QAM	48 $Mbps$	52 ft (16 m)
8	64-QAM	54 $Mbps$	42 ft (13 m)

With the standard, most current works, e.g., Auto Rate Fallback (ARF) [2], Receiver-Based Auto Rate (RBAR) [3], and Opportunistic Auto Rate (OAR) [4], pay their attentions to provide higher throughputs for MHs in WLAN. However, these works only focus on the throughput improvement, and do not explicitly consider the problem of transmitting data with energy-efficiency. That is to say, even adopting the methods in these works, MHs in WLAN still can not insist on using the highest-level modulation scheme to obtain the maximal channel utilization for the data rate is inversely proportional to the transmission distance between a pair of MHs, and a high-level modulation scheme requires a higher SNR to obtain the same bit error rate.

For solving this problem, we propose here an Energy-Efficiency Cut-Through Protocol (ECTP) as an enhanced protocol in WLAN. ECTP slightly modifies the IEEE 802.11 MAC protocol by introducing a new message exchange procedure for a relay node between a pair of communication nodes. The core idea of ECTP is that after the 4-way handshake of a pair of communication nodes, the relay node should not compete for the channel again, which obviously would waste the valuable bandwidth, because the channel is already reserved by the original communication nodes. Our analysis and experiment show that the energy-efficiency of MHs can be significantly improved if a suitable relay node can be obtained.

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2 Energy-Efficiency Cut-Through Protocol (ECTP)

The system model of WLAN is considered as follows. Given K different modulation schemes, a WLAN can be logically segmented into K concentric circles surrounding AP. Thus, this network can be divided into K disjoint regions: the innermost circle (R_1) and a number of $K-1$ 'doughnut' like regions which are numbered as R_2, R_3, ..., R_K from inner to outer. The data rate that can be obtained in R_i is denoted as TR_i.

Given this model, the aim of ECTP is for nodes located at the outer region, e.g., R_K, to transmit packets at a higher rate. For this, ECTP introduces a suitable relay node between the sender and AP to segment the long distance between the communication ends into two shorter pieces. To this end, whenever a MH wants to communicate with another node, AP should find a suitable relay node, and guide the sender to deliver its data via this node. AP can uses, for example, broadcasting approach given in [5] to let all MHs know their locations and use the best modulation scheme. In addition, each MH can overhear packets transmitted in air, measure their signal to noise ratios (SNRs), estimate the distances and the modulation schemes to be adopted between itself and the transmitting nodes, and finally record these information in a so-called neighbor-list. AP can then obtain the information about the MHs in its transmission range, and collect these MHs' neighborhood information by means of the neighbor-list delivered with some kinds of periodical reports or routing information exchanges. With these, AP can decide the relay node for each MH without the requirement of exact knowledge about the directions of these MHs.

Figure 1 illustrates the ECTP time-line for transmission of data packets. In principle, this is the IEEE 802.11 fragmentation mechanism extended for the incorporation of relay nodes. However, instead of the direct implementation of IEEE 802.11 4-way handshake, we let the relay node, MH_j, forward DATA/FRAGs from the sender, MH_i, to AP without exchanges of RTS/CTS in advance. This can improve the network throughput because in the very beginning, MH_i and AP have reserved the channel using RTS/CTS transmitted at the base rate. Consequently, the relay node, MH_j, has no need to reserve the channel for MH_i and AP again, which obviously would waste bandwidth for the same transmission.

2.1 The Degraded Method: D-ECTP

In ECTP, it is possible that no relay node can be found or a given relay node is missed due to mobility or channel condition change. If happens, the sender can be changed to transmit multiple back-to-back frames to AP directly (as shown in Fig. 2). In these cases, ECTP reverts to a degraded version of this method, namely Degraded-ECTP, or D-ECTP. That is, a MH can send multiple back-to-back data frames directly from itself to AP by means of the IEEE 802.11 fragmentation standard, without the aid of a relay node.

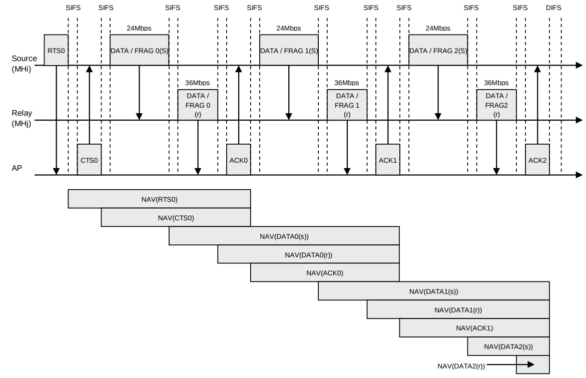

Figure 1: An example of the control message flow of ECTP

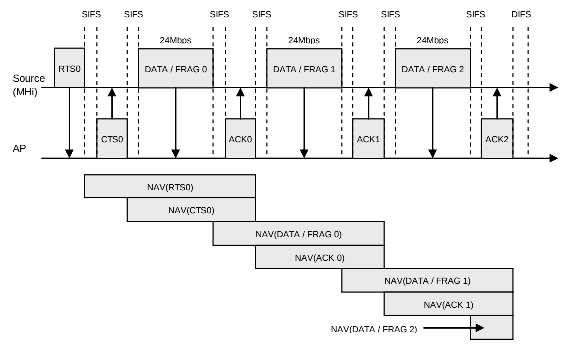

Figure 2: An example of the control message flow of D-ECTP.

3 Energy Consumption Components

For the energy-efficiency calculation, we consider the energy consumption components in the transmission process of ECTP first. Unlike the most of previous works concerning only that the power consumption is different for receiving mode and transmission mode due to different circuits used in different modes, we also consider the fact that the significant power may be consumed by other sources as well, such as the energy required by the card for computation and channel sensing. In order to investigate the overall power consumption, we classify these sources into two categories: the base power sink, and the incremental power sink. More precisely, let P_{base} be the power required for basic operations, which includes the power consumed by the circuits, converter, baseband processor, and MAC processing. The incremental parts due to transmitting, receiving and channel sensing (idle) are denoted by P_{tx}, P_{rec}, and P_{idle}, respectively. Consequently, the total power required for transmitting state, PTX, for receiving state, PRX, and for idle state, PI, are given respectively by

$$\begin{aligned} PTX &= P_{base} + P_{pa} = P_{base} + \frac{P_{tx}}{\zeta(P_{tx})} \\ PRX &= P_{base} + P_{rec} \\ PI &= P_{base} + P_{idle} \end{aligned} \quad (1)$$

where ζ denotes the power conversion efficiency.

4 Energy-Efficiency Model of ECTP

4.1 State Duration and Energy Consumption

Given the IEEE 802.11a MAC/PYH, and the energy consumption components, we now consider the total consumed energy with regard to how long a station stays in each state: transmitting, receiving, and idle, from the perspective of a tagged node. With a careful study on the transmission process (as shown in Fig. 3), we can obtain the probabilities and energy consumptions in the protocol. However, due to space limitations, the corresponding formulas for obtaining these values are summarized in the Appendix as reference.

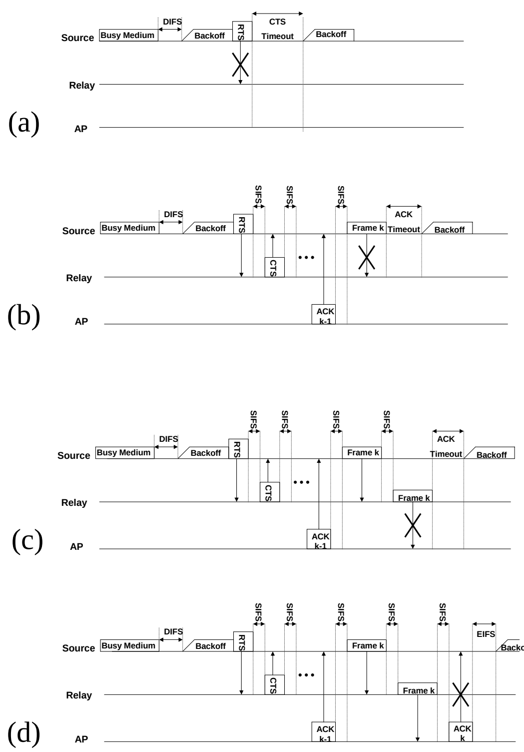

Figure 3: Timing of failed frame transmissions under ECTP: (a) RTS failure, (b) erroneous data frame reception by the relay node, (c) erroneous data frame reception by AP, and (d) ACK failure.

4.2 Transmission Probability under Imperfect Channel

We next consider the failure probability in ECTP under imperfect channels. In principle, ECTP adopts the same IEEE 802.11 RTS/CTS access method, which involves the 4-way handshake procedure of RTS/CTS/DATA/ACK. So, similar to IEEE 802.11 MAC, this probability can be obtained by considering the failures due to collision between stations and channel error. To be specific, let $P_{fail}^{(m)}$ denote the failure probability of a frame with the PHY mode m, which can be simply obtained by 1 minus the corresponding success probability, i.e., $1 - P_{succ}^{(m)}$. For the latter, because of the assumption that CTS frames can always be received correctly, the success probability of transmission therefore involves only RTS frames, data frames, and ACK frames. That is,

$$\begin{aligned} &P_{succ}^{(m)} = P_s^{(m)}(L_{rts}, L_{cts}, L_{data}, L_{ack}) \\ &= P_s^{(m)}(L_{rts}) \cdot P_s^{(m)}(L_{cts})(=1) \cdot P_s^{(m)}(L_{data}) \cdot P_s^{(m)}(L_{ack}) \\ &= P_s^{(m)}(L_{rts}) \cdot P_s^{(m)}(L_{data}) \cdot P_s^{(m)}(L_{ack}) \end{aligned} \quad (2)$$

In addition, assuming that only RTS frames can have collisions, thus only the success probability of RTS, $P_s^{(m)}(L_{rts})$, should be considered as the product of the two success probabilities, i.e.,

$$P_s^{(m)}(L_{rts}) = (1 - P_c^{(m)}(L_{rts})) \cdot (1 - P_{er}^{(m)}(L_{rts})) \quad (3)$$

where $P_c^{(m)}(L_{rts})$ denotes the probability of collision, and $P_{er}^{(m)}(L_{rts})$ denotes the frame error probability (FER) of a RTS frame. Apart from that, other frames are considered with only channel error. For these frames, since there are in total $2 \cdot G_R$ data frames transmitted by the sender and the relay node, while there are only G_R ACK frames delivered from AP in a time slot. Thus, the success probability of data transmission, $P_s^{(m)}(L_{data})$, and that of ACK transmission, $P_s^{(m)}(L_{ack})$, are given by

$$P_s^{(m)}(L_{data}) = (1 - P_{er}^{(m)}(L_{data}))^{2 \cdot G_R} \quad (4)$$

$$P_s^{(m)}(L_{ack}) = (1 - P_{er}^{(m)}(L_{ack}))^{G_R} \quad (5)$$

where $P_{er}^{(m)}(L_{data})$ denotes the error probability of data transmission, and $P_{er}^{(m)}(L_{ack})$ denotes that of ACK transmission. By combing Eqs. (2) to (5), $P_{succ}^{(m)}$ can be obtained, and thus, $P_{fail}^{(m)}$ can be given by

$$\begin{aligned} &P_{fail}^{(m)}(= 1 - P_{succ}^{(m)}) = 1 - \{\underbrace{(1 - (1 - (1 - \tau^{(m)})^{N-1}))}_{(1-P_c^{(m)})} \cdot \\ &(1-P_{er}^{(m)}(L_{rts})) \cdot (1-P_{er}^{(m)}(L_{data}))^{2 \cdot G_R} \cdot (1-P_{er}^{(m)}(L_{ack}))^{G_R}\} \end{aligned} \quad (6)$$

where the first item, $1 - (1 - \tau^{(m)})^{N-1}$, denotes the collision probability, $P_c^{(m)}(L_{rts})$, and $\tau^{(m)}$ denotes the transmission probability as shown below.

With this failure probability, $P_{fail}^{(m)}$, the initial contention window, CW, and the maximum backoff stage, s, as defined in IEEE 802.11a, we can obtain the transmission probability $\tau^{(m)}$ with PHY mode m for a tagged node by using the equation in [6] as

$$\tau^{(m)} = \frac{2}{1 + CW + P_{fail}^{(m)} \cdot CW \cdot \sum_{i=0}^{s-1}(2 \cdot P_{fail}^{(m)})^i} \quad (7)$$

Given the above, we can solve the nonlinear system resulting from Eqs. (6) and (7) to find the transmission probability, $\tau^{(m)}$.

4.3 State Probability and Energy-Efficiency Expression

We now derive the energy-efficiency for ECTP. With the probabilities and the energy consumptions given in the previous subsections, we can obtain the total energy consumed for a tagged station in a time slot as

$$E_{ECTP}^{slot} = E_{ECTP}^{tag} + E_{ECTP}^{other} + P^{idle} \cdot E^{idle} \quad (8)$$

where

$$E_{ECTP}^{tag} = P^{tag,succ} \cdot E^{tag,succ} + P_{rts}^{tag,fail} \cdot E_{rts}^{tag,fail}$$
$$\sum_{i=1}^{G_R} (\underbrace{P_{data,odd}^{tag,fail}(i) \cdot E_{data,odd}^{tag,fail}(i)}_{i \in odd} + \underbrace{P_{data,even}^{tag,fail}(i) \cdot E_{data,even}^{tag,fail}(i)}_{i \in even}) +$$
$$\sum_{i=1}^{G_R} P_{ack}^{tag,fail}(i) \cdot E_{ack}^{tag,fail}(i) + P_{others}^{tag,fail} \cdot E_{others}^{tag,fail}$$

and

$$E_{ECTP}^{other} = P^{other,succ} \cdot E^{other,succ} + P_{rts}^{other,fail} \cdot E_{rts}^{other,fail} +$$
$$\sum_{i=1}^{G_R} (\underbrace{P_{data,odd}^{other,fail}(i) \cdot E_{data,odd}^{other,fail}(i)}_{i \in odd} + \underbrace{P_{data,even}^{other,fail}(i) \cdot E_{data,even}^{other,fail}(i)}_{i \in even}) +$$
$$\sum_{i=1}^{G_R} P_{ack}^{other,fail}(i) \cdot E_{ack}^{other,fail}(i) + P_{others}^{other,fail} \cdot E_{others}^{other,fail}$$

In addition, by means of notations given in the Appendix, the total number of data bits that can be successfully transmitted in a time slot is given by

$$msg_{ECTP} = N \cdot (\sum_{i=1}^{G_R} (P_{data,odd}^{tag,fail}(i) + P_{data,even}^{tag,fail}(i) + P_{ack}^{tag,fail}(i)) \cdot (i-1) + P^{tag,succ} \cdot G_R) \cdot L_{data} \quad (9)$$

which includes the number of data bits correctly received before encountering a failure in a time slot. Given the above, the bandwidth share of a station can be obtained with

$$BW = \frac{1}{N} \cdot \frac{msg_{ECTP}}{T_{interval}} \quad (10)$$

Consequently, the energy-efficiency can be expressed as the transmitted data per unit energy as follow

$$\eta_{ECTP} = \frac{BW}{E_{ECTP}^{slot} / T_{interval}} = \frac{msg_{ECTP}}{N \cdot E_{ECTP}^{slot}} \quad (11)$$

4.4 Energy Efficiency of D-ECTP

With slight modifications of formulas given previously, the energy efficiency of D-ECTP (and even IEEE 802.11 MAC) can also be obtained. However, due to space limitations, these similar calculations are not shown here.

5 Experiment Results

In this section, we report on experiments made in order to understand the energy-efficiency performances of ECTP, D-ECTP and IEEE 802.11 MAC, based on the IEEE 802.11a PHY. To this end, each method is evaluated for its energy-efficiency value, η, in varying path loss condition. For a reasonable comparison, the relay node of ECTP is assumed to be located in the middle point between the sender and receiver. Other parameters for the experimental environment are introduced as follows. According to the IEEE 802.11 standard [7], the length of a MAC service data unit (MSDU) can be up to 2304 octets; and for the middle band of the 5 GHz, the maximum transmission power is limited to 200 mW (23 dBm). Accordingly, in this work we consider all MSDUs to be of 2000 bytes for each experiment, and consider the transmission power with values ranging from -19 to 23 dBm, further divided into 15 transmit levels with 3 dBm steps. The exponential E-P curve is adopted, with which the PA reaches the maximum energy-efficiency, ζ_{max}, when the transmission power is 23 dBm.

In this experiment, the best $mode$-$power$ pair, i.e., the best combination of PHY mode and transmission power level to achieve energy-efficient data transmission, is considered as the maximization problem so that the energy-efficiency value of τ can be obtained with the different methods.

Figure 4 shows the energy-efficiency performance in the environment where one node transmits data with the 2-ray ground reflection model shown in [8] and the low efficiency PA. The best energy-efficiency value, η_{IEEE}, η_{D-ECTP} and η_{ECTP}, under different path loss conditions are shown in Fig. 4(a). The best combinations of PHY mode and transmission power level, which achieve the most energy-efficient data transmissions, are shown in Figs. 4(b) and (c), respectively.

As shown in Fig. 4(a), under all path loss conditions, D-ECTP achieves higher energy-efficiency than the IEEE 802.11 MAC. Clearly, with the capability of transmitting multiple back-to-back data frames in a basic time slot, D-ECTP indeed reduces the communication overhead, and thus effectively increases the energy-efficiency when compared with IEEE 802.11 MAC. On the other hand, ECTP can obtain higher energy-efficiency than the other two methods when

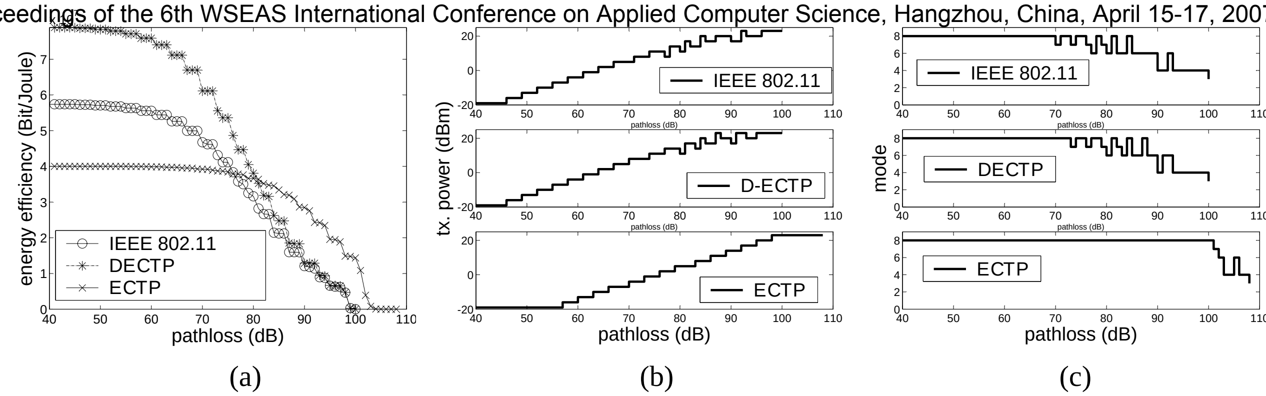

Figure 4: Fifteen power levels with low-efficiency PA: (a) energy-efficiency, (b) power level selection, and (c) PHY mode selection (top in (b) and (c) is IEEE 802.11 MAC, middle is D-ECTP, and bottom is ECTP).

the path loss condition is approximately higher than 80 dBm. However, due to the fact that, despite the effect of FEP, the average time required by ECTP to transmit a data frame is at least twice that required by D-ECTP for the same frame, the energy-efficiency of ECTP is actually close to $1/2$ that of D-ECTP when the path loss condition is low.

There are further observations from Fig. 4 to be illustrated. First, for all methods, the lower PHY modes are preferred when the path loss is high because these modes are more robust and have better error performance. On the other hand, the higher PHY modes are used to save energy when the path loss is low because in this condition, the duration of a single data transmission is shorter. Second, for each method, the selection of the best mode-power pair can fluctuate when the path loss is high, as shown in Figs. 4(b) and (c). In other words, with high path loss, the combination of a higher PHY mode with a higher transmission power may result in lower energy-efficiency than the combination of a lower PHY mode with a lower transmission power. With the same trend as in the other two methods, ECTP however begins its fluctuation with relatively higher path loss. In fact, due to the incorporation of relay nodes, ECTP can segment the long distance between the source and destination into two shorter pieces, and thus provide better SNR and FEP than the other methods. As a result, ECTP can tolerate the worst path loss condition.

6 Conclusion

So far in this paper we have introduced the Energy-Efficiency Cut-Through Protocol, and addressed the corresponding energy-efficient transmission problem in WLAN. The experiment results in above clearly confirmed the performance benefits of ECTP and D-ECTP by showing their energy-efficiency to be significantly higher than that of IEEE 802.11 MAC for each reasonable pathloss condition.

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Table 2: State Probabilities and Energy Consumptions of ECTP

State	Notation	Formula
(1) The tagged station transmits and succeeds	$E^{tag,succ}$	$PTX \cdot (T_{rts} + G_R \cdot T_{data}) + PRX \cdot (T_{cts} + G_R \cdot (T_{data} + T_{ack})) + PI \cdot ((3 \cdot G_R + 1) \cdot T_{sifs} + T_{difs})$
	$P^{tag,succ}$	$\tau \cdot (1-\tau)^{N-1} \cdot (1-P_{er,rts}) \cdot (1-P_{er,data})^{2 \cdot G_R} \cdot (1-P_{er,ack})^{G_R}$
(2) The tagged station transmits a RTS frame and fails	$E^{tag,fail}_{rts}$	$PTX \cdot T_{rts} + PI \cdot T_{ctstimeout}$
	$P^{tag,fail}_{rts}$	$\tau \cdot (1-\tau)^{N-1} \cdot P_{er,rts}$
(3) The tagged station transmits its ith data frame to its relay node and fails	$E^{tag,fail}_{data,odd}(i)$	$PTX \cdot (T_{rts} + i \cdot T_{data}) + PRX \cdot (T_{cts} + (i-1) \cdot (T_{data} + T_{ack})) + PI \cdot ((3 \cdot i - 1) \cdot T_{sifs} + T_{acktimeout})$
	$P^{tag,fail}_{data,odd}(i)$	$\tau \cdot (1-\tau)^{N-1} \cdot (1-P_{er,rts}) \cdot (1-P_{er,data})^{2 \cdot (i-1)} \cdot (1-P_{er,ack})^{i-1} \cdot P_{er,data}$
(4) The tagged station can not overhear its ith data frame from its relay node	$E^{tag,fail}_{data,even}(i)$	$PTX \cdot (T_{rts} + i \cdot T_{data}) + PRX \cdot (T_{cts} + i \cdot T_{data} + (i-1) \cdot T_{ack}) + PI \cdot (3 \cdot i \cdot T_{sifs} + T_{acktimeout})$
	$P^{tag,fail}_{data,even}(i)$	$\tau \cdot (1-\tau)^{N-1} \cdot (1-P_{er,rts}) \cdot (1-P_{er,data})^{2 \cdot i-1} \cdot (1-P_{er,ack})^{i-1} \cdot P_{er,data}$
(5) The tagged station can not correctly receive its ith ACK frame from AP	$E^{tag,fail}_{ack}(i)$	$PTX \cdot (T_{rts} + i \cdot T_{data}) + PRX \cdot (T_{cts} + i \cdot (T_{data} + T_{ack})) + PI \cdot ((3 \cdot i + 1) \cdot T_{sifs} + T_{eifs})$
	$P^{tag,fail}_{ack}(i)$	$\tau \cdot (1-\tau)^{N-1} \cdot (1-P_{er,rts}) \cdot (1-P_{er,data})^{2 \cdot i} \cdot (1-P_{er,ack})^{i-1} \cdot P_{er,ack}$
(6) The tagged station fails due to the other stations' competitions	$E^{tag,fail}_{others}$	$PTX \cdot T_{rts} + PI \cdot T_{ctstimeout}$
	$P^{tag,fail}_{others}$	$\tau - \tau \cdot (1-\tau)^{N-1}$
(7) No station transmits	E^{idle}	$PI \cdot T_{slot}$
	P^{idle}	$(1-\tau)^N$
(8) The tagged station does not transmit, but one of the other stations transmits and succeeds	$E^{other,succ}$	$PRX \cdot (T_{rts} + T_{cts} + G_R \cdot (2 \cdot T_{data} + T_{ack}) + PI \cdot ((3 \cdot G_R + 1) \cdot T_{sifs} + T_{difs})$
	$P^{other,succ}$	$(N-1) \cdot \tau \cdot (1-\tau)^{N-1} \cdot (1-P_{er,rts}) \cdot (1-P_{er,data})^{2 \cdot G_R} \cdot (1-P_{er,ack})^{G_R}$
(9) The tagged station does not transmit, but one of the other stations transmits a RTS frame and fails	$E^{other,fail}_{rts}$	$PRX \cdot T_{rts} + PI \cdot T_{ctstimeout}$
	$P^{other,fail}_{rts}$	$(N-1) \cdot \tau \cdot (1-\tau)^{N-1} \cdot P_{er,rts}$
(10) The tagged station does not transmit, but one of the other stations transmits its ith data frame to its relay node and fails	$E^{other,fail}_{data,odd}(i)$	$PRX \cdot (T_{rts} + T_{cts} + ((2 \cdot i - 1) \cdot T_{data} + (i-1) \cdot T_{ack}) + PI \cdot ((3 \cdot i - 1) \cdot T_{sifs} + T_{acktimeout})$
	$P^{other,fail}_{data,odd}(i)$	$(N-1) \cdot \tau \cdot (1-\tau)^{N-1} \cdot (1-P_{er,rts}) \cdot (1-P_{er,data})^{2 \cdot (i-1)} \cdot (1-P_{er,ack})^{i-1} \cdot P_{er,data}$
(11) The tagged station does not transmit, but one of the other stations can not overhear its ith data frame from its relay node	$E^{other,fail}_{data,even}(i)$	$PRX \cdot (T_{rts} + T_{cts} + 2 \cdot i \cdot T_{data} + (i-1) \cdot T_{ack}) + PI \cdot (3 \cdot i \cdot T_{sifs} + T_{acktimeout})$
	$P^{other,fail}_{data,even}(i)$	$(N-1) \cdot \tau \cdot (1-\tau)^{N-1} \cdot (1-P_{er,rts}) \cdot (1-P_{er,data})^{2 \cdot i-1} \cdot (1-P_{er,ack})^{i-1} \cdot P_{er,data}$
(12) The tagged station does not transmit, but one of the other stations can not correctly receive its ith ACK frame from AP	$E^{other,fail}_{ack}(i)$	$PRX \cdot (T_{rts} + T_{cts} + 2 \cdot i \cdot T_{data} + i \cdot T_{ack}) + PI \cdot ((3 \cdot i + 1) \cdot T_{sifs} + T_{eifs})$
	$P^{other,fail}_{ack}(i)$	$(N-1) \cdot \tau \cdot (1-\tau)^{N-1} \cdot (1-P_{er,rts}) \cdot (1-P_{er,data})^{2 \cdot i} \cdot (1-P_{er,ack})^{i-1} \cdot P_{er,ack}$
(13) The tagged station does not transmit, but one of the other stations fails due to other nodes' competitions	$E^{other,fail}_{others}$	$PRX \cdot T_{rts} + PI \cdot T_{ctstimeout}$
	$P^{other,fail}_{others}$	$(1-\tau) - P_{idle} - (N-1) \cdot \tau \cdot (1-\tau)^{N-1}$