Energy-Efficient Rate Adaptation for Outdoor Long Distance WiFi Links

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***Abstract*—WiLD (WiFi-based Long Distance) mesh networks have been broadly deployed for bringing extremely low-cost IT revolution to developing regions. However, external WiFi/non-WiFi interferences severely aggravate network performance. Besides, over-provisioning transmission power without considering the channel dynamics and interferences can result in unnecessary energy consumption, which will eventually lead to the network outage. In this paper, an energy efficient rate adaptation algorithm is proposed for WiLD links. It adopts an online measurement of FDR (Frame Delivery Ratio)-RSSI mapping to choose bit rate based on the joint considerations of RSSI and transmission power. Moreover, a novel algorithm called CNP-CUSUM (Continuous Non-Parameter-CUmulative Sum) is presented to detect changes of external interference intensity at receivers by leveraging beacon loss ratio statistics. Our simulation results show that it significantly outperforms fixed bit-rate, fixed transmission power schemes by achieving higher energy efficiency and considerable link throughput gain.**

***Index Terms*—Rate adaptation, Energy Efficiency, Long distance, Mesh networks**

1. Introduction

WiLD mesh networks have been deployed in many areas of the world with the aim of providing economically viable Internet access solutions for the population scattered across rural regions [1,2]. Despite its popularity, long-distance WiFi links are suffering from poor link performance because of 1) severe external interferences exposed by (non-)WiFi devices operating at the same/adjacent ISM band, and 2) time-variant link quality contributed by path loss, shadowing, multipath fading and directional antenna misalignment. In addition, energy saving is critical for the design and operation of these WiLD mesh networks due to their limited power supply.

Rate adaptation is an efficient method to improve the link throughput [3-12]. However, all of them are designed for WiFi networks with links less than hundreds of meters. Moreover, links spreading out from one node have to transmit/receive frames simultaneously to avoid the impact of the near-field effect caused by the high-gain directional antennas. Therefore, the one-to-one frame acknowledgment used in most existing rate adaptation algorithms would not work in WiLD networks. Finally, none of the current algorithms takes energy efficiency into considerations since they always have adequate power supply.

In this paper, we have designed an ERAA (Energy-efficient Rate Adaptation Algorithm) for the WiLD networks. We seek to achieve two objectives in the proposed solution. 1) Maximizing link throughput. Our ERAA needs to be robust to the time-variant link quality, and selects such a rate that makes full use of the current link capacity. 2) Minimizing energy consumption. ERAA must operate in an energy-efficient way to prolong the lifetime of WiLD networks.

ERAA achieves both objectives by integrating several innovative techniques. First, an efficient probing algorithm is proposed to obtain the FDR-RSSI envelope mapping for each bit rate. Second, an energy-efficient rate selection scheme is adopted, which leverages the path loss information by applying the channel reciprocity theory[1] [13]. It selects bit rate and transmission power according to the FDR-RSSI mapping to maximize the efficient link throughput but at a minimal energy consumption level. Third, we provide a CNP-CUSUM technique to detect the distortion of FDR-RSSI that arises from external interferences. Beacon loss ratio is used as an accurate indicator of the external interference. In addition to using long real world traces to verify the CNP-CUSUM, we have also implemented the proposed algorithms in QualNet 4.5 [14]. The results show that ERAA can improve link throughput efficiently with the minimal energy consumption. To the best of our knowledge, this is the first work that achieves energy-efficient rate adaptation for WiLD networks.

2. Related work

Prior adaptation algorithms can be classified into two categories, statistical based ones and PHY-metric based ones. The former uses either long-term or short-term statistics to select bit rate while the latter leverages PHY layer metrics such as RSSI to justify rate adaptation.

Statistical based algorithm. The first documented bit-rate selection algorithm, ARF [3], increases the transmission rate after ten consecutive successful frame transmissions and lowers rates when encountering two successive transmission failures. Its extensions, Adaptive ARF [4] and Fast-LA [5], try to reduce probing overhead by choosing adaptive success/failure threshold for rate increase/decrease. LD-ARF [6]

[1] If the role of the transmitter and receiver are instantaneously interchanged, the signal transfer function between them remains unchanged.

and CARA [7] seek to differentiate losses between wireless channel fading and frame collisions. Other statistical based algorithms, such as SampleRate [8] and RRAA [9], also require explicit feedback of transmission result of each frame. *They cannot work in WiLD networks, since long distance links usually adopt a TDMA-like MAC that divides time into TX (Transmission), RX (Reception) timeslots without one-to-one acknowledgment frames*.

PHY-metric based algorithm. RBAR [10] adopts RTS/CTS to obtain SNR (Signal-to-Noise Ratio) and selects data rates by looking up a pre-determined SNR-data rates table. SoftRate [11] uses confidence information calculated by the physical layer to estimate the prevailing channel BER (Bit Error Rate) and then to pick good bit rates. *Those PHY-metric based ones can not be applied to WiLD links, since, 1) RTS/CTS exchange does not conform to the slotted communication manner; 2) SoftRate requires PHY layer coding on software radios, which limits its prevalence on off-the-shelf 802.11 commodity hardware*.

In CHARM [12], the source station leverages channel reciprocity to obtain channel information and then lookups a pre-determined RSSI-Bit Rates table to select a bit rate. CHARM shares some elements with ERAA, but there are significant differences. ERAA deploys the CNP-CUSUM to process beacon loss ratio sequences, which can detect the variations of interference intensity in time. Moreover, ERAA selects not only bit rate but also transmission power to achieve energy efficiency. In contrast, CHARM takes the multi-rate retry feature of the Atheros hardware, which is infeasible at TDMA based WiLD links.

Besides, all above mentioned schemes have no concerns about energy efficiency, which remains a significant problem for rural mesh networks.

3. Network Model and Operations

We consider a static long distance wireless mesh network consisting of leaf (user) nodes and relay nodes laid out in an arbitrary manner in a rural area. Nodes in this network form a tree topology in which the root node is a typical router with wired Internet access and is usually placed in an urban area with many interfering WiFi sources. On the other hand, relay nodes as well as leaf nodes are commonly located in rural regions. Due to their locations, WiLD links can have lengths ranging from several to hundreds of kilometers. Over such distances, the wireless channels experience high channel dynamics due to uncontrolled RSSI fluctuations incurred by time-variant wireless channel fading and external interferences mainly other WiFi networks operating at the same/adjacent bands. Therefore, these links have high loss rates ranging from 2% to as high as 80%, which can be highly asymmetric [15]. Additionally, the duration of loss bursts also varied from a transient high burst to a long burst lasting over 25∼30 minutes.

In view of the inefficient CSMA/CA, we adopted a simple TDMA-like MAC that has the capability of offering bulk ACKs and PHY-metrics. In particular, we allow the timeslot length to be adaptive according to the traffic load of senders as well as the maximum allowed value (usually 20ms). A marker frame is adopted for link synchronization. The transmitting host ends its TX timeslot with a marker frame sending to the destination host as a notification of its status change (from TX to RX). After correct reception of a marker frame, the receiver begins its TX timeslot with a link layer ACK frame preceding data frames. The link layer ACK frame is intended to acknowledge all correctly received data packets at the last RX timeslot.

4. Rate Adaptation Algorithm for Outdoor Long Distance WiFi Links

4.1. Design overview

In this section, we present our ERAA in details. ERAA is designed for WiLD mesh networks with the intention of addressing the challenges below.

- **How to determine the link quality accurately and quickly?** It is a primary problem for rate adaptation, and even harder in WiLD networks. On the one hand, the link quality is highly fluctuated and therefore difficult to model. On the other hand, there is no one-to-one frame acknowledgment since the time is divided into TX and RX timeslot. In view of this, ERAA leverages FDR-RSSI probing to indicate the link quality, since the mapping keeps invariant in a period of time. The sender in its TX timeslot sends probing frames to obtain the FDR-RSSI mapping with an algorithm capable of reducing probing pairs. Additionally, ERAA makes use of receivers' feedback along with channel reciprocity to obtain path loss in both directions of a link and then predicts RSSIs in the upcoming TX timeslot, which enables us to obtain an estimation of the link quality in an accurate manner.
- **How to identify the variations of external interference?** External WiFi/non-WiFi sources working in the same/adjacent ISM band are the key interference degrading the performance of the long-distance mesh networks. We found beacon loss ratio has the ability of indicating the variations of the external interference. Therefore, beacon loss ratio sequences are applied to the CNP-CUSUM to identify intensity changes. If a change takes place, the FDR-RSSI probing will be triggered.
- **How to save energy without compromising the link throughput?** Over-provisioning transmission power may provide throughput gains at the cost of much unnecessary energy consumption while under-provisioning could lead to excessive frame retransmissions. Consequently, ERAA leverages an energy cost function to avoid over/under-provisioning without compromising of link throughput.

In general, ERAA consists of a probing and an adapting stage. The details of each component will be described in the following sections.

4.2. The Probing Stage

In the probing stage, the sender transmits a group of probing frames at different combinations of (bit rate, transmission power) to determine the FDR-RSSI mappings. FDR is the probability of the frame received successfully, and can be estimated as:

$$FDR = \frac{\text{\# of frames received successfully}}{\text{\# of frames sent}}.$$

RSSI is a good predictor of FDR when the multipath fading is negligible (This is the case in WiLD networks) [12]. The relationship of FDR and RSSI remains approximately invariant for a period of time. One technical difficulty is the high probing overhead. Taking the IEEE 802.11b protocol as an example, if there are 4 bit rates with each TX power adjustment ranging from 0dBm to 24dBm, a step size of 1dBm would require 100 combinations to be considered. Worse still, sending frames at lower bit rates significantly prolongs the transmission time especially for larger packets.

Theoretically, at a certain TX power, only one combination with the highest effective throughput is meaningful. The effective throughput is defined as

$$ET_{tr}(rssi) = FDR_{tr}(rssi) \times tr, \quad (1)$$

where tr is the bit rate adopted. $FDR_{tr}(rssi)$ and $ET_{tr}(rssi)$ denote the frame deliver ratio and the effective throughput at the bit rate tr and RSSI $rssi$. One obvious but important observation is that it is unnecessary to consider other combinations with lower bit rates (than the bit rate currently used) at the same TX power, because no higher effective throughput can result even if they have the highest FDR at 1 according to Eq. (1).

4.3. The Adaptation Stage

When the FDR-RSSI relationship is determined, the algorithm enters this stage to adapt its bit rates as well as transmission power to achieve energy efficiency based on a cost function which takes energy consumption ratio per bit into consideration.

4.3.1. Path loss calculation and RSSI prediction: Given a bit rate and transmission power, the rate adaptation algorithm needs to estimate the RSSIs of frames sent at that specified settings. RSSI can be predicted by estimating the path loss information at the forward direction (from the sender to the receiver), which is expressed as [15]:

$$RSSI = P_{tx} - PL + NF. \quad (2)$$

P_{tx} is the transmission power of the sender. PL is the forward-direction pass loss, and NF is the noise floor. Both of them can be obtained in practice, since NF is usually constant.

Path loss calculation According to the channel reciprocity theory, the forward-direction path loss is approximately the same of the backward-direction (from the receiver to the sender) path loss. The backward-direction path loss can be obtained from the information in the last timeslot (i.e. RX timeslot). That is to say, in RX timeslot, the RSSIs can be measured from the received frames. The TX power can be piggybacked in the frames. Therefore, we can estimate the backward-direction path loss using Eq.2 again.

RSSI prediction It is straightforward to predict the RSSI when the forward-direction pass loss is known, i.e. submitting the pass loss into Eq.2.

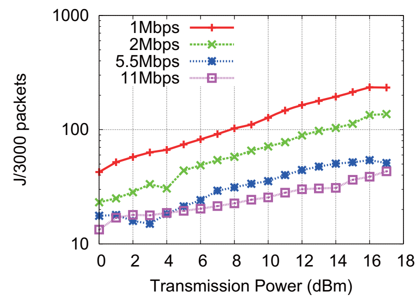

Fig. 1. Energy consumption for transmitting 3000 1000-byte frames at different TX power and PHY rates on the Atheros chips

4.3.2. Bit-rates selection: Energy consumption should be considered jointly with rate selection. According to FDR-RSSI mapping, when the FDR exceeds a certain threshold, a small improvement of FDR requires significant increase of RSSI. This comes at a very high price that much more energy consumption leads to little improvement of FDR. Furthermore, it could be aggravated in the presence of interferences, as high medium contention results in much more frame collisions. To avoid such circumstances, a cost function called ERB (Energy Ratio per Bit) is introduced representing energy consumed per bit at that $rssi$. Let tr be a PHY rate and tp be TX power. Then, we have:

$$\begin{aligned} ERB(rssi) &= \frac{EC(\Delta t)}{BS(\Delta t)} = \frac{\eta_{tr}(tp) \times tr \times \Delta t}{ET_{tr}(rssi) \times \Delta t} \\ &= \frac{\eta_{tr}(tp) \times tr \times \Delta t}{FDR_{tr}(rssi) \times tr \times \Delta t} \approx \frac{10^{k_{tr} \times (tp) + b_{tr}}}{FDR_{tr}(rssi)} \end{aligned} \quad (3)$$

where $EC(\Delta t)$ and $BC(\Delta t)$ are the total energy consumed and the total bits correctly received in time interval Δt respectively. $\eta_{tr}(tp)$ is the energy utilization factor for transmitting 1 bit at the PHY rate tr and at the TX power tp. It can be indeed regarded as a linear function in log scale, as shown in Fig. 1, denoted as:

$$Log(\eta_{tr}(tp)) = k_{tr} \times tp + b_{tr},$$

which yields Eq. (3).

The next step is to determine the valid range of Δ_{rssi}. Since the $rssi$ is predicted at TX power tp, and NIC chips support only a limited range of TX power levels (conforming to FCC regulations), the valid Δ_{rssi} ranges from $(tp_{min} - tp)$ to $(tp_{max} - tp)$, where tp_{min} and tp_{max} are the min/max TX power supported respectively.

The range of $rssi + \Delta_{rssi}$ is divided into several continuous subintervals that at each, the effective throughput (ET_{tr}), is always the highest one compared to any other tr', as follows:

$$RSSI_{tr} = \{rssi | ET_{tr}(rssi) > ET_{tr'}(rssi), \forall tr' \in R \backslash \{tr\}\},$$

where R is a set including all valid PHY rates. Each subinterval is continuous since $FDR_{tr}(rssi)$ is a monotonic function. Then, the sender tries to calculate each $ERB(rssi+\Delta_{rssi})$ with each discrete Δ_{rssi} decreasing from the maximum achievable value $(tp_{max} - tp)$ to the minimum value $(tp_{min} - tp)$ with corresponding tr that suffices $(rssi + \Delta_{rssi}) \in RSSI_{tr}$. Let $rssi^*$ denote the RSSI at which the minimum ERB is obtained,

$$rssi^* = \underset{rssi+\Delta_{rssi}}{\text{argmin}} \ (ERB).$$

Then, to achieve energy efficiency, the sender selects the bit rate tr satisfying $rssi^* \in RSSI_{tr}$ and the corresponding tp.

4.3.3. CNP-CUSUM to handle interferences: Another aspect influencing the algorithm performance is WiFi/non-WiFi interferences. The FDR-RSSI relationship could be severely distorted in the presence of high medium contention that a considerable raise of RSSI produces little FDR improvement. To overcome this issue, ERAA leverages beacon loss ratio of each external WiFi network observed by the receiver and monitors its abnormal changes meaning that the interference intensity has been dramatically altered. Thus, the sender is required to re-probe FDR-RSSI mapping as stated in Sec. 4.2.

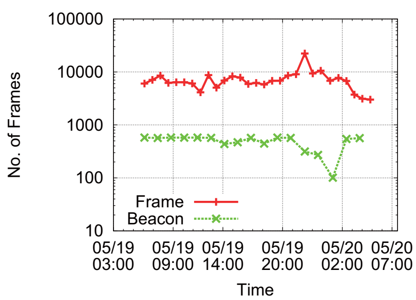

Fig. 2. Number of Frames (beacons) Per Minute Received by a 802.11 Router

The frame collision probability can be indirectly observed by monitoring beacon loss ratio. One may argue that channel fading also incurs fluctuations of beacon loss ratio. However, channel fading causes the ratio fluctuating up and down around its average, which in a statistical way does not show drifts beyond its average. On the other hand, frame collision incurred losses do express its drifting behavior since WiFi interference usually lasts tens of minutes [15] in view of people's behavior. Our outdoor experiments also show similar results. A mesh router is set to monitor mode to sniff all frames for nearly one day long on the top of our teaching building. We group frames as well as beacons from a specific AP every minute and plot the results in Fig. 2, which show that beacon loss ratio is almost 0% (received 585 out of 600 beacons per minute) with network traffic of 5000∼6000 frames/min while beacon losses is dramatically increased when it exceeds 10^4 frames/min from 22:00 to 0:00. Thus, a rise/decline of contention level will result in a higher/lower beacon loss ratio statistically.

A key challenge lies in abrupt change detection of beacon loss ratio. Fortunately, CUSUM [16] is an effective technique to detect the distribution change of observations as quickly as possible. As for this case, a bilateral CUSUM is qualified to identify upward/downward drifts.

Let $\{X_i | i = 0, 1, \cdots\}$ be a time sequence of beacon loss ratio. Since both wireless channel fading and interferences are random processes, we can consider $\{X_i\}$ being a stationary random process. Note that CUSUM algorithm has an assumption that the average value of the random sequence should be negative, and it becomes positive after change. Therefore, without losing any statistics properties, we transfer the sequence $\{X_i\}$ into another random sequence $\{\overline{X}_i\}$ with a negative mean. Let $\overline{X}_i = X_i - a$ and $E(X_i) = c$, then $E(\overline{X}_i) = c - a$. In a given network environment, the parameter a is a constant, used to produce a negative random sequence $\{\overline{X}_i\}$, so the entire negative value of $\{\overline{X}_i\}$ will not be cumulated along the time. When drifts of beacon loss ratio are taking place, $\{\overline{X}_i\}$ will suddenly become large positive. Let

$$Z_i = \begin{cases} max(0, Z_{i-1} + X_i - a) & i > 0 \\ 0 & i = 0, \end{cases} \tag{4}$$

it is straightforward that Z_i is the maximum continuous increment until time i. A large Z_i is a strong indication of the rising of interference intensity. For the case of an opposite drifting (less intensive interference), it is equivalent to detect the increasing of the sequence $\{-X_i\}$, thus we get,

$$D_i = \begin{cases} min(0, D_{i-1} + X_i - b) & i > 0 \\ 0 & i = 0, \end{cases} \tag{5}$$

where b is greater than 0 and satisfying $E(X_i) - b > 0$. We can determine the alarm time as follows,

$$\tau_1 = min\{i : i \geq 1, Z_i > h\} \tag{6}$$

$$\tau_2 = min\{i : i \geq 1, D_i < -h\}, \tag{7}$$

where h is the alarm threshold and it could be set to different values in Eq. (6) and Eq. (7). Thus, for a bilateral detection, the alarm time is $min\{\tau_1, \tau_2\}$. In order to achieve continuous detection of intensity change, after detecting the abnormal change, the algorithm needs to calculate a new a since the mean of beacon loss ratio is changed, and begins sampling with i reset to 0. In the presence of multiple APs, a receiver applies the proposed CNP-CUSUM to each AP with carefully selected h and a.

5. Performance Evaluation

To demonstrate the CNP-CUSUM's as well as ERAA's effectiveness we applied real trace data to the former and conduct extensive simulations for the latter. We measured its performance against fixed bit-rate, fixed transmission power schemes. The performance metrics concerned are link throughput and energy consumption ratio defined as the total energy consumed to the total number of frames successfully received in a given time interval. We normalize the ratio of our algorithm as 1.

5.1. Interference Intensity Change Detection

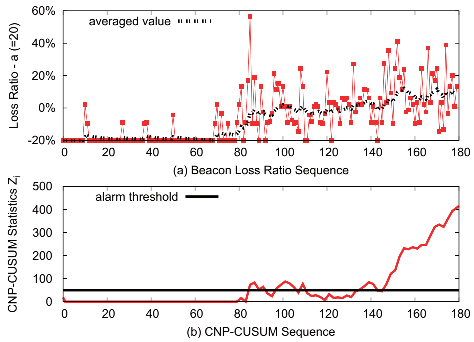

Fig. 3. (a) Beacon loss ratio sequence $\{\overline{X}_i\}$; (b) CNP-CUSUM sequence $\{Z_i\}$

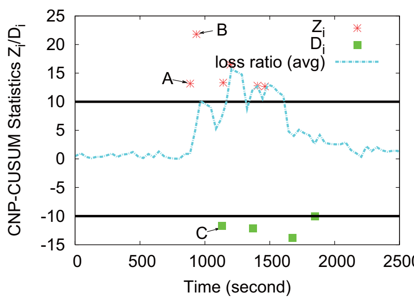

Fig. 4. Bilateral drifts detection of beacon loss ratio

5.1.1. Experimental settings: The CNP-CUSUM algorithm is applied to the real trace collected by a wireless node operating in monitor mode to sniff frames whole day long in our research lab with a sampling period of 1 second. Moreover, throughout the experiment analysis, a number of randomly selected pieces of trace data are applied to our CNP-CUSUM algorithm and the algorithm keeps its effectiveness on all pieces of trace data. Thus, due to limited space, we omit similar results obtained from other pieces of trace and pick one to present here.

5.1.2. CNP-CUSUM Performance: The beacon loss ratio sequence $\{\overline{X}_i\}$ and the test statistics $\{Z_i\}$ are plotted in Fig. 3(a) and Fig. 3(b) respectively. From the figures we observe that the loss ratio drifts by fluctuating rapidly after 80 samples. As shown in Fig. 3(b), the drift is detected when the CUSUM statistics exceeds the given threshold $h = 50$. It also demonstrates that our algorithm can identify the upward drifts in a timely manner.

The bilateral case is shown in Fig. 4. The straight line at y-axis 10 and -10 are thresholds for $\{Z_i\}$ and $\{D_i\}$ respectively. The curve line represents the averaged beacon loss ratio sampled during 2500 seconds, and it drifts upward at approximately 800, which is alarmed at asterisk "A". However, the drift does not stop increasing and begins climbing up at 920, which is detected at point 930, denoted as "B". In addition, downward drifts are also alarmed. Point "C" at 1090 alarms the decreasing of beacon loss ratio started at 1050.

5.2. Rate Adaptation Performance

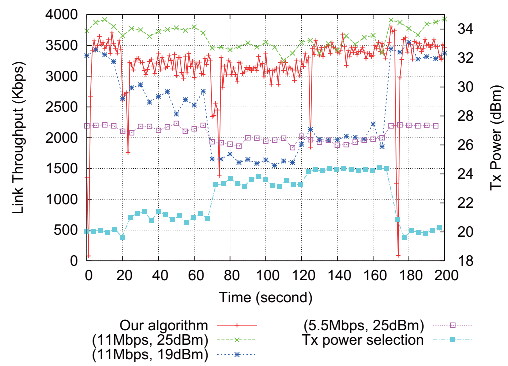

Fig. 5. Link performance: ERAA versus. Fixed schemes

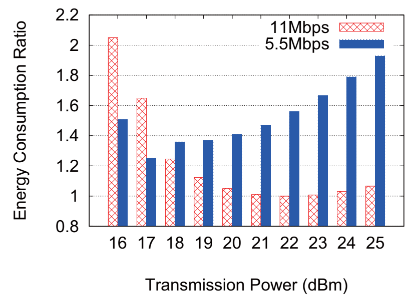

Fig. 6. Energy consumption ratio

TABLE I: Probing pairs for interference changes

	w/o Interference	**CBR 1**	**CBR 1, 2**	**CBR 2**
11Mbps:	14∼25dBm	14∼25dBm	16∼25dBm	16∼25dBm
5.5Mbps:	9∼15dBm	7∼16dBm	10∼18dBm	9∼18dBm
2Mbps:	8, 11dBm	12dBm	16dBm	16dBm
1Mbps:	1∼9dBm	N/A	N/A	N/A
Total:	30 pairs	21 pairs	20 pairs	21 pairs

5.2.1. Simulation settings: In this scenario, a point-to-point 25km-long 802.11b WiFi link is set up operating on the aforementioned TDMA MAC with the maximum allowed timeslot of 20ms. Both nodes equip with directional antennas of 24dBi gain on its main beam direction and have an adjustable transmission power ranging from 1dBm to 25dBm. The receiver is surrounded by two BSS networks with one AP for each. Every BSS network has several clients associated with the corresponding AP. This scenario represents a typical WiLD link with time-variant interference at the receiver side. In addition, the two-ray model and the Rician model with parameter K set to 3.8dB are used for path loss model and fading model respectively, whereas the shadowing model is constant with a mean of 4dB. There are three CBR flows of packet size 1000 bytes in the scenario. One is for the point-to-point link with packet interval 1.5ms spanning the whole simulation time (0s∼200s). The second is from a client station to another node in the same BSS network with a 5ms packet interval. It begins at 20s and terminates at 120s. At 70s, the last CBR traffic is injected into another BSS network with a 2ms interval and lasts 100s. We have run 50 simulations with different seeds and obtained similar results, but only describe one due to the lack of space.

5.2.2. Simulation results and analysis: The red line in Fig. 5 is the link throughput of the proposed algorithm. The sender sets its initial TX rate, TX power to 11Mbps and 19dBm separately after the FDR-RSSI probing to achieve maximum energy efficiency without link performance degradation, which takes less than 2s for completion. When the first interfering traffic starts at 20s, the sender re-probes the FDR-RSSI mapping on receiving the notification of the interference intensity change detected by the receiver and then chooses a higher TX power (21dBm on the average). This is in sharp contrast with the fixed scheme (11Mbps, 19dBm) that exhibits significant throughput degradation, approximately 650Kbps drop, when encountering the first interfering traffic. This situation is further exacerbated when another interfering traffic is injected into the network, which leads to the drop of link throughput to about 1650Kbps. In contrast, ERAA roughly maintains its performance by raising its TX power to about 23dBm∼24dBm.

The deep throughput drop on the red line stands for the FDR-RSSI re-probing, since re-probing requires transmitting packets at lower bit rates. However, the probing overhead is considerably reduced according to the discussion in Sec. 4.2, as is shown in Table I. Moreover, it can be seen that the stronger the interference intensity is, the further the probing overhead is reduced, since lower bit rates prolong the transmission time which incurs a higher probability of frame error.

On the other hand, sending frames at the maximum TX power (25dBm) outperforms ERAA slightly but leads to much lower energy efficiency, which is depicted in Fig. 6. All fixed (TX rate, TX power) schemes have a higher energy consumption ratio except the one (11Mbps, 22dBm), which achieves the lowest ratio at 0.99956 among those schemes. However, the above one is only optimal for this simulation scenario since WiLD links with different length, channel characteristics as well as interference intensity result in the diversity of optimal parameter settings. On the contrary, our algorithm is self-adaptive and can maintain high energy efficiency in different interfering environments. From the simulation results, we found that our algorithm adopted 11Mbps for majority of time (285790 out of 286528 frames) and 5.5Mbps for the remaining 738 frames, because for most of time, raising TX power is sufficient to offer higher energy efficiency, which could avoid stepping down bit rates. Besides, Fig. 6 shows that reducing TX power at 11Mbps before 22dBm will improve the energy efficiency but degrade it after 22dBm, since insufficient TX power incurs severe frame losses.

6. Conclusion

We have proposed a rate adaptation algorithm based on FDR-RSSI mapping, path loss calculation, predictions of RSSIs as well as TX power adjustments to choose bit rates in order to achieve energy efficiency and to maintain effective throughput maximization. The RX node monitors the beacon loss ratio of each external AP in its frame reception range and notifies the TX node the result whether the interference intensity at the receiver has changed beyond a threshold by exploiting the CNP-CUSUM. Accordingly, the TX node could rebuild the FDR-RSSI relationship. Simulations showed that our algorithm achieves high energy efficiency while still retaining considerable throughput gain by jointly selecting TX rates and TX power.

Acknowledgment

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