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Nulls in the Air: Passive and Low-Complexity QoS Estimation Method for a Large-Scale Wi-Fi Network Based on Null Function Data Frames

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ABSTRACT In this paper, we propose, implement, and evaluate a simple yet powerful estimation method for the quality of service of a large-scale Wi-Fi network, which is achieved using our passive and low-complexity measurements. Specifically, our proposed method estimates a time-varying frame error rate at an access point (AP) by counting null function data frames, which are emitted periodically by stationary user equipments (UEs), such as mobile phones and tablets. We implemented our method as a user-level script and a production-level firmware. Our real-world measurements in an uncontrolled 1500-seat hall demonstrated that our method exhibited high scalability against the increase in the numbers of APs and UEs with the aid of its simple structure and was capable of detecting the quality-of-service loss induced by an unexpected dynamic frequency selection.

INDEX TERMS IEEE 802.11, Wi-Fi, passive estimation, quality of service (QoS), frame error rate (FER), large-scale network.

I. INTRODUCTION

Wireless devices such as mobile phones and tablets have become indispensable for daily life. Their widespread and intensive use has given rise to the severe spectrum shortage crisis [1], [2]. Due to its rapid growth, the number of Wi-Fi access points (APs) has increased year-by-year. In fact, APs are even available in high-speed trains and airplanes. As the AP density increases, within the limited spectrum, the radio interference at the industry science medical (ISM) band has also become worse. Consequently, in the IEEE 802.11ac specifications, only the 5 [GHz] band is exploited, and multi-antenna-aided beamforming (BF) mitigates inter-user interference (IUI) [3]–[5]. Furthermore, IEEE 802.11ad/ay rely on the millimeter-wave frequency band and mitigate IUI by invoking a narrow line-of-sight (LoS) beam [6], [7].

The achievable performance of an indoor wireless network is determined by multiple-access IUIs, rather than the path loss, thermal noise, and radio phase fluctuation [8]. Although the most effective option for mitigating IUI is a narrow BF, this is achieved only by numerous antenna elements [9] that are spaced with at least half wavelength, which leads to adoption of a power-thirsty and high-cost wireless module. It is impractical to implement such a narrow BF system for a consumer AP due to its strict size, power, and cost limitations.

The radio interference is difficult to measure because of its high frequency. A spectrum analyzer can measure the magnitude of input radio signals in the frequency domain. However, Wi-Fi, as well as other Bluetooth and radar equipment, are allocated in the same 2.4 and 5 [GHz] bands. It is difficult to identify the desired Wi-Fi signals. In the physical layer, radio propagation coefficients between the transmitter and the receiver, which are also known as channel state information (CSI) [10], [11], are estimated periodically with an extremely low error rate. This CSI directly indicates the reliability of a radio path between an AP and a user equipment (UE) at allocated frequency subcarriers. However, in realistic multiple-access scenarios, the CSI is unable to grasp the user-level quality-of-service (QoS) because IUIs have dominant effects.

In the IEEE 802.11e specifications, a sophisticated QoS-based channel access technique is adopted, which was

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firstly proposed by Benveniste [12] in 2002 and was termed as enhanced distributed channel access (EDCA). This technique assigns four priority classes to different applications, such as video streaming and web browsing. It reduces communication delay considerably [12]. This approach is especially effective for high-priority communications under severe IUIs. However, based on this priority information, it is evident that third parties are unable to grasp the QoS of a specific Wi-Fi network.

Against this background, the major contributions of this paper are summarized as follows:

1) We propose a simple yet powerful QoS estimation method for a large-scale Wi-Fi network, which is capable of grasping the effects of severe IUIs. Here, we count null function data frames (NFDFs) periodically emitted from UEs and calculate its retransmission ratio. Because this simple and device-free method functions in a passive manner, its computational complexity is much lower than those of conventional methods.
2) We implement our method as a user-level script and a production-level firmware, which work respectively on a notebook and an AP. With the aid of its simple structure, it can be implemented with reduced human resources and time. Furthermore, since its process complexity is nearly negligible, the proposed method does not interrupt the strict product requirements in terms of performance and energy consumption.
3) We evaluate our proposed method in controlled and uncontrolled environments, rather than computer simulations, and consider the IEEE 802.11a and 11ac specifications. Particularly, we investigate the correlation between the proposed NFDF retry ratio and FER, where the IUIs are perfectly controlled. Then, we investigate the correlation at a large-scale conference at which 1559 devices were connected and 4.8 billion frames were observed in three days.
4) We demonstrate that the NFDF retry ratio is capable of detecting the QoS loss induced by dynamic frequency selection (DFS) at a large-scale conference. It is important to estimate FER based on NFDFs because it represents the link reliability of a wireless channel. According to this time-varying metric, an operator can ascertain the current network status.

The remainder of this paper is organized as follows. Section II presents a review of invaluable related studies. Section III proposes our NFDF-based QoS estimation method. Section IV describes investigation of its performance in a controlled environment, whereas Section V considers an uncontrolled environment. Section VI presents conclusions obtained from this study.

II. RELATED WORK

Since the direct spectrum measurement is a difficult task, researchers have focused on collecting 802.11 frames in a passive manner and have proposed QoS estimation methods. The salient advantages of the passive approach, which have been pointed out by the conventional valuable studies [13]–[22], are organized as shown below:

- Passive monitoring is not intrusive [16], whereas the active measurement method [23], [24] periodically transmits probe packets. Because the current Wi-Fi system relies on half-duplex communications, the additional probe packets interfere with the other ordinary packets. Consequently, the QoS estimated by the active approach might include the effects of increased interference, which might not be accurate.
- Passive monitoring is a third-party solution [19], [21]. It requires no UE modifications and imposes no additional overhead on UEs. By relying on this approach, anyone can investigate the QoS of an 802.11 network. By virtue of this advantage, the passive method works efficiently in a chaotic uncontrolled environment.
- Passive monitoring exhibits high scalability against the increase in APs and UEs. For example, Mahajan *et al.* [16] evaluated their method in the SIGCOMM 2004 conference, where five APs served 550 attendees. Cheng *et al.* [17] deployed 150 radio monitors and collected 1.5 billion events. The passive method works efficiently in a large-scale network.

Against the salient benefits described above, the passive approach has three fundamental limitations [16]. Firstly, it cannot obtain lost frames, that are failed to be decoded at a monitor, although the radio signal itself might reach. Secondly, it cannot estimate whether the frames were received by their destination. Thirdly, it cannot access the internal state of a UE. Despite these limitations, the conventional studies [13]–[22] have achieved promising results. To summarize the relevant literature, Fig. 1 presents milestones of passive QoS estimation methods. In the following, we review four representative studies.

A. BEACON-BASED AP SELECTION [14]

Vasudevan *et al.* [14] addressed the optimum AP selection problem that offers the best QoS, since the widely used AP selection method relying on the receive signal strength indicator (RSSI) is typically trapped into a sub-optimum solution. Here, the authors defined a pioneering metric called *potential bandwidth* and identified that this metric is dependent on the delayed beacon arrival time. The experimental results in an ideal environment suggested that the proposed method was capable of estimating the available bandwidth.

As described in [14], the beacon-based method was evaluated in a noise-free environment. Additionally, the beacon frames were transmitted with the same probability as the data frames. The major drawback of [14] is the optimistic assumption where the beacon interval is assumed to be perfectly known at a monitor. Thus, using this beacon-based method is a challenging task in an uncontrolled environment.

B. CONTROL-FRAME-BASED THROUGHPUT ESTIMATION [15]

Dong and Varaiya [15] proposed a sophisticated estimation method for the saturation throughput of an IEEE

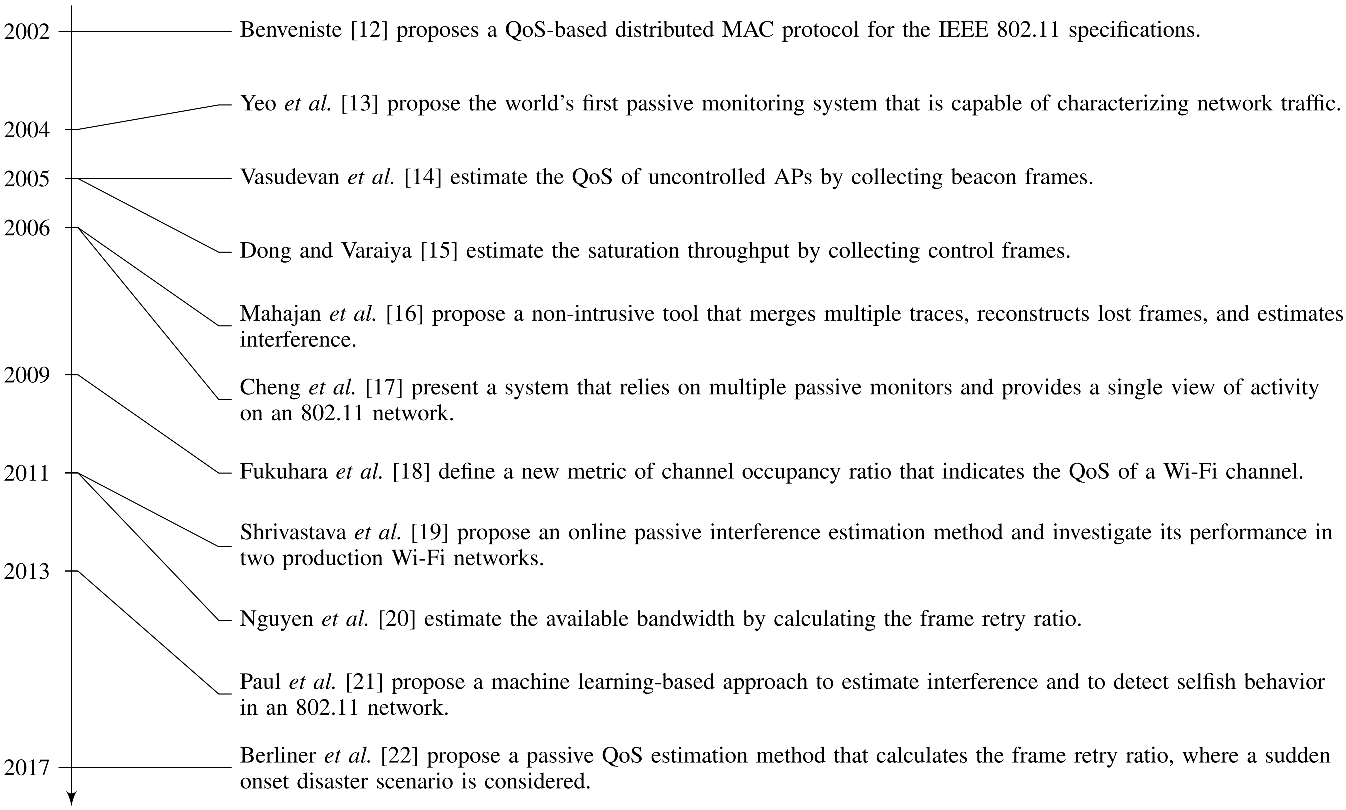

FIGURE 1. **Timeline of passive QoS estimation methods designed for the IEEE 802.11 specifications.**

802.11 network based on a *virtual slot* concept. The virtual slot is the unit of channel activity. It comprises seven types of slots such as the physical slot time δ and $\delta +$ propagation delay. The transition between the virtual slots was modeled by a two-dimensional Markov chain model, where a lossy channel condition was assumed. It was demonstrated that the proposed method estimated the simulated saturation throughput perfectly.

In practice, the RTS/CTS frames, which are the control frames intended to avoid collisions, are not observed in a typical Wi-Fi network [25]. This function mitigates the well-known hidden terminal problem, but it does induce an additional overhead. Thus, most of network operators disable this function. Furthermore, this method has not been investigated in the real world.

C. CHANNEL-OCCUPANCY-BASED THROUGHPUT ESTIMATION [18]

Fukuhara *et al.* [18] proposed a sophisticated passive estimation method for the time occupancy ratio of a specific Wi-Fi channel, which is defined as "channel occupancy ratio (COR)." Specifically, an independent analyzer, which supports the proposed method, collects the inter-frame space, the average of random backoff, the data packet duration, and the ACK packet duration for all the received packets. Then, it calculates the actual occupied time ratio within a collecting time window. Additionally, this method records all the sequence numbers and takes lost packets into account. The authors developed a real-world prototype and demonstrated that the estimated COR was almost identical to the theoretical time occupancy ratio. Furthermore, the calculated COR was shown to correlate with the UDP throughput.

The major drawback of this COR-based method is its high-complexity calculation at the analyzer. The analyzer has to calculate the inter-frame space and the average of random backoff for all the UEs that are dependent on the vendor implementation. This estimation is a challenging task in uncontrolled scenarios, which is also pointed out in [16]. In realistic scenarios, a large number of unknown UEs are trying to connect with an uncontrolled AP, where it is difficult to estimate the UE's internal state.

D. RETRY-RATIO-BASED THROUGHPUT ESTIMATION [20], [22]

Nguyen *et al.* [20] proposed a novel estimation method for the available bandwidth of an IEEE 802.11 based multi-hop wireless network. The authors first considered the use of retransmitted frames, instead of the collision probability [26], because the frame retry is caused mainly by collisions. Similar to other passive estimation methods [14], [15], [18], this proposed scheme imposes no complexity on the UE. Moreover, it avoids additional interference. The computer simulation results obtained using ns-2[1] showed that the estimated throughput was close to the ground truth, where the corresponding mean error ratio was 17%.

Berliner *et al.* [22] implemented this method on Raspberry Pi. Then, the authors investigated the relation between the frame retry ratio and other metrics such as one-way delay, throughput, and jitter. The performance results demonstrated the frame retry ratio as a promising metric for assessing network activity. The performance evaluation in [22] was conducted in a vast park because the authors needed to control IUIs. Different from [22], we specifically examine uncontrolled scenarios where severe IUIs have a dominant effect, as explained in Section V.

III. PROPOSED NFDF-BASED QoS ESTIMATION METHOD

In this section, we propose an NFDF-based QoS estimation method incorporating a different approach from those of earlier studies reviewed in Section II.

A. NFDF POWER-SAVING MECHANISM

Since the UE battery is a limited resource, IEEE 802.11 is designed to minimize the power consumption of a wireless module [27]. One of the power saving mechanisms [28] is the buffer-based data transmission [29, p. 1599], which is controlled by the power management subfield (PMS). Fig. 2 shows the format of the frame control field, which is the first 16 bits of the general 802.11 frame. All IEEE 802.11 frames contain the PMS bit, which is located in B12 of Fig. 2. The PMS bit of 1 implies that the associated UE is in the power-saving mode. Accordingly, the PMS bit of 0 implies that the UE is in the continuous active mode. This mode is changed automatically based on the current throughput. Its transition must be notified to the corresponding AP [29]. For example, a UE is switched into the power-saving mode if the current throughput is less than 500 [kbps] [28]. When the AP receives the PMS bit of 1 from a UE, the AP stores data frames that will be transmitted to the UE. Then, after receiving the PMS bit of 0, the AP starts to send the stored frames. This mechanism enables the UE to receive the data frames continuously, which mitigates the power consumption of the physical layer.

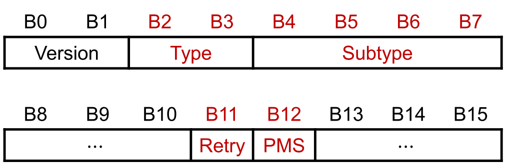

FIGURE 2. The format of the IEEE 802.11 frame control field, which was illustrated based on [29, p. 638].

If the AP fails to receive the PMS bit of 1 from a UE, then the UE must receive data frames at random intervals unintentionally. Moreover, its power consumption increases. Thus, when the UE switches to the power-saving mode, it tries to send a fixed-length frame without data multiple times until the AP successfully receives it. This fixed-length frame is known as 'null' or 'no data' frame. For descriptions in this paper, we refer to this frame as NFDF. The NFDF has type and subtype values of [B3 B2 B7 B6 B5 B4] $=$ $[1\ 0\ 0\ 1\ 0\ 0]_2 = (36)_{10}$ or $[101100]_2 = (44)_{10}$,[2] which are designated respectively as "Null (no data)" and "QoS Null (no data)" in [29, p. 640]. Thus, the NFDF can be extracted based on the B2–B7 bits of Fig. 2. The transmission frequency of NFDF is not defined in the IEEE 802.11 specifications. It is also dependent on the vendor's specific implementation [30].

B. NFDF APPLICATIONS

In 2004, Chandra *et al.* [31] proposed MultiNet, which facilitates simultaneous connections to multiple APs by a single wireless card. By sending an NFDF to a connected AP, it stops data transmissions to a UE. During the stopped period, the UE communicates with another AP, which enables dual simultaneous connections. Based on MultiNet [31], Giustiniano *et al.* [36] proposed WiSwitcher, which can switch multiple APs efficiently by sending NFDFs. Furthermore, Kim *et al.* [32] proposed a spectrum-sharing scheme for both Wi-Fi and WiMAX. Here, a UE observes NFDFs continuously and identifies an AP that will temporarily stop its data transmissions. When the AP stopped its transmission, the UE communicates with a WiMAX base station at the same frequency band. To the best of our knowledge, the NFDF has been utilized to control communications and has not been used to estimate communication quality.[3]

C. PROPOSED SIMPLE ESTIMATION METHOD

For all the received 802.11 frames, the proposed method first reads the frame control field, which includes the 2-bit type (B2–B3), 4-bit subtype (B4–B7), and 1-bit retry (B11) fields, as shown in Fig. 2. Here, B* denotes the bit index. The same notation is used in the IEEE 802.11 specifications [29]. In our method, only the NFDFs are extracted based on their type and subtype fields. Then, within a finite time window, such as 30 [sec], the total number of NFDFs N_t is counted, and the number of retried NFDFs N_r, that have the retry flag of 1, is counted. Finally, the NFDF retry ratio is calculated by N_r/N_t. Here, this calculation is carried out for a specific channel, rather than for a specific UE. Thus, the QoS of each Wi-Fi channel is estimated, and the QoSs of all the UEs on the same channel are averaged.

Fig. 3 shows a specific example for the calculation of NFDF retry ratio. Here, the number of NFDFs is $N_t = 10$ and the number of retried NFDFs is $N_r = 4$. Thus, the NFDF retry ratio is calculated by $N_r/N_t = 4/10 = 40\%$.

The proposed estimation method achieves lower complexity than that of conventional methods. Specifically, the beacon-based method of [14] requires four equa-

[1] https://www.isi.edu/nsnam/ns/

[2] Here, $[\cdot]_2$ denotes a binary number, while $(\cdot)_{10}$ denotes a decimal number.

[3] In [33], that is written in Japanese, Koshimizu and Kamioka first exploited NFDF. However, the authors specifically examined control of UE and considered the single-user and outdoor environment.

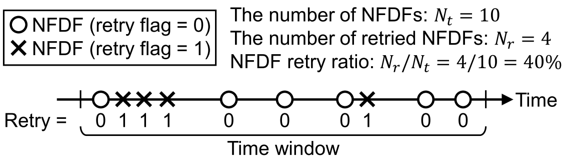

FIGURE 3. **Example of the NFDF retry ratio calculation.**

tions for calculating the potential bandwidth, while the control-frame-based method of [15] requires 18 equations for calculating the saturation throughput. The COR-based method of [18] requires only three equations, which is the simplest among the conventional methods. Additionally, the retransmission-ratio-based method of [20] requires 14 equations for calculating the available bandwidth. Different from these sophisticated methods [14], [15], [18], [20], the proposed method requires one equation for calculating the NFDF retry ratio, where only two variables N_r and N_t are used. This simple structure enables a low-cost implementation, as detailed in the following subsection.

D. IMPLEMENTATION

Since our proposed estimation method is passive, low-complexity, and device-free, it can be implemented as a user-level script or can be embedded in a production-level AP.

1) USER-LEVEL SCRIPT

We used the terminal-based wireshark,[4] which is known as `tshark` command, in order to calculate the NFDF retry ratio. Wireshark is an open-source network traffic analyzer and is released under the GNU general public license. The NFDFs are extracted based on their subtypes, i.e.,

$$\text{wlan.fc.type\_subtype} == (36)_{10} \;||$$
$$\text{wlan.fc.type\_subtype} == (44)_{10}.$$

Then, within a specific time window, such as [0, 30) [sec], [30, 60) [sec], or [60, 90) [sec], the script reads the retry field, which is represented as wlan.fc.retry, and calculates the NFDF retry ratios. Here, the wireshark's variable wlan.fc.type_subtype denotes the concatenated type and subtype fields of Fig. 2, i.e., $[\text{B3 B2 B7 B6 B5 B4}]_2$. Additionally, wlan.fc.retry denotes the retry flag of Fig. 2, i.e., $[\text{B11}]_2$.

Let us check a specific environment in which the user-level script runs successfully. Here, the `tshark` command is used at an AP. The corresponding command-line options are specified as

```
tshark –i wlan1 –y IEEE802_11_RADIO
  –T fields –E separator=, –E quote=n
  –Y "wlan.fc.type_subtype == 36 ||
   wlan.fc.type_subtype == 44"
  –e frame.time_epoch
  –e wlan.fc.retry > output.csv
```

[4]https://www.wireshark.org/

This command enables the AP to collect IEEE 802.11 frames. These `tshark` options are heavily dependent on the platform, network adapter, and network driver. In our environment, we used FreeBSD on a laptop equipped with a Wi-Fi dongle (Buffalo WLI-UC-G300HP). The corresponding Wi-Fi driver was the open-source `run` for the Ralink Technology wireless chipsets, which supports the 5 [GHz] IEEE 802.11a specifications, the host AP function and the power save mode.

FIGURE 4. **APs that support our proposed method.**

2) PRODUCTION-LEVEL FIRMWARE

We used an Internet Initiative Japan's AP product, which has a code name of SA-W2, and modified its firmware to support the proposed NFDF-based method. Fig. 4 shows APs that have our modified firmware. For all received 802.11 frames, the modified AP extracts the NFDFs by the following filter.

$$[\text{B3 B2 B7 B6 B5 B4}]_2 == [1\ 0\ 0\ 1\ 0\ 0]_2 \;||$$
$$[\text{B3 B2 B7 B6 B5 B4}]_2 == [1\ 0\ 1\ 1\ 0\ 0]_2.$$

Then, based on the retry flag (B11), the AP calculates the NFDF retry ratio within a specific time window.

We introduce details of the background of our implementation. Our AP is equipped with both Atheros AR9287 and QCA9880 chipsets, which respectively support the 2.4 and 5 [GHz] bands. Additionally, this AP supports the power over Ethernet function, which enabled flexible installation. In general, a typical network interface defines integer kernel parameters such as `net.inet.ip.ttl` and `net.inet.ip.ifq.drops`. Here, we added four kernel parameters to support the NFDF-based QoS estimation method. Specifically, the following extended parameters store N_t and N_r for the "Null" frames.

```
net.link.ieee80211.wlan0.
         cnt_recv_subtype_nodata
net.link.ieee80211.wlan0.
         cnt_recv_subtype_nodata_r
```

Similarly, the following two parameters are used for the "QoS Null" frames.

```
net.link.ieee80211.wlan0.
            cnt_recv_subtype_qosnull
net.link.ieee80211.wlan0.
            cnt_recv_subtype_qosnull_r
```

Here, the suffix `_r` implies that it records the number of retried frames. The above parameters are increased based on the retry flag of the extracted frames and are obtained using the `sysctl` command. It is noteworthy that this extension requires no modifications of a Wi-Fi driver. This counting function successfully works for both AP and monitor modes. In our implementation, the extended parameters were transmitted periodically to a data-collecting server.

IV. PERFORMANCE EVALUATION IN A CONTROLLED ENVIRONMENT

We evaluated our proposed method in a controlled environment, where a simple multi-user scenario and the CDMA2000 HTTP model [34] were assumed. We increased the network interference step-by-step and investigated the correlation coefficient between the proposed NFDF retry ratio and FER. The relation between RSSI and FER was shown for reference. Furthermore, we compared the NFDF method with the conventional IEEE 802.11e enhanced distributed channel access (EDCA) [12] and with the channel occupancy ratio (COR) [18].

A. MEASUREMENT ENVIRONMENT

We conducted our measurement in an interference-free room, where a spectrum analyzer indicated that interference to the 40ch (5.20 [GHz]) of IEEE 802.11a was below the noise floor. We used three UEs that were affiliated with a FreeBSD-based AP. Here, this AP has an open-source Wi-Fi driver. It enables us to collect IEEE 802.11 frames without switching to the monitor mode. The three UEs were installed 3 [m] distant from the AP. Thus, the RSSI at the AP remained constant. Two out of the three UEs exchanged UDP traffic by iPerf3.[5] We increased its traffic volume from zero to the maximum throughput. The remaining one UE was controlled by the CDMA 2000 HTTP model described in the next subsection.

B. CDMA2000 HTTP MODEL [34]

We adopted the HTTP model defined by CDMA2000 [34]. This HTTP model was designed to match the HTTP traffic volume with typical probability density functions (PDFs), based on the large data set obtained in 2009. We used this simple model because it readily reproduces the same results, while the total data traffic has increased further at the time of this writing.

The HTTP model [34] defines a web page size as $S_m + N \cdot S_e$ [bytes] and defines a reading time as r [sec]. Here, a main object size S_m follows $\Lambda(\mu = 8.35, \sigma^2 = 1.88)$, an embedded object size S_e follows $\Lambda(\mu = 7.53, \sigma^2 = 2.86)$, a number of embedded objects N follows $P(a = 1.1, k = 2)$, and reading time r follows $\mathrm{Exp}(\lambda = 0.033)$. The PDF of the log-normal distribution $\Lambda(\mu, \sigma^2)$ is given as

$$p(x) = \frac{1}{\sqrt{2\pi}\sigma x} \exp\left(-\frac{(\log x - \mu)^2}{2\sigma^2}\right). \tag{1}$$

That of the Pareto distribution $P(a, k)$ is given as

$$p(x) = \frac{ak^a}{x^{a+1}}. \tag{2}$$

Additionally, the PDF of exponential distribution $\mathrm{Exp}(\lambda)$ is defined as

$$p(x) = \lambda \exp(-\lambda x). \tag{3}$$

Here, the random variables S_m and S_e are limited by $\min(\max(S_m, 100), 2 \cdot 10^6)$ and $\min(\max(S_e, 50), 2 \cdot 10^6)$. In cases where the number of embedded objects exceeds 53, it is generated again until it satisfies $N \leq 53$.

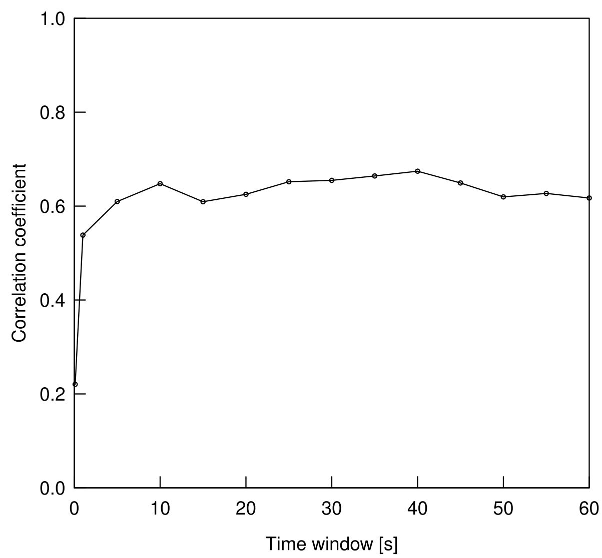

FIGURE 5. Correlation between the NFDF retry ratio and FER, where the time window was increased from 0.1 to 60 [sec].

C. PERFORMANCE RESULTS

Firstly, in Fig. 5, we investigated the optimal time window in terms of maximizing the correlation coefficient between the NFDF retry ratio and FER. The time window was increased from 0.1 to 60 [sec]. As shown in Fig. 5, it was found that the time window did not affect the achievable correlation coefficient when it was larger than 5 [sec]. The correlation significantly decreased if we set the time window too small, such as 0.1 [sec]. This small time window also increases the NFDF calculation cost. Therefore, we used the time window of 30 [sec] for all of our performance evaluation.

Secondly, in Fig. 6, we investigated the correlation between RSSI and FER. Since the distance between UE and AP was fixed to 3 [m], and we did not interrupt its LoS radio path, the RSSI was constant at approximately −33 [dBm] over time. Although the RSSI was constant, the FER varied from

[5] https://iperf.fr/

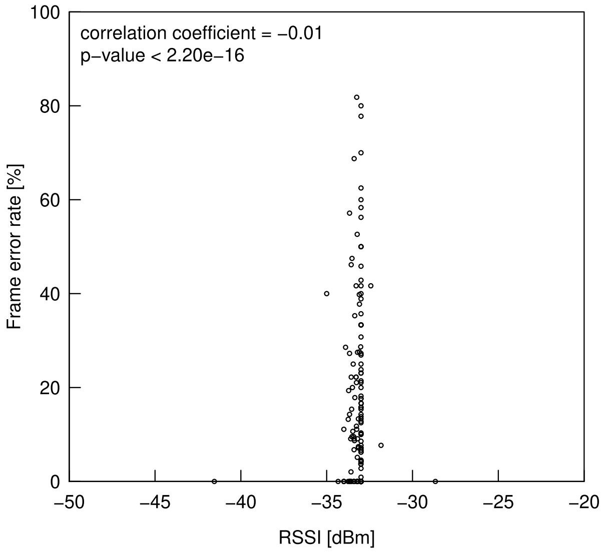

FIGURE 6. Relation between RSSI and FER.

0 to 80% because the traffic load was increased gradually. Thus, the RSSI was unable to detect the QoS loss caused by interference. Furthermore, the RSSI is smoothed by a non-public function defined by a chipset vendor [29] and contains the additive thermal noise. As with the previous study [14], we verify again that the RSSI is not an effective metric for estimating QoS.[6]

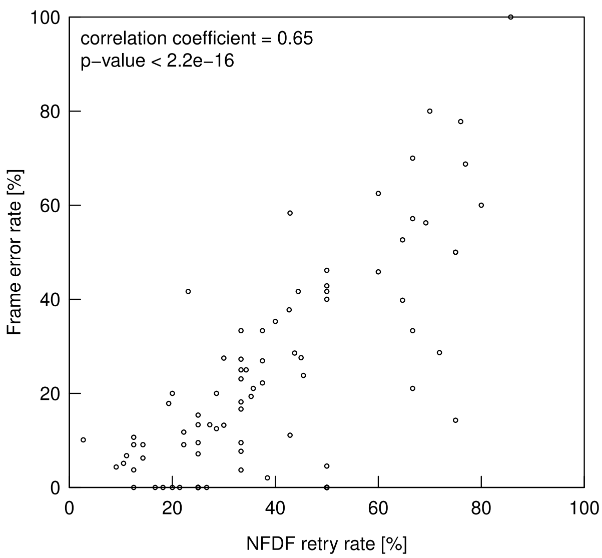

FIGURE 7. Relation between NFDF retry ratio and FER.

Thirdly, in Fig. 7, we investigated the correlation between the proposed NFDF retry ratio and FER. In our measurement, the UE periodically emitted NFDFs multiple times. The PMS bits of the emitted NFDFs were constantly one. Thus, it was not necessary for the UE to repeat NFDFs. The authors expected that this UE tried to preserve affiliation with the AP by repeating NFDF transmissions. This behavior is not defined in the IEEE 802.11 specifications [29]. Different from Fig. 6, as shown in Fig. 7, we observed the correlation coefficient of 0.65. The corresponding p-value was less than 2.20×10^{-16}. Since the p-value was less than 0.005 [35], we verified that the proposed NFDF retry ratio was capable of estimating FER, which also correlated with QoS.

Finally, we conducted a video streaming experiment, in which the proposed NFDF retry ratio, the conventional EDCA, and the conventional COR were compared. In Figs. 6 and 7, one UE followed the CDMA2000 HTTP model and worked as an HTTP client, which was disabled during the video streaming experiment. This UE had been receiving an h.264 video streaming from another server, where the initial streaming rate was 6 [Mbps].

Fig. 8(a) shows the NFDF retry ratio and the COR, where we increased the traffic load from 0 to 10 [Mbps]. As shown in Fig. 8(a), the COR converged to about 32% above the 3 [Mbps] region, while the NFDF retry ratio increased monotonically on increasing the traffic load. Thus, the proposed NFDF retry ratio is capable of tracking IUI and is more effective than the conventional COR.

Fig. 8(b) shows the number of successfully received packets through the video streaming experiment, where the conventional EDCA having the highest priority was considered for reference. Different from Fig. 8(a), the traffic load was fixed to 5 [Mbps]. Here, we defined a threshold of 10% for the NFDF retry ratio based on the results shown in Fig. 8(a). The UEs might be suffered from severe IUIs if the NFDF retry ratio exceeds 10%. Then, we decrease the streaming rate from 6 to 3 [Mbps]. Similarly, we defined a threshold of 30% for the conventional COR. As shown in Fig. 8(b), after 50 [sec] passed, the conventional EDCA was unable to stream video to the UE due to the severe IUI. Here, both the NFDF retry ratio and the COR succeeded in detecting the severe IUI condition, and the streaming rate was changed from 6 to 3 [Mbps]. The stream was not interrupted until the video ended. Based on this observation, we conclude that the NFDF retry ratio is as effective as the conventional COR, although the calculation of NFDF is much simpler than that of COR.

V. REAL-WORLD EVALUATION

We implemented the proposed estimation method of Section III as a production-level firmware and conducted its evaluation experiments in a 1500-seat hall in January 2018.

A. MEASUREMENT ENVIRONMENT

We provided a large-scale Wi-Fi network at a conference held in Hiroshima, Japan, and evaluated our method. Fig. 9 shows the conference hall, which has 1500 seats. During the three day conference, 1171 participants visited here. Since this conference focused on the Internet technology, most participants used their notebooks, tablets, or mobile phones,

[6]Here, if no interference exists, the FER might exhibit a constant value at an RSSI level. Then, upon increasing the AP-UE distance, we might observe a correlation between RSSI and FER. However, such an interference-free network is unrealistic.

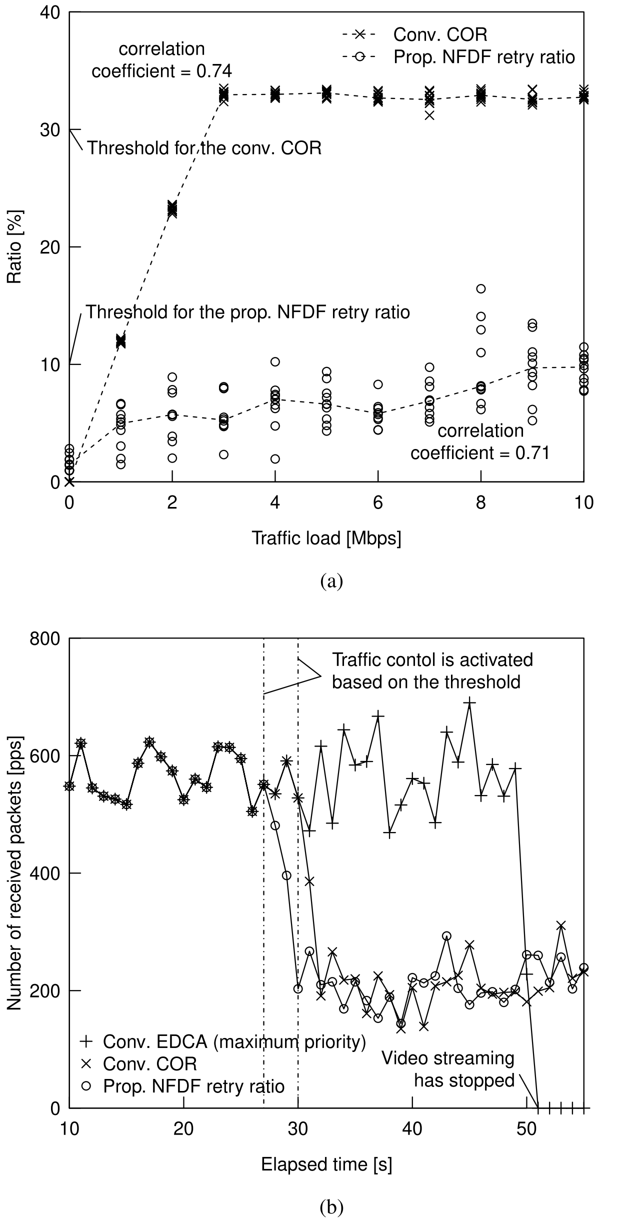

FIGURE 8. A video streaming experiment in which the proposed NFDF method was used to control the transmission rate. The conventional EDCA and COR were considered for reference. (a) Thresholds for the proposed NFDF retry ratio and the conventional COR. (b) Traffic control comparison.

FIGURE 9. Conference hall at which our measurement campaign was conducted.

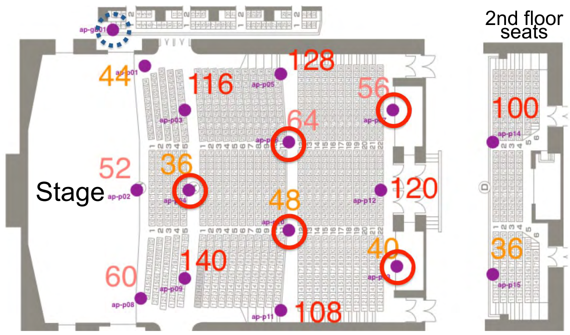

FIGURE 10. IEEE 802.11ac channel assignment in the hall.

as shown in Fig. 9. The total number of registered Wi-Fi devices was 1559. Thus, the average number of Wi-Fi devices per participant was 1.33.

We installed 15 number of 802.11ac APs inside the hall. The corresponding channel assignment is detailed in Fig. 10, where the numbers 36, 40, 44, $\cdots$, 140 respectively denote the IEEE 802.11ac channels. We monitored 36, 40, 48, 56, and 64 channels, which are indicated by solid circles in Fig. 10. We strove to set different channels for the neighboring APs, while we observed a channel switch induced by the DFS function during our measurement, as analyzed in Section V-B.

B. PERFORMANCE RESULTS

Our monitoring system collected about 4.8 billion 802.11 frames in 3 days; 14.27% of them were NFDF, where all the participants had uncontrolled Wi-Fi devices. Since we observed a large number of NFDFs steadily, it became evident that we were able to exploit NFDFs for the estimation of QoS.

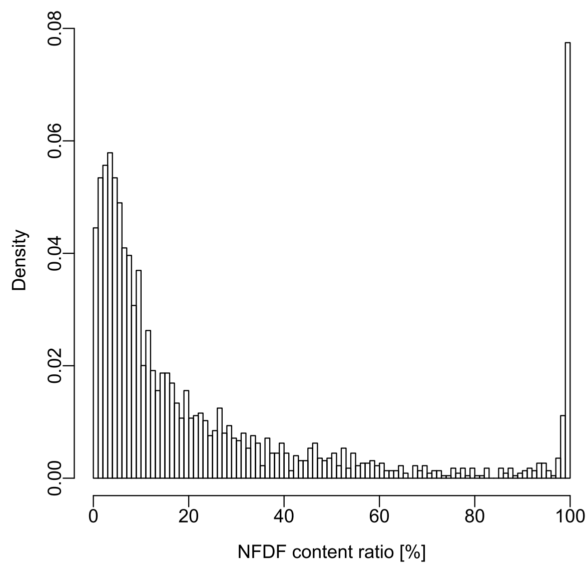

FIGURE 11. Histogram of NFDF transmission ratios.

Firstly, Fig. 11 shows a histogram of NFDF transmission ratio, which is calculated by the number of NFDFs divided

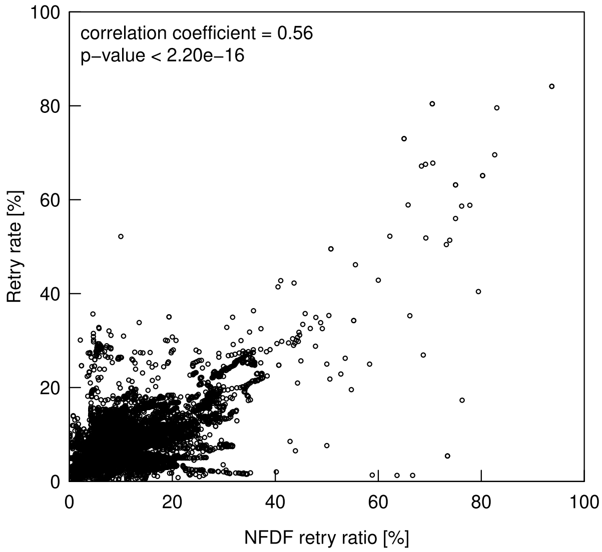

FIGURE 12. Relation between the NFDF retry ratio and all retry ratios.

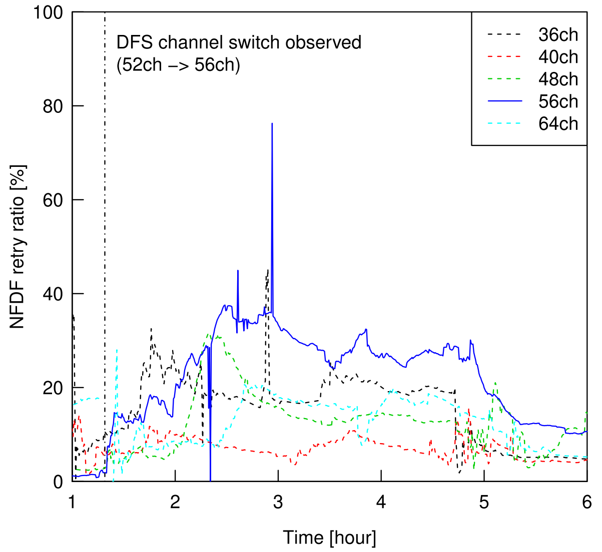

FIGURE 13. Time-varying NFDF retry ratio and the effect of channel reassignment.

by the total number of 802.11 frames. Approximately 30% of UEs transmitted NFDF more than once. Then, we only considered those UEs for clear illustration. As shown in Fig. 11, we observed a peak at the NFDF content ratio between 99 and 100%. We inferred from this result that a large number of UEs did not communicate at all after connecting to the AP. Additionally, we observed a second-largest peak at the NFDF transmission ratio of around 5%. Therefore, without loss of generality, a lot of NFDFs can be observed at a large-scale conference.

According to Fig. 11, it was also found that the NFDF observation was equivalent to 14.27% random sampling of all the frames. The FER obtained by a random-sampled set of 802.11 frames might not be reliable because the frame length is not constant. The NFDF frame length is constant since it contains no payload, and it works as if it were a fixed-length probe frame, which can be exploited for grasping the network QoS. Thus, the NFDF retry ratio is more reliable than the retry ratios of other variable-length frames. Additionally, the computation complexity is reduced because our method counts only 14% out of all the received 802.11 frames, which differs from the conventional passive family [18], [20], [22].

Next, Fig. 12 shows a relation between the proposed NFDF retry ratio and the retry ratio calculated by all the frames. Here, we were unable to calculate FER because all the participant devices were uncontrolled. Thus, we considered the pure retry ratio instead of FER. Similar to Fig. 13, we calculated the NFDF retry ratio for each channel within the 30 [sec] time window. Different from Fig. 7, the network connections inside the hall were almost stable. Thereby, the frame retry ratio was kept below 20%. In Fig. 12, the correlation coefficient was 0.56. The corresponding p-value was below 0.005 [35]. Thus, the proposed NFDF retry ratio is a reliable QoS metric for severe IUI scenarios.

Finally, Fig. 13 shows time series of NFDF retry ratios, where the 802.11ac 36, 40, 48, 56, and 64 channels were considered. Here, the time-series data from 1 to 6 hours of the first day were extracted for clear illustration. After all the sessions of the first day ended, we noticed that a 52ch AP was switched to the 56ch by the IEEE 802.11 DFS function. As shown in Fig. 13, the NFDF retry ratio for 56ch increased suddenly when 1 hour and 20 minutes passed. It remained worse until the sessions ended. Here, our NFDF-based estimation method was capable of detecting this drop in QoS, which was caused by the increased IUIs. On the second day, based on this NFDF-based information, we restored the channel assignment setting and observed a decrease in the NFDF retry ratio. Thus, the proposed NFDF retry ratio is an effective metric for estimating the network QoS.

VI. CONCLUSION

In this paper, we proposed an NFDF-based estimation method for the QoS of a large-scale Wi-Fi network. Since the proposed metric is calculated by a passive and low-complexity manner, we were able to implement it as a user-level script and a production-level firmware. We investigated its achievable performance both in controlled and uncontrolled environments. Under the controlled conditions, the NFDF retry ratio was capable of estimating the FER between UE and AP, where the correlation coefficient was 0.65. In our real-world measurement, 1559 Wi-Fi devices were considered; about 4.8 billion 802.11 frames were collected. In that environment, our proposed NFDF retry ratio exhibited a correlation coefficient of 0.56. Additionally, the proposed method successfully detected the QoS loss induced by DFS and helped the authors to reconfigure the AP settings. Based on these real-world observations, we conclude that the passive-measurement-based NFDF retry ratio is effective for estimating the network QoS.

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