

Sampleless Wi-Fi: Bringing Low Power to Wi-Fi Communications

Wei Wang, *Member, IEEE*, Yingjie Chen, Lu Wang, *Member, IEEE*, and Qian Zhang, *Fellow, IEEE*

Abstract—The high sampling rate in Wi-Fi is set to support bandwidth-hungry applications. It becomes energy inefficient in the post-PC era in which the emerging low-end smart devices increase the disparity in workloads. Recent advances scale down the receiver’s sampling rates by leveraging the redundancy in the physical layer, which, however, requires packet modifications or very high signal-to-noise ratio. To overcome these limitations, we propose *Sampleless Wi-Fi*, a standard compatible solution that allows energy-constrained devices to scale down their sampling rates regardless of channel conditions. Inspired by rateless codes, *Sampleless Wi-Fi* recovers under-sampled packets by accumulating redundancy in packet retransmissions. To harvest the diversity gain as rateless codes without modifying legacy packets, *Sampleless Wi-Fi* creates new constellation diversity by exploiting the time shift effect at receivers. Our evaluation using GNURadio/USRP platform and real Wi-Fi traces has demonstrated that *Sampleless Wi-Fi* significantly outperforms the state-of-the-art downclocking technique in both decoding performance and energy efficiency.

Index Terms—Energy efficiency, low power Wi-Fi, sub-Nyquist sampling, Internet of Things.

I. INTRODUCTION

The dramatic increase in Wi-Fi speeds in recent years has promised to deliver sufficient bandwidth to support high data rate services such as high-definition video streaming and bulky file transfer. As we are entering the post-PC era in which an ever-larger variety of mobile devices such as smartphones and wearables are increasing the disparity between the types of traffic demands. While high speed Wi-Fi fits high-end devices well for their heavy workloads, it brings little benefit to low-end devices with light workloads but rather becomes an overwhelming energy burden. The need for low-power Wi-Fi increases as growing numbers of wearables have enabled Wi-Fi to directly connect to the Internet. For example, Google’s latest Android Wear release [1] allows

android smartwatches to connect to Wi-Fi without smartphones; Apple Watch is already equipped with a built-in Wi-Fi chipset and may enable direct Internet connectivity in future WatchOS releases. Unfortunately, the current crop of Wi-Fi designs are ill-suited for the coming wave of power-constrained smartphones and wearables, as they are primarily designed for high-end devices.

Growing attempts and extensive efforts have been devoted to providing energy efficient Wi-Fi connectivity to embrace the coming wave of energy-constrained smartphones and wearables. It has been shown that the primary cause of Wi-Fi’s high power consumption comes from the high sampling rate of its radios [2], [3]. Recent advances have demonstrated the feasibility of downclocking the sampling rate of Wi-Fi radios while detecting [3] and receiving packets [4], [5] under high channel quality conditions. However, hardly any of them have made it to receive packets from today’s Wi-Fi access points (APs). They either require modifications to legacy preambles [3], or excess redundancy at the physical layer (PHY) (direct sequence spread spectrum (DSSS) [4] or radically conservative data rates under high channel quality conditions [5]). Unfortunately, the current crop of Wi-Fi techniques have almost used up the redundancy at PHY by employing orthogonal frequency-division multiplexing (OFDM) and rate adaptation schemes.

Instead of relying on PHY redundancy which is barely left in today’s Wi-Fi networks, we argue that a more practical and controllable way is to exploit the media access control layer (MAC) that can be directly controlled on existing Wi-Fi access points (APs), while making minimum PHY changes only at downclocked receivers. As such, future mobile devices with downclocking capabilities can be seamlessly integrated into current Wi-Fi networks without requiring dedicated APs.

In this work, we propose *Sampleless¹ Wi-Fi*, which aims to provide reliable communications between legacy Wi-Fi APs and mobile devices at various sampling rates. *Sampleless Wi-Fi* is inspired by the wisdom of *rateless codes* [6] in that an undecodable packet in a single transmission can be recovered by combining multiple transmissions. In *Sampleless Wi-Fi*, in a same data transmission, effective packet reception with different energy consumption can be achieved for receivers at different sampling rates. The concept of *Sampleless Wi-Fi* is illustrated in Fig. 1, where versatile devices with various workloads access the Internet via a Wi-Fi AP. A laptop communicates with the AP at the Nyquist sampling rate (40 MHz)

¹Sampleless implies that packets can be sampled at various rates regardless of data rates and channel conditions.

Manuscript received February 16, 2016; revised August 4, 2016; accepted December 8, 2016; approved by IEEE/ACM TRANSACTIONS ON NETWORKING Editor D. Goeckel. Date of publication January 25, 2017; date of current version June 14, 2017. This work was supported in part by the China NSFC under Grant 61502114 and Grant 61502313, in part by the 973 Project under Grant 2013CB329006, in part by the RGC under Contract CERG M-HKUST609/13, Contract 622613, Contract 16212714, Contract 16203215, and Contract ITS/143/14FP-A, and in part by the Huawei-HKUST joint lab, IoT Wi-Fi key technologies.

W. Wang is with the School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan 430074, China, and also with the Fok Ying Tung Research Institute, The Hong Kong University of Science and Technology, Hong Kong (e-mail: weiwangw@hust.edu.cn).

Y. Chen and Q. Zhang are with the Department of Computer Science and Engineering, The Hong Kong University of Science and Technology, Hong Kong (e-mail: qianzh@cse.ust.hk).

L. Wang is with the College of Computer Science and Software Engineering, Shenzhen University, Shenzhen 518060, China.

Digital Object Identifier 10.1109/TNET.2016.2643160

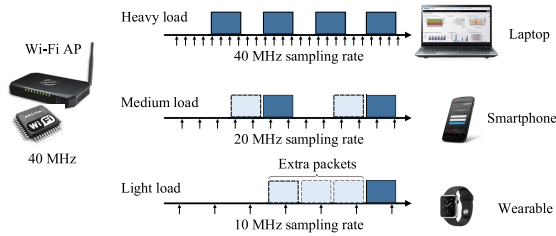


Fig. 1. Illustration of Sampleless Wi-Fi.

to meet heavy traffic demands; while for less bandwidth-hungry mobile devices that use sub-Nyquist sampling rates (20 MHz or 10 MHz) for energy saving, the AP incrementally adds redundancy by sending extra packets until successful reception. As a result, the AP sends legacy packets without PHY modifications, and energy-constrained devices can downclock their sampling rates without requiring specific channel conditions or PHY redundancy.

A key challenge in Sampleless Wi-Fi is how to add redundancy through multiple transmissions without modifying AP's PHY. Rateless codes generally require senders to transmit correlated symbols, which incurs baseband modifications that are not supported by today's APs. Departure from rateless codes, in Sampleless Wi-Fi, APs send repeated legacy packets through retransmissions, and receivers yield correlated symbols by exploiting the *time shift* effect. Specifically, Sampleless Wi-Fi receivers leverage the fact that one under-sampled symbol contains multiple subcarrier symbols due to *frequency aliasing*, and a time shift results in different phase rotations at different subcarriers. Thus, the receivers inject various time shifts for repeated packets to obtain different constellation symbols, and then combine these symbols for decoding.

Another challenge stems from reliable and efficient packet reception under low signal-to-noise ratio (SNR) conditions. Previous work [5] demonstrates the feasibility of receiving under-sampled OFDM packets under high SNR conditions (>25 dB), while reliable frame synchronization at low SNR remains challenging. Sampleless Wi-Fi jointly utilizes under-sampled preambles across repeated packets to achieve desirable correlation results. In addition, Sampleless Wi-Fi carefully designs the decoding algorithm to minimize overhead. It enables multiple retransmissions using Transmit Opportunity (TXOP) [7]. As a result, extra packets generated in Sampleless Wi-Fi do not increase the contention overhead. To improve decoding efficiency, Sampleless Wi-Fi leverages PHY hints to gradually screen out erroneous intermediate results during the decoding process.

We implement Sampleless Wi-Fi on the GNURadio/USRP platform. Evaluation results validate Sampleless Wi-Fi in reliably receiving and decoding legacy packets at sub-Nyquist rates across a wide range of channel conditions. Furthermore, from real traffic traces in a large-scale Wi-Fi network and across types of smartphone applications, we observe that Sampleless Wi-Fi largely improves Wi-Fi energy efficiency when compared to the state of the arts.

The contributions of this paper are summarized below. First, we provide a thoughtful study towards providing low-power

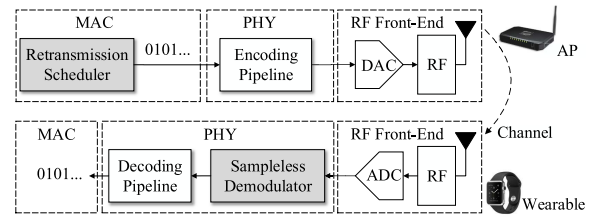


Fig. 2. Architecture of Sampleless Wi-Fi Design.

Wi-Fi for future energy-constrained mobile devices. Our solution can be seamlessly integrated into existing Wi-Fi networks: it requires no PHY modifications on existing APs and completely conforms to 802.11 protocols. Second, we propose a reliable reception pipeline that can decode legacy packets at sub-Nyquist rates under a wide range of SNRs. The key underlying technique is a new decoding algorithm based on time shift induced constellation maps. Finally, we prototype Sampleless Wi-Fi on USRP testbeds, and validate its performance with experiments and real traces.

II. SAMPLELESS WI-FI OVERVIEW

Sampleless Wi-Fi facilitates clients to reliably receive and decode legacy Wi-Fi packets at flexible sampling rates lower than the Nyquist criterion. It provides robust under-sampled reception under various SNR conditions. Consequently, low-end devices like wearables can downclock their sampling rates to save energy, while still enjoying comparable packet reception rates as traditional Wi-Fi receivers.

Architecturally, Sampleless Wi-Fi borrows from the wisdom of rateless codes in that an undecodable packet can be recovered by transforming original constellation symbols to points in a higher dimensional space through multiple transmissions of correlated symbols. Sampleless Wi-Fi recovers under-sampled baseband samples by multiple retransmissions. Different from rateless codes, Sampleless Wi-Fi requires no PHY modifications at the transmitters, but rather creates correlated symbols through time shifts at the receivers.

Fig. 2 shows the system flow of Sampleless Wi-Fi transmission and reception. Sampleless Wi-Fi extends legacy Wi-Fi by adding the following two core components to legacy protocol stack.

- **Retransmission Scheduler** residing atop AP's MAC. Sampleless Wi-Fi simply adds the retransmission scheduler at the MAC of Wi-Fi APs, while other MAC blocks such as the CSMA mechanism and the entire PHY still conforms to standard Wi-Fi. When an AP sends packets to a wearable device, the retransmission scheduler overrides the standard retransmission scheme and allows the AP to send multiple repeated frames in a single TXOP.
- **Sampleless Demodulator** incorporated in the client's decoding pipeline. To reliably receive and decode packets at sampling rates below the Nyquist frequency, the sampleless demodulator is incorporated at the PHY of wearables. A wearable receiver first feeds under-sampled baseband samples to the sampleless demodulator to recover the encoded bits, and then forwards the recovered

bits to the traditional decoding pipeline, including deinterleaving, error correction codes decoding, descrambling, and cyclic redundancy check (CRC).

Sampleless Wi-Fi makes PHY changes (decoding pipeline algorithms) at the client side only, while the AP still conforms to the legacy PHY/MAC except that packet scheduling is performed by the retransmission scheduler, which can be easily implemented in commercial APs. Therefore, it allows next-generation wearables implemented with the new decoding pipeline to receive legacy packets from existing Wi-Fi APs at sub-Nyquist sampling rates with high reliability.

In what follows, we detail the essential components in Sampleless Wi-Fi.

III. CREATING DIVERSITY THROUGH MULTIPLE RETRANSMISSIONS

The core and challenging part of Sampleless Wi-Fi is to design a receiver that can recover under-sampled constellation symbols through multiple retransmissions. In particular, the Sampleless Wi-Fi receiver must overcome the following challenges: (i) it must be able to receive and decode legacy packets without any modifications at the sender; (ii) it must be resilient to the changes of sampling rates and the variations of unpredictable channel conditions. To meet these challenges, we propose *time shift constellation mapping* to create diversity through multiple transmissions of repeated legacy frames.

A. Frequency Aliasing Effect

When a receiver samples signals at sub-Nyquist criterion, the sample rate is insufficient to capture the changes in the signal, thereby causing frequency aliasing, that is, the signal spectrum folds up.

We illustrate the frequency aliasing effect on a typical OFDM symbol sampled at $1/2$ -Nyquist rate. The transmitted N samples in one OFDM symbol can be expressed as $x[n] = \frac{1}{N} \sum_{k=0}^{N-1} e^{j\frac{2\pi kn}{N}} X_k$, $n = 0, \dots, N-1$, where X_k is the data encoded on the k th subcarrier. When $x[n]$ is sampled at $1/2$ -Nyquist rate, the receiver yields

$$\begin{aligned} y[n] &= x[2n] * h[2n] + w[2n] \\ &= \frac{1}{N} \sum_{k=0}^{N-1} e^{j\frac{4\pi kn}{N}} X_k H_k + w[2n], n = 0, \dots, \frac{N}{2} - 1, \end{aligned} \quad (1)$$

where H_k is the channel response at the k th subcarrier, and $w[n]$ is noise. Then, the receiver performs $\frac{N}{2}$ -point FFT to obtain received subcarrier data $Y_{k'}$, $k' = 0, \dots, N/2 - 1$.

$$\begin{aligned} Y_{k'} &= \sum_{n=0}^{\frac{N}{2}-1} e^{-j\frac{2\pi k' n}{N/2}} y[n] \\ &= \frac{1}{N} \sum_{n=0}^{N/2-1} \left(\sum_{k=0}^{N-1} e^{j\frac{2\pi(k-k')n}{N/2}} X_k H_k + w[2n] e^{-j\frac{2\pi k' n}{N/2}} \right) \\ &= \frac{X_{k'} H_{k'} + X_{k'+\frac{N}{2}} H_{k'+\frac{N}{2}}}{2} + \frac{1}{N} \sum_{n=0}^{\frac{N}{2}-1} w[2n] e^{-j\frac{2\pi k' n}{N/2}}. \end{aligned} \quad (2)$$

We observe that the receiver yields compound frequency samples: the k th sample after FFT consists of two subcarriers $X_{k'}$ and $X_{k'+N/2}$. Correspondingly, when sampling rate is downclocked to be $1/M$ Nyquist rate, each frequency sample captured at the receiver consists of M compound samples.

Though several recent efforts [5], [8], [9] have employed sparse recovery techniques to decode symbols under frequency aliasing, they require certain sparsity properties that can hardly be guaranteed in general Wi-Fi transmissions. Current Wi-Fi transmissions have almost made the best use of channel resources, and leave little redundancy that can barely support direct decoding at sub-Nyquist rates. For example, Enfold [5] uses BPSK and requires very high SNR (>25 dB), while commodity APs normally employ much higher modulation schemes such as QAM-64 in high SNR conditions.

In order to decode under-sampled packets in various SNR conditions, in the next subsection we propose to exploit new diversity through multiple retransmissions. Specifically, we map under-sampled constellation symbols to higher dimensional space by utilizing the time shift effect.

B. Time Shift Induced Constellation Mapping

Inspired by the design rationale of rateless codes, we use multiple retransmissions to map under-sampled constellation symbols to higher dimensional space. The essential intuition behind rateless codes is that the minimal distance between nearby constellation points can be increased when we map the conventional symbols to a higher dimensional space by sending a batch of correlated symbols. However, rateless codes cannot be implemented in commercial Wi-Fi APs due to PHY modifications, i.e., transmitting correlated packets instead of legacy packets. To overcome this obstacle, we exploit new diversity that can be obtained from the existing retransmission scheme in Wi-Fi networks.

Exploiting the Time Shift Effect: Recall that frequency aliasing results in compound constellation symbols consisting of multiple frequency samples at different subcarriers. Intuitively, as the frequency of each subcarrier is unique, if we add frequency-specific operations before the decoding process, we can yield new compound constellation symbols at the receivers without modifying the transmitted packets. Specifically, we leverage the *phase-rotation property* [10] of the Fourier transform, that is, a shift in the time domain translates into a phase rotation in the frequency domain. Mathematically, after shifting the input signal $x[n]$ by τ samples, and performing N -point FFT, the input signal in the frequency domain changes by

$$\hat{X}_k = e^{j\frac{2\pi k\tau}{N}} X_k, \quad (3)$$

where X_k and \hat{X}_k are the signals in the frequency domain before and after the time shift, and k is the subcarrier frequency. Thus, each subcarrier has a unique rotation speed with respect to time shift.

Constellation Diversity Induced by Time Shifting: Based on the above observation, if we inject different time shifts for repeated packets, we can obtain different constellation symbols, thereby creating multiple constellation maps at

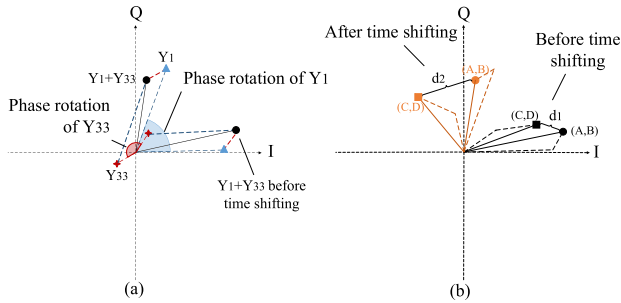


Fig. 3. Illustration of time shift effect. (a) Time shift induced phase rotation. (b) Constellation point distance diversity.

the receiver. Suppose we shift received signals by τ_i for the i th retransmission. According to Eq. (2) and (3), the k th sub-carrier data sampled in the i th retransmission (noise omitted) is

$$Y_{k'}^i = \frac{1}{2} \left(e^{j\frac{2\pi k' \tau_i}{N}} H_{k'}^i \cdot X_{k'} + e^{j\frac{2\pi(k'+\frac{N}{2}) \tau_i}{N}} H_{k'+\frac{N}{2}}^i \cdot X_{k'+\frac{N}{2}} \right), \quad (4)$$

Note that the subcarrier data is the sum of rotated versions of $H_{k'}^i \cdot X_{k'}$ and $H_{k'+\frac{N}{2}}^i \cdot X_{k'+\frac{N}{2}}$, whose rotations are different and controlled by τ_i . We can rewrite each component of $Y_{k'}^i$ in the form of phase and amplitude as

$$Y_{k'}^i = \frac{1}{2} \left(|H_{k'}^i X_{k'}| e^{j2\pi k' \tau_i / N + \varphi(H_{k'}^i X_{k'})} + |H_{k'+\frac{N}{2}}^i X_{k'+\frac{N}{2}}| e^{j2\pi(k'+\frac{N}{2}) \tau_i / N + \varphi(H_{k'+\frac{N}{2}}^i X_{k'+\frac{N}{2}})} \right), \quad (5)$$

where $\varphi(\cdot)$ and $|\cdot|$ are the phase and amplitude of a complex constellation point, respectively. Due to the different rotation speed of each component, the compound symbol $Y_{k'}^i$ has a unique phase and amplitude corresponding to the time shift τ_i . Consequently, we generate a distinct constellation map for each retransmission by adding different time shifts.

Fig. 3 illustrates how a time shift at the receiver with 1/2-Nyquist rate generates a new constellation map. We consider a compound constellation sample consisting of received frequency samples $Y_1 = H_1 X_1$ and $Y_{33} = H_{33} X_{33}$, where H_k , X_k denote the channel response and transmitted data at the subcarrier k ($k = 1$ or 33), respectively. As illustrated in Fig. 3(a), after a time shift at the receiver, Y_{33} rotates a larger angle than Y_1 according to Eq. (3). As a consequence, both the amplitude and phase of the compound symbol $Y_1 + Y_{33}$ change after time shifting. Such changes are reflected in the constellation map, as shown in Fig. 3(b). Without loss of generality, we consider four constellation points, denoted as A, B, C, D (e.g., A can be “1101” in 16QAM). Due to frequency aliasing, the receiver only obtains compound points, which are irregularly scattered in the constellation map according to Eq. (2). Suppose the compound points (A, B) and (C, D) have a very small distance d_1 in the constellation map, which can be very hard to distinguish at low SNRs. After time shifting as shown in Fig. 3(a), the compound points (A, B) and (C, D)

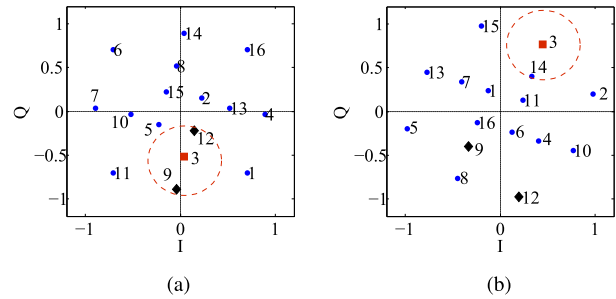


Fig. 4. Constellation diversity induced by time shift. Constellation maps are constructed based on packets received at 1/4-Nyquist rate using USRP. (a) Constellation map without time shift. (b) Constellation map with time shift.

change in both amplitudes and phases. As components in (A, B) and (C, D) have different amplitudes, the amplitudes and phases changes of (A, B) and (C, D) are also different. Consequently, the distance between (A, B) and (C, D) after time shifting, denoted as d_2 , also changes. Generally, neighboring points in the constellation map become faraway points, and vice versa. As such, a time shift creates a new constellation map with different point distances.

By combining multiple transmissions, we can map constellation points to higher dimensional space with a larger minimum distance. Fig. 4 shows the constellation maps of BPSK-modulated packets captured by USRP at 1/4-Nyquist rate. Note that frequency aliasing at 1/4-Nyquist rate converts the BPSK constellation to a 16-point irregular constellation. The red circle denotes the minimum distance required to distinguish two points in demodulation. In Fig. 4(a), point 3 is likely to be mixed up with its neighboring points 9 and 12 during demodulation due to channel noise. In another transmission with time shifting (Fig. 4(b)), constellation points are completely shuffled: points 9 and 12 move far beyond the minimum distance of point 3. This distance diversity benefits demodulation by separating mixed-up points. By combining these two transmissions, the minimum distance in one transmission (e.g., the distance between points 9 and 3) is transformed to a higher dimensional metric (e.g., accumulated distance in two transmissions), which is generally much larger and thereby more resistant to noise.

IV. SAMPLELESS DECODING

Thus far we have explained how a sub-Nyquist receiver can create distinct constellation maps through time shifting without any modifications at the sender’s side. Based on this basic idea, we design a Sampleless Wi-Fi receiver that harvests the diversity in retransmissions to receive and decode under-sampled frames.

A. Joint Synchronization

A Wi-Fi receiver continuously performs idle listening in order to detect Wi-Fi preambles and synchronize arriving frames. The Wi-Fi preamble consists of Short Training Field (STF) and Long Training Field (LTF), which are used for synchronization and channel estimation, respectively. The legacy STF contains ten repetitions of a 16-sample sequence,

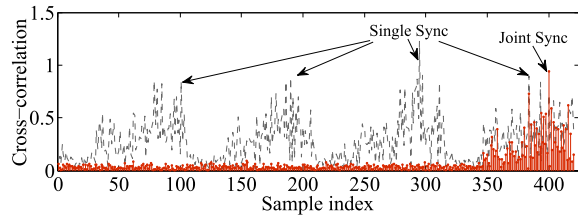


Fig. 5. Cross-correlation responses at 1/4 Nyquist rate. We set up a USRP link to capture raw data samples of four consecutive Wi-Fi packets at 10 dB SNR. Joint synchronization combines four LTFs.

while the LTF contains two repetitions of a 64-sample symbol. Wi-Fi receivers generally leverage the auto/cross-correlation properties of the STF to synchronize incoming frames.

As the number of the STF is reduced under sub-Nyquist sampling, the correlation results of the STF are not strong enough for fine synchronization. Experiments in [5] have shown that the cross-correlation result of the under-sampled LTF can be used for synchronization in a high SNR range (>13 dB). However, when the SNR is poor, noise cannot be canceled out during cross-correlation.

To perform synchronization for sub-Nyquist receivers under low SNR conditions, we employ a joint synchronization algorithm that utilizes multiple preambles in consecutive transmissions to add LTF samples in cross-correlation. It is worth noting that commercial APs can precisely control inter-frame timing with quite a small clock error (e.g., 40 MHz clock oscillators) that is much lower than the frame synchronization error (e.g., due to multipath delays). Thus, the AP can send repeated frames at a fixed interval, e.g., SIFS in one TXOP, which is predetermined and known by the receiver. As such, the receiver can perform a joint cross-correlation across the LTFs of the consecutive frames. First, the receiver uses the STF and LTF to synchronize the first frame, and buffers the baseband samples. After detecting the second frame, the receiver computes one joint cross-correlation over the STFs of the two frames. The joint cross-correlation can be realized by modifying the sliding window. We denote the length of the LTF as T_L and the time offset between two consecutive frames as T . Specifically, instead of using a sliding window of length T_L , a joint sliding window consisting of two windows of length T_L spaced by $T - T_L$. Consequently, the samples for cross-correlation is doubled, thereby exhibiting stronger cross-correlation properties that are more robust under poor SNR conditions. Then, we synchronize each frame based on the correlation spike and the corresponding time offset T .

Fig. 5 illustrates the merits of joint synchronization at 1/4 Nyquist rate. As the LTF samples are reduced by quarter at 1/4 Nyquist rate, the cross-correlation result of a single LTF contains multiple comparable peaks at a low SNR (10 dB), and thus the receiver can easily aligned to a wrong peak. By jointly utilizing four LTFs, we can achieve a desirable cross-correlation result where the highest peak corresponds to the full alignment of OFDM symbols.

B. Decoding Over Multiple Retransmissions

Prior to data decoding, the receiver performs channel estimation based on LTF. The only departure from the standard

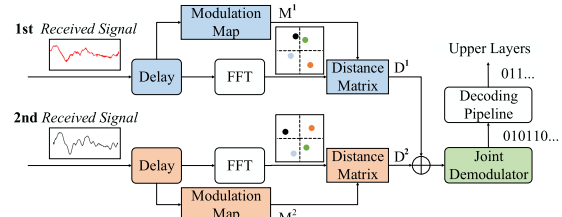


Fig. 6. Sampleless Demodulator.

channel estimation is that Sampleless receivers obtain compound frequency responses in the form of (2) due to frequency aliasing [5]. Then, the receivers construct a constellation map based on channel estimation, and combine the frequency responses in multiple retransmissions to convert compound constellation symbols to a higher dimensional space to recover the original symbols. The high-level pipeline is illustrated in Fig. 6.

The Sampleless Demodulator combines multiple packets based on the maximum likelihood (ML) algorithm. From L transmissions, the receiver obtains L symbols $Y = y_1, \dots, y_L$ of a symbol x_j . An ideal ML decoder minimizes the probability of error with respect to a uniform prior, which is,

$$\hat{X} = \arg \min_{x_j} \sum_{i=1}^L \frac{1}{\sigma^2} \|\bar{y}_i - \tilde{x}_j\|^2, \quad (6)$$

where \hat{X} is the decoded symbol, $\|\cdot\|^2$ the squared Euclidean distance in the constellation map, and σ the noise variance. With more transmissions, the distance in the constellation diagram increases and it becomes easier to separate symbol x_j from neighboring constellation points.

The ideal ML decoder can achieve optimal capacity over AWGN channels. However, with multiple transmissions, the decoding complexity grows dramatically. To reduce the computational complexity, we continuously prune the constellation based on *soft hints*, which are the outputs from the standard ML or maximum a posteriori probability (MAP) decoder. Soft hints represent the reliability of the decoding bits, e.g., posteriori Log-Likelihood Ratios (LLRs) [11]. Upon receiving a symbol x , the LLR of its k th bit x_k is

$$LLR(x_k) = \log \frac{P(x_k = 1|r)}{P(x_k = 0|r)}. \quad (7)$$

The basic idea of soft hint based constellation pruning is that instead of searching all possible constellation points, we prune the constellation by discarding the unreliable points based on their LLRs, thereby reducing the search space and hence complexity. However, due to channel impairments, the LLR itself may become unreliable and cannot represent the real confidence level of a bit. Therefore, we adopt normalized confidence level (NCL) as the pruning criteria,

$$NCL(x_k) = \frac{|LLR(x_k)|}{\max(|LLR(x_k)|)}. \quad (8)$$

Suppose each pruning screens out pN constellation points out of total N constellation points, and the total computations to decode one transmission is C_N . In the i th transmission, we only require $(1 - p)^{i-1} C_N$ computations. Fig. 7 illustrates

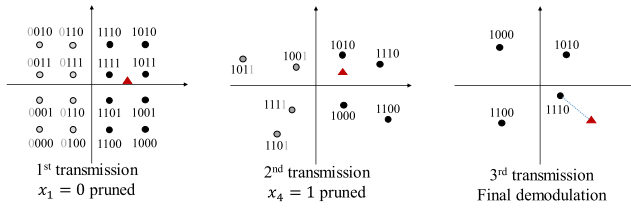


Fig. 7. An example of constellation pruning using NCL. The triangle point is the received symbol of 1110. Grey points are discarded as they contain bits with low NCLs.

Algorithm 1 Sampleless Decoding

Data: Compounded constellation symbols
while A new packet received in the TXOP duration **do**
 Generate time shift induced modulation map;
 Compute squared distance matrix D^2 ;
 Update squared accumulated distance matrix
 $D_a^2 \leftarrow D_a^2 + D^2$;
 Prune bits based on NCL ;
end
if Decoding is successful **then**
 send ACK;
else
 wait;
end

the constellation pruning using NCL. As $x_1 = 1$ in the first transmission cannot satisfy the NCL criteria, we discard the eight corresponding constellation points, and leave the reminders to compute the accumulated distance matrix upon the next transmission. Similarly, the points with $x_4 = 1$ are discarded in the second transmission according to the NCL criteria. After receiving three transmissions, only four points are left for final demodulation, which reduces unnecessary computations. Compared to the standard ML decoder, we save 50% computations in decoding the second transmission, and save 75% in decoding the third transmission.

The detailed decoding process is summarized in Algorithm 1. For each packet received during the TXOP duration, the receiver applies a delay to the received signals and obtains time-shifted compounded constellation symbols. Then, the receiver generates a modulation map based on the amount of time shift. The receiver computes the squared distance matrix D^2 , which consists of the square Euclidean distance of each compounded constellation symbol to each constellation symbol in the modulation map. The receiver updates the squared distance matrix D^2 by accumulating the corresponding squared distances of all transmissions. Then, the receiver screens out constellation symbols based on the NCL criteria, and shrinks the distance matrix accordingly. As such, the distance computations are gradually reduced. Finally, the receiver demodulates the packet based on the updated D^2 in the final transmission, and sends an acknowledgment frame (ACK) if demodulated bits pass the checksum.

V. IMPLEMENTATION

We implement Sampleless Wi-Fi atop the OFDM implementation of the GNURadio/USRP platform. We adopt the

legacy PHY layer convergence procedure (PLCP) format of 802.11n, where the PLCP preamble consists of 2 OFDM symbols for the short training field (STF) and 2 OFDM symbols for the LTF. Nodes in our experiments are USRP N210 devices equipped with RFX2450 daughterboards as RF front-end, which operates in the 5.1-5.2GHz range. Each USRP node is connected to a DELL OptiPlex 9010 desktop with Intel i3 dual-core CPU running Ubuntu 10.04. Since USRP cannot be downclocked while receiving full bandwidth signals, we digitally downscale the sampling rate after ADC by decimation. Specifically, we decimate every other sample for 50% and three of every four samples for 25%.

We modify the synchronization algorithm and decoding pipeline in the USRP Hardware Drive (UHD) to empower sampleless reception, as specified in Section IV. Due to large processing delay of USRP and its connected computer, CSMA MAC cannot be performed in real-time. To evaluate energy consumption of Sampleless Wi-Fi, we leverage real-world Wi-Fi traces and emulate the MAC protocol. The multiple retransmissions of Sampleless Wi-Fi are realized using the 802.11 TXOP scheme [7], in which packets within one TXOP duration are sent back-to-back without requiring additional channel contention.

VI. EVALUATION

A. Packet Reception Performance

A primitive function of Sampleless Wi-Fi is providing reliable packet reception at sub-Nyquist rates under various SNR conditions. We use USRP testbeds to evaluate its synchronization and decoding performance.

Experimental Setup: We conduct our experiments using two USRP nodes in a 10 m \times 10 m office. We vary the location and transmission power of USRP nodes to test Sampleless Wi-Fi under different channel conditions. We fix the location of the sender node and move the receiver node to different locations in the office. Unless otherwise stated, Sampleless Wi-Fi adds one (three) retransmissions for each packet at 1/2 (1/4)-Nyquist rate.

We compare Sampleless Wi-Fi with the state-of-the-art downclocking technique Enfold [5], which exploits under-sampled constellation characteristics for decoding. The comparison shows the merits of combining time shifted constellations in Sampleless Wi-Fi. We also show the performance of the standard 802.11 packet reception at the Nyquist rate as the benchmark.

Synchronization: First, we show that the Sampleless Wi-Fi addresses the synchronization issue at sub-Nyquist rates under low SNRs. We compare the joint synchronization over multiple transmissions with the previous synchronization algorithm in Enfold [5], which uses the cross-correlation of LTF in one transmission. We set the USRP receiver at full sampling rate to capture raw samples, and perform different synchronization algorithms offline for comparison. We use the synchronization algorithm at full sampling rate as the benchmark, and estimate the relative error of synchronization at sub-Nyquist rates. To perform under-sampling offline, we digitally downscale the sampling rate by decimation. We continuously send 5000 packets under each setting to estimate the error rate.

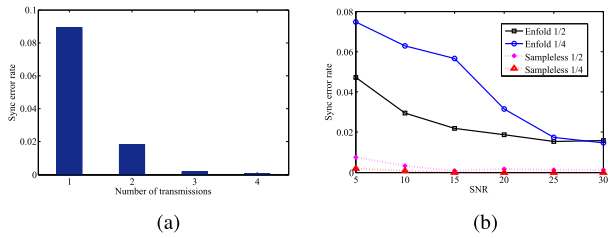


Fig. 8. Synchronization performance evaluation. (a) Joint synchronization error rate with various numbers of transmissions. SNR is set to be 10 dB. (b) Comparison with Enfold under various SNRs.

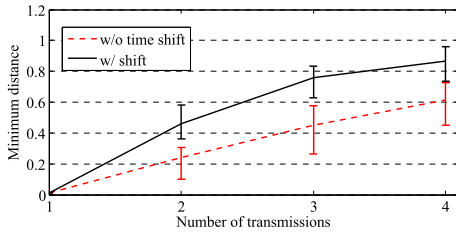


Fig. 9. Minimum distance at 1/4 Nyquist rate.

Fig. 8(a) evaluates the performance of joint synchronization at 1/4-Nyquist rate with various numbers of transmissions. The synchronization error drops significantly as the number of transmissions increases, and approaches zero at four transmissions. This shows the merits of using multiple LTFs to compensate the lack of LTF samples in one transmission. The number of samples at four transmissions equal to the samples at full rate in one transmission, and thus synchronization in these two cases performs the same. The observation in Fig. 8(a) explains the results in Fig. 8(b). For Enfold, the synchronization error rate grows substantially when SNR drops below 20 dB. This is because the lack of samples at sub-Nyquist rates fails to show strong correlation property over noise. Sampleless Wi-Fi employs joint synchronization to amortize this issue by combining multiple transmissions.

Retransmission Diversity: The decoding performance is dictated by the minimum distance between any two constellation points [12]. We set this experiment as follows. The USRP transmitter sends 5000 QPSK-modulated packets to the receiver node at 1/4-Nyquist rate. The receiver estimate channels and then derives the compound constellation map after channel equalization.

Fig. 9 compares the minimum distances by combining multiple transmissions. The minimum distance is normalized with respect to that of full clock rate. We observe that the minimum distance in one transmission is quite small. This is because frequency aliasing results in an irregular constellation of compound symbols, some of which are co-located, as illustrated in Fig. 4. This is the reason Enfold requires high SNR for decoding. By adding a time shift into each received packet, Sampleless Wi-Fi achieves $\times 1.5 - \times 2$ minimum distance compared to standard retransmissions. As such, Sampleless Wi-Fi can reliably decode under-sampled packets under low SNR conditions.

Sampleless Demodulation: We evaluate the reliability of Sampleless Wi-Fi under various SNR conditions. We use the same sampling rate for Enfold and Sampleless Wi-Fi for

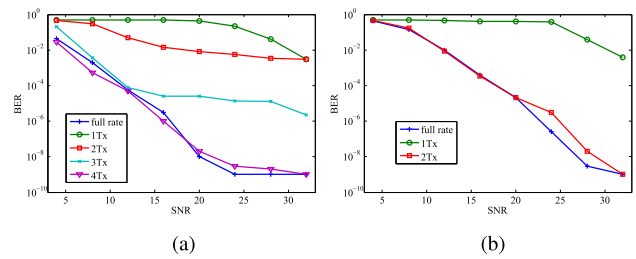


Fig. 10. BER under various numbers of transmissions. (a) QPSK at 1/4-Nyquist rate. (b) 16QAM at 1/2-Nyquist rate.

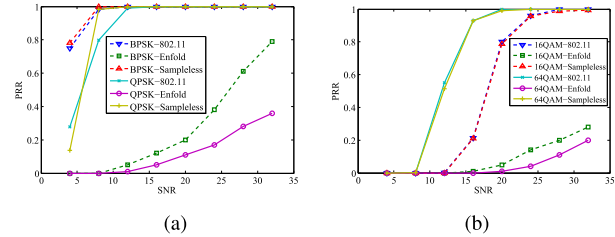


Fig. 11. PRR under various SNR conditions. (a) BPSK and QPSK. (b) 16QAM and 64QAM.

comparison, while using the full sampling rate for 802.11 as the benchmark. To keep reasonable decoding overhead, we use 1/2-Nyquist rate for PSK and 1/4-Nyquist rate for QAM by default.

Fig. 10 shows the BER of Sampleless Wi-Fi with various numbers of transmissions. We have the following observations: i) the down-sampled receiver suffers significantly high BERs for SNRs below 25 dB, and ii) the receiver with 1/ M -Nyquist rate requires M transmissions to achieve comparable BERs with respect to the receiver with the full sampling rate. The results demonstrate the necessity and merits of leveraging retransmissions for reliable under-sampled packet decoding.

Overall Packet Reception: We now evaluate the overall packet reception performance under a range of SNR conditions. We first measure the packet reception ratio (PRR), which is defined to be the ratio of the number of correctly decoded packets to the total number of packets. We use the same sampling rate for Enfold and Sampleless Wi-Fi, while using full sampling rate for the standard 802.11. The packet length is set to 100 bytes, and the coding rate is set to 1/2 for all modulations.

Fig. 11 show the results of these experiments. As shown in Fig. 11(a), Sampleless Wi-Fi achieves almost 100% PRR when SNR is over 8dB and 12dB for 1/2 BPSK and 1/2 QPSK, which is consistent with the performance of the standard 802.11. Fig. 12(b) also shows that Sampleless Wi-Fi and the standard 802.11 achieve comparable PRR for 1/2 16QAM and 1/2 64QAM. The results demonstrate that Sampleless Wi-Fi can maintain the decoding performance of the standard 802.11 for different modulation schemes under various SNR conditions. On the other hand, Enfold suffers from low PRR when SNR is lower than 20dB. This is because the Enfold needs under-selected modulation schemes, i.e., low-order modulation scheme under high SNR conditions, to create enough redundancy in PHY for decoding.

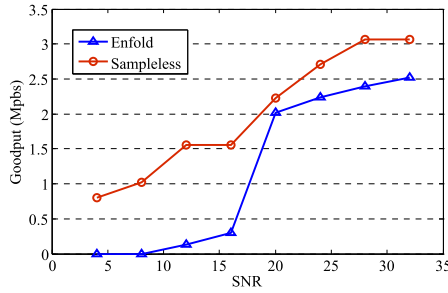


Fig. 12. Goodput under various SNR conditions. MCSs are selected according to the SNR-based rate adaptation.

As Wi-Fi transmissions normally select different modulation and coding schemes using rate adaptation schemes, we further compare the goodput of Sampleless Wi-Fi and Enfold with rate adaptation enabled in Fig. 12. The data rate for each transmission is selected based on the link's SNR according to the standard SNR-data rate mapping table as listed in [13]. We observe that Sampleless Wi-Fi achieves higher goodput compared to Enfold under all SNR conditions. When SNR is lower than 20dB, the goodput of Enfold diminishes quickly, while Sampleless Wi-Fi still maintains reasonable goodput. It shows that Sampleless Wi-Fi is applicable to receive legacy packets with rate adaptation enabled under various SNR conditions.

B. Energy Efficiency Performance

Since we cannot directly measure power consumption on Wi-Fi devices with sub-Nyquist rates, we turn to trace-driven simulations to evaluate the energy efficiency performance.

1) *Simulation Methodology*: We adopt a Wi-Fi power model [5], [14] to parameterize the network energy consumption of each device given its traffic traces. A Wi-Fi radio stays in a high power state when it is actively sending or receiving packets, while it switches to the idle state once packet transmitting/receiving completes. The radio further enters the light sleep state and then the deep sleep state if there is no network activities for a while. Detailed parameters are given in [4] and [14]. In our simulation, we use the power model to infer the instantaneous power of Wi-Fi radio, and combine traffic traces to compute the overall energy consumption. As Wi-Fi traces do not contain SNR, we estimate the SNR of each packet based on the data rate according to [13].

Large-Scale Wi-Fi Network Traces: We use the SIGCOMM'08 traces [15] to evaluate our design in real large-scale Wi-Fi networks. The SIGCOMM'08 trace captures Wi-Fi traces during the conference event that has a peak of 31 clients. The average inter-arrival times are 47 ms and 88 ms for TCP and UDP traffic, respectively.

Smartphone app Traces: To further understand the detailed energy efficiency of Sampleless Wi-Fi under various types of applications, we collect Wi-Fi traces of popular smartphone apps of different types. We cover both delay sensitive and non-sensitive apps, low data rate apps and bandwidth-hungry apps. Specifically, we select *Skype* (VoIP, 118 kbps), *FaceTime* (video call, 762 kbps), *Chrome* (website browsing, 196 kbps), *YouTube* (video streaming, 2150 kbps), *Instagram*

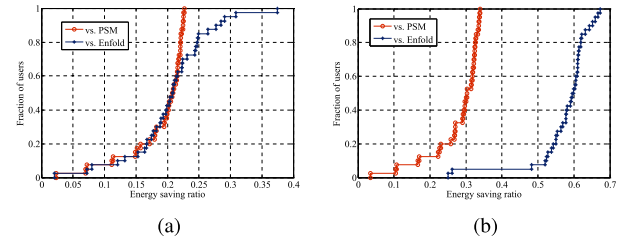


Fig. 13. Energy saving gain for large-scale networks. (a) 1/2 Nyquist rate. (b) 1/4 Nyquist rate.

(online picture browsing, 877 kbps), *Spotify* (music streaming, 636 kbps). These app traces are collected as follows. We set up a sniffer (ThinkPad X201) using *Wireshark*, and place it near an iPhone 5S, which is associated with an 802.11n AP. Each app is actively used for two minutes. There are around ten other active Wi-Fi devices on the same channel.

Baselines: We compare Sampleless Wi-Fi with the standard power saving mode (PSM) in 802.11 [16] and the state-of-the-art downclocking approach Enfold [5]. As Enfold only experiences extremely high packet loss rate for higher modulation schemes, we fix the data rate of Enfold to be 6 Mbps (1/2 BPSK) as suggested in [5]. Note that the packet loss rates of Enfold are consistent with [5]. We set the same sampling rate for Enfold and Sampleless Wi-Fi for comparison.

2) *Results*: Fig. 13 shows the energy saving ratios of Sampleless Wi-Fi compared to PSM and Enfold. At 1/2 Nyquist rate in Fig. 13(a), for 80% of the clients, Sampleless Wi-Fi saves 17.2% and 16.7% or more energy compared to PSM and Enfold, respectively. Though Enfold sets the same sub-Nyquist sampling rate as Sampleless Wi-Fi, its packet loss rate is high under normal indoor SNR conditions, thereby incurring substantial retransmission overhead and extra packet decoding energy costs. Compared with PSM, Sampleless Wi-Fi achieves comparable BER under all SNR conditions, and still harvests the benefits of under-sampling. At 1/4 Nyquist rate in Fig. 13(b), the energy saving ratios of Sampleless Wi-Fi grows to 25.8% and 55% compared to PSM and Enfold, respectively. This is because the packet loss rate of Enfold increases significantly, which overwhelms the benefits of lower sampling rate. Sampleless Wi-Fi overcomes this limitations by adding back-to-back retransmissions, which largely reduces the power consumption in all states at the cost of merely small duration increment in packet receiving state.

Fig. 14 compares the energy consumption under various types of smartphone apps. Sampleless Wi-Fi consumes 77.6% – 88.7% energy at 1/2 Nyquist rate, and 66.8% – 94% energy at 1/4 Nyquist rate compared to PSM. Sampleless Wi-Fi saves the most energy for *Skype* (22.4% and 33.2%), and the least energy for *YouTube* (11.3% and 6%). *Skype* provides a VoIP service that generates an ON/OFF UDP stream with intermittent short packets. The intermittent short VoIP packets leave room for multiple retransmissions in Sampleless Wi-Fi, while the frequent packet arrivals prevent PSM from entering the sleep state. On the other hand, *YouTube* prefetches chunks of video data at high data rates every few seconds. Sampleless Wi-Fi yields little benefit due to the heavy workloads of *YouTube*, while PSM enters the sleep state after

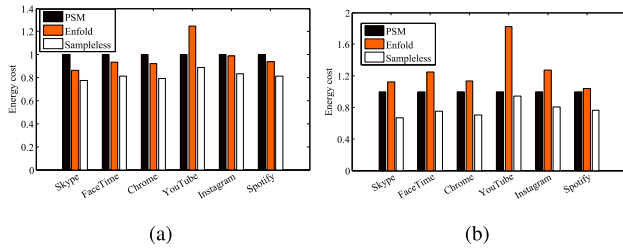


Fig. 14. Energy saving comparison for various smartphone apps. The energy cost is normalized with respect to PSM. (a) 1/2 Nyquist rate. (b) 1/4 Nyquist rate.

fast downloading periods. Sampleless Wi-Fi achieves appreciable energy savings for other apps: Chrome (20.7% and 29.6%), FaceTime (19% and 24.8%), Spotify (19.5% and 23.9%), and Instagram (16.8% and 19.6%).

VII. DISCUSSION

Sampleless Wi-Fi is a standard-compliant design that can be integrated with existing Wi-Fi networks. Sampleless receivers can communicate with commercial Wi-Fi APs and conform to 802.11 standards, as described below.

AP Modification: To support Sampleless Wi-Fi receivers, APs need to add a new scheduling algorithm, i.e., the Retransmission Scheduler, at MAC as shown in Fig. 2. When an AP sends packets to a Sampleless Wi-Fi receiver, the Retransmission Scheduler overrides legacy retransmission algorithm. Instead of waiting for ACK, the Retransmission Scheduler proactively send one or multiple retransmission packets back-to-back in one TXOP period or through aggregation [17]. The Retransmission Scheduler is an add-on at MAC, and can be implemented on commodity devices, e.g., by patching Openwrt and network interface card (NIC) drivers.

Data Scrambling: In IEEE 802.11, the raw bits are scrambled before mapping to subcarriers. Scrambling is used to randomize the raw bits to avoid long strings of binary 1s or 0s. Our current implementation uses IEEE 802.11a scrambler, where the raw bits are XORed with the scrambler bits with an initial state. We set identical initial state for sampleless retransmissions, which is consistent to [18]. The receiver deterministically derives the scrambling sequence, and then performs descrambling before demodulation. As the initial state and the scrambling sequence are identical for retransmissions, the data encoded on a subcarrier would be the same for retransmissions.

Rate Adaptation: Commercial APs may employ rate adaptation schemes to adjust the MCS of each packet. Commercially-implemented rate control algorithms, such as Auto Rate Fallback (ARF) [19] and MadWiFi Ministrel [20], mainly adjust the modulation and coding scheme of a packet by counting ACKs of previous transmission attempts. In Sampleless Wi-Fi, only one ACK is expected for a packet transmission and its following sampleless retransmissions. These retransmissions are considered as one transmission attempt, and thus are not counted as legacy retransmissions in rate adaptation schemes. Therefore, the MCS in sampleless retransmissions remain identical.

Channel Access: Sampleless Wi-Fi is fully compatible with 802.11 protocols. Sampleless Wi-Fi nodes conform to

CSMA/CA to contend channel, and enable multiple retransmissions of a packet using TXOP [7], which is proposed to improve MAC efficiency. During a TXOP period, the sender can send multiple packets without entering the backoff procedure, and then the receiver replies one block ACK. We leverage TXOP to enable consecutive retransmissions of repeated packets. As we target at devices with light workloads (e.g., VoIP, web browsing), the negative impact of increased transmission duration would be tolerable. Our evaluation using SIGCOMM'08 trace [15] shows that extra retransmissions in Sampleless Wi-Fi do not cause congestion.

VIII. RELATED WORK

Wi-Fi Downclocking: Several recent efforts have demonstrated the benefits and feasibility of downclocking Wi-Fi radios. E-Mili [3] first brings downclocking to design low-power Wi-Fi by reducing receiver's sampling rate during idle listening. E-Mili modifies packet preamble to ensure packet detection while downclocking. SloMo [4] leverages PHY sparsity in DSSS to decode 802.11b packets using downclocked radio. Enfold [5] extends SloMo to OFDM-based Wi-Fi. However, Enfold requires very high SNR (>25dB) and low-density modulation schemes to provide sufficient redundancy in constellation symbols. These approaches either require packet modifications [3], or large PHY redundancy that can hardly be guaranteed by today's Wi-Fi networks. Sampleless Wi-Fi overcomes this limitation by exploiting MAC redundancy, which can be easily satisfied by simple retransmission scheduling amendments.

Sparse Recovery: Our decoding algorithm is also related to sparse FFT [8], [9] and compressive sensing techniques [21], [22]. BigBand [9] utilizes sparse FFT [23] to allow multiple receivers of low sampling rates to perform GHz-wide realtime spectrum sensing. SEER [8] extend sparse FFT to non-sparse Wi-Fi band for preamble detection by designing a pulse-shape preamble structure. Different from sparse FFT techniques, our decoding algorithm exploits the sparsity lying in the constellation map based on the properties of time shifting and the idea of rateless transmission.

Power Saving Protocols: 802.11 PSM [16] puts devices into a low-power sleep mode whenever they are in inactive periods. Many variants of PSM have been proposed to dynamically adjust sleep mode periods based on traffic patterns [24], or extend the sleep mode to intervals between packets for devices with light workloads [25], [26]. However, the effectiveness of the PSM-based approaches is limited in real networks. First, the performance of these approaches heavily relies on traffic patterns, which are unpredictable in many cases [3], [4]. Additionally, the power used for contention and packet reception is not reduced. Finally, some popular frameworks allow applications to override the PSM mechanism, forcing Wi-Fi chipset to stay awake to retain application services. Sampleless Wi-Fi can still reduce power consumption in these cases as it decreases the sampling rates across all Wi-Fi states.

IX. CONCLUSION

This paper presents Sampleless Wi-Fi, an architecture that provides reliable communications between legacy APs and

low-power devices with various sampling rates. By exploiting the time shift effect on constellation mapping, Sampleless Wi-Fi leverages retransmission opportunities to decode legacy packets with sub-Nyquist rates under a wide range of channel quality conditions. The main merit of Sampleless Wi-Fi design is that it can be seamlessly integrated with existing Wi-Fi networks, and works reliably for various channel conditions and traffic types. Our experimental evaluation and trace-driven simulations validate Sampleless Wi-Fi in real Wi-Fi networks. We hope the design of Sampleless Wi-Fi can contribute the wireless community by improving the energy efficiency to mitigate the mismatch between high sampling rate required by Wi-Fi and the energy constraints of post-PC devices.

Sampleless Wi-Fi allows future low-end receivers to connect with existing Wi-Fi infrastructures to decode legacy packets at lower sampling rates under a wide range of SNRs. Sampleless Wi-Fi receivers can be seamlessly integrated into existing Wi-Fi networks with minimal modifications at APs. We believe that with these features, Sampleless Wi-Fi can provide some insights for future Wi-Fi receiver design.

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Wei Wang (S'10–M'16) received the bachelor's degree in electronics and information engineering from the Huazhong University of Science and Technology, Hubei, China, in 2010, and the Ph.D. degree from the Department of Computer Science and Engineering, Hong Kong University of Science and Technology. He is currently a Professor with the School of Electronic Information and Communications, Huazhong University of Science and Technology.



Yingjie Chen received the M.Phil. degree from Computer Science Department, Hong Kong University of Science and Technology, in 2012. He is currently a Research Assistant with The Hong Kong University of Science and Technology.



Lu Wang (S'09–M'14) received the B.S. degree in communication engineering from Nankai University in 2009, and the Ph.D. degree in computer science and engineering from the Hong Kong University of Science and Technology in 2013. She is currently an Assistant Professor with the College of Computer Science and Software Engineering, Shenzhen University. Her research interests focus on wireless communications and mobile computing.



Qian Zhang (M'00–SM'04–F'12) received the B.S., M.S., and Ph.D. degrees in computer science from Wuhan University, China, in 1994, 1996, and 1999, respectively. She was with Microsoft Research Asia, Beijing, China, in 1999, where she was the Research Manager of the Wireless and Networking Group. She was with the Hong Kong University of Science and Technology in 2005, where she was a Tencent Professor of Engineering and the Chair Professor with the Department of Computer Science and Engineering. She contributed the mobility and spectrum management of wireless networks and mobile communications.