# Design and Implementation of a Frequency-aware Wireless Video Communication System

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***Abstract*—In an orthogonal frequency division multiplexing (OFDM) communication system, data bits carried by each subcarrier are not delivered at an equal error probability due to the effect of multipath fading. The effect can be exploited to provide unequal error protections (UEP) to wireless data by carefully mapping bits into subcarriers. Previous works have shown that this frequency-aware approach can improve the throughput of wireless data delivery significantly over conventional frequency-oblivious approaches. We are inspired to explore the frequency-aware approach to improve the quality of wireless streaming, where video frames are naturally not of equal importance.**

**In this work, we present *FAVICS*, a Frequency-Aware Video Communication System. In particular, we propose three techniques in FAVICS to harvest the frequency-diversity gain. First, FAVICS employs a searching algorithm to identify and provide reliable subcarrier information from a receiver to the transmitter. It effectively reduces the channel feedback overhead and decreases the network latency. Second, FAVICS uses a series of special bit manipulations at the MAC layer to counter the effects that alter the bits-to-subcarrier mapping at the PHY layer. In this way, FAVICS does not require any modifications to wireless PHY and can benefit existing wireless systems immediately. Third, FAVICS adopts a greedy algorithm to jointly deal with channel dynamics and frequency diversity, and thus can further improve the system performance. We prototype an end-to-end system on a software defined radio (SDR) platform that can stream video *real-time* over wireless medium. Our extensive experiments across a range of wireless scenarios demonstrate that FAVICS can improve the PSNR of video streaming by 5$\sim$10 dB.**

## I. Introduction

According to Cisco Visual Index, mobile video will increase 25-fold between 2011 and 2016, accounting for over 70 percent of total mobile data traffic by the end of 2016 [6]. In fact, video streaming has already been increasingly used in our daily life, such as video chat, live broadcasting and mobile TV. The quality of wireless streaming video, however, is often unsatisfactory because of the unstable wireless channels.

One property of wireless channels that can be exploited to improve wireless streaming is frequency diversity. In a wireless multi-carrier communication system, such as OFDM, data bits carried by subcarriers are not delivered at an equal error probability. This is because each subcarrier can experience different signal attenuations due to the effect of frequency-selective fading [8], [11], [21].

The effect, however, can be exploited to provide UEP to wireless data by carefully mapping data bits into subcarriers. Previous works employing this approach have demonstrated significant throughput improvements of data transmissions [3]. We are inspired to exploit this approach to provide UEP for wireless streaming, where video frames are naturally not of equal importance.

In MPEG-4 AVC standard [13], one of the most commonly used formats for the recording, compression, and distribution of high definition video, I-frame is a basic frame for decoding a sequence of following video frames, thus is of more importance than P-frame or B-frame. In video streaming, the loss of I-frame will cause more serious degradations to video quality than the loss of P-/B- frames. Therefore, intuitively, I-frame should be better protected than P- or B- frames. If video frames can be loaded into subcarriers based on their importance, e.g. I-frames are loaded into more reliable subcarriers and P-/B- frames are mapped into less reliable subcarriers, it naturally provides UEP to video contents. To this end, we design and implement - FAVICS, a Frequency-Aware VIdeo Communication System.

**Design Goals:** FAVICS sets the following four design goals. (i) FAVICS is aiming to harvest the frequency diversity gain for wireless video streaming, rather than for generic wireless data delivery. (ii) FAVICS is trying to minimize channel feedback overhead and network latency induced by exploiting the diversity. (iii) FAVICS is targeting at working with existing wireless PHY (Wi-Fi style systems) and standard video codec (MPEG-4). It thus can facilitate immediate deployment and benefit existing systems. (iv) FAVICS is striving to deal with channel dynamics along with frequency diversity, which can further improve the performance.

**Challenges:** To this end, the design of FAVICS, however, posts non-trivial challenges. First, feeding back subcarrier information from a receiver to the transmitter can consume non-trivial bandwidth of networks. At the transmitter, aligning data bits to map into desirable subcarriers can be costly due to the lack of hardware support. It not only introduces extra latency to delay-sensitive video streaming, but also increases the power consumption of mobile devices. Second, the mapping from data bits at the MAC layer to OFDM subcarriers at the PHY layer is not a simple linear function. In fact, data bits will undergo a series of processing such as scrambling, FEC coding, interleaving, and modulating before they are mapped into OFDM subcarriers. Thus a careful bit manipulation at the MAC layer is needed to achieve the desirable mapping. Last but not least, the diversity exists in both temporal and spectral domains. Due to the dynamics of wireless channels, it is possible that even the best subcarrier at this moment is less reliable than any of the subcarriers at the previous or the next moment. In this case, the decision of mapping important bits into which subcarriers should also take time diversity into consideration.

**Contributions:** In this study, we present the design, implementation and evaluation of FAVICS that allows the wireless PHY to natively provide differential error protection to video contents. Briefly, the main contributions of our work can be summarized as follows:

- We design and implement a frequency-aware video communication system - FAVICS. We are the first to demonstrate the feasibility of exploiting frequency diversity on a full-fledged, real-time video communication prototype system. It is developed based on a software defined radio platform - WARP and can stream H.264 video over the air.
- In particular, we propose a series of techniques for FAVICS. First, FAVICS employs a low-overhead, low-complexity algorithm to search and feedback reliable subcarriers information from a receiver to the transmitter. Second, FAVICS employs a series of bit alignment processes to map data bits into subcarriers based on channel conditions fed back from the receiver. This avoids modifying the existing wireless PHY in Wi-Fi systems. Third, FAVICS introduces a greedy algorithm to jointly deal with channel dynamics along with frequency diversity, and thus further improves the system performance.
- We experimentally show significant performance gain of FAVICS over traditional systems in a range of wireless scenarios. In different experiments, we vary the modulations, the coding schemes, the levels of frequency selectivity, the transmit power, the location of receivers, the degree of external interference, and the mobility to demonstrate the efficacy and robustness of our system. Our results demonstrate 5∼10 dB PSNR gain of wireless video streaming over various experimental scenarios.

The rest of this paper is organized as follows. We first introduce the background in Section 2. We then describe the design of FAVICS in Section 3, and present the evaluation results in Section 4. Finally, the related works are discussed in Section 5, and conclusions are drawn in Section 6.

## II. Background

In this section, we provide a brief background on our system model, particularly on why we choose to use contiguous subcarrier allocations.

Loading bits to subcarriers based on the relative data importance is not the only way to explore frequency diversity. One alternative is to load different amount of bits into each subcarrier, such as the frequency-aware bit rate adaptation - FARA [21]. However, this approach requires non-trivial modifications to wireless PHY, and thus recent research advocates using the same bit rate (modulation) across subcarriers [3], [24]. We follow the trend as our goal is to harvest frequency diversity gain without modifications to existing wireless PHY.

### A. Channel State Information

According to the IEEE 802.11n-2009 standard [12], wireless network interface cards should report Channel State Information (CSI). The signal amplitude and phase specified by CSI describe how a signal propagates from a transmitter to the receiver, combined the effects of scattering, fading, and power decay with regard to distance. The SNR can then be derived from: $SNR = 10log_{10}(A^2/N)$, where A and N denote the amplitude and the average power of white noise, respectively. The frequency diversity can be reflected from the difference of SNR across subcarriers.

### B. Cost of Updating Reliable Subcarriers

The reliability of subcarriers can be measured by SNR. The higher the subcarrier's SNR is, the more reliable is the subcarrier. If we want to select the best *m* subcarriers out of *n* subcarriers, a naive approach is simply sorting the subcarriers by SNR, and then selecting the best *m* subcarriers. Because the best *m* subcarriers are not necessarily contiguous, we consider it *non-contiguous subcarrier allocation*. The alternative is *contiguous subcarrier allocation*, where *m* contiguous subcarriers with the highest aggregated SNR are selected.

With both approaches, there are two associated overhead - feedback overhead of updating reliable subcarriers, and processing overhead of bit-level interleaving. There is an important tradeoff between the performance and the overhead. The non-contiguous allocation gets a better SNR from selected subcarriers but incurs a higher overhead. On the other hand, the contiguous allocation has possibly a lower SNR but also introduces less overhead. In the follows, we argue that the latter is more suitable for our purpose due to its lower complexity and lower overhead.

We first compare the feedback overhead of two schemes. To load data bits into reliable subcarriers, it is sufficient to know which subcarriers are more reliable than the others at the transmitter. Thus only the sequence numbers of *m* reliable subcarriers are needed, but not their SNR values. For non-contiguous subcarriers, it takes $mlog_2n$ bits to feed this information back to the transmitter. If the subcarriers are contiguous, knowing the sequence number of the first subcarrier in the reliable group is sufficient, which only needs $log_2n$ bits. The IEEE 802.11a/g utilizes 48 data subcarriers over a 20MHz channel. The IEEE 802.11n, on the other hand, uses 108 data subcarriers over a 40 MHz channel. Assuming *m* is *n*/2 and the subcarrier information is fed back via ACK packet every 1 ms. When the non-contiguous scheme is employed, it takes extra 144 kbps for feedback per link in IEEE 802.11a/g, and 378 kbps per antenna in IEEE 802.11n. Consider a Wi-Fi network with 10 users, the feedback alone can easily consumes 1.44 Mbps for 802.11a/g, or 11 Mbps (assume 3 antennas are equipped at the AP) for 802.11n. In contrast, if the contiguous scheme is used, the overhead for 10 users reduces to 60 kbps and 210 kbps, respectively.

We next discuss the processing overhead. Mapping I- and P-/B- frames to different subcarriers requires interleaving data bits. Interleaving data bits with software/firmware alone is a time-consuming operation as it mostly manipulates data at bit level. For example, to deliver a 1000 byte packet with QPSK (2 bits per subcarrier), the non-contiguous scheme has to interleave every 2 bits of I-frame with every 2 bits

| Modulation | Non-cont. Allocation | | Cont. Allocation | |
|---|---|---|---|---|
| | CPU | Latency | CPU | Latency |
| QPSK | 278,343 | 1.20 | 37,884 | 0.15 |
| 16-QAM | 261,846 | 1.09 | 30,801 | 0.13 |

**TABLE I:** Processing overhead comparison: contiguous subcarrier allocation vs. non-contiguous subcarrier allocation. CPU time is measured by CPU cycles, and latency is measured by millisecond.

of P-/B-frame. In the worst case, the total number of *bit-level* operations is 4000 per packet. On the other hand, the contiguous scheme can align data bits by batch, which changes the nature of operation from bit-level to byte-level, or word-level. Consider the previous example again, we can reduce the number of interleaving operations to 334. Note this operation is associated with every video packet delivery. A large number of operations is not desirable not only because of the end-to-end latency increase, but also because of the increase of CPU load and power consumption in mobile devices.

Table I compares the overhead of two approaches with WARP (the specification of WARP can be found in Section IV). In particular, it measures the CPU time used for interleaving two video packets and the additional latency incurred for the same period. The payload length is 1374 bytes, which is the same as a real video packet when MPEG/RTP protocol is used for streaming. In terms of both CPU time and latency, the non-contiugous allocation spends almost 8 times more time on interleaving than the contiugous allocation does.

## III. Design of FAVICS

In this section, we propose a series of techniques for FAVICS, which include searching reliable subcarriers, aligning data bits for subcarrier mapping and jointly dealing with time diversity. In addition, we also explain the necessary modifications to existing Wi-Fi systems.

### A. Reliable Subcarrier Group Search

We first propose a simple sliding-window algorithm to identify the most reliable subcarrier subgroup. Given the SNRs of *n* subcarriers, we are interested in finding a subgroup consisted of *m* contiguous subcarriers that has the highest aggregated SNR. If we use a sliding window to sum up the SNR of *m* subcarriers within the window, then the problem becomes finding the window with the maximum value. One improvement we made is that we assume the subcarrier sequence is cyclic, and thus the windows does not stop sliding until its head slides to the last subcarrier. The sliding window algorithm is sketched in Algorithm 1, which has the complexity $O(n)$. On the other hand, if the non-contiguous subcarriers allocation is used, the complexity would be $O(n \log_2 n)$ because the sorting is necessary.

**Algorithm 1** Reliable subcarrier group searching at receiver

**Input:** SNR of n subcarriers: $s_1, s_2, ..., s_n$
**Output:** the first subcarrier *c* of the reliable group, average SNR $A_r$ (reliable group) and $A_n$ (all subcarriers)

```
S_m ← sum(s_1, s_2, ..., s_m)  //SNR sum of m subcarriers
S_n ← sum(s_1, s_2, ..., s_n)  //SNR sum of all subcarriers
S_max ← 0
c ← 1
for (i←1; i ≤ n; i++) do
    p ← (i+m) mod n        //use cyclic subcarrier shift
    S ← S - s_i + s_p
    if (S > S_max) then
        S_max ← S
        c ← i
    end if
    A_r ← S_max/m
    A_n ← S_n/n
end for
```

### B. MAC-Layer Data Bits Placement

After reliable subcarriers are identified, the next step is to interleave data bits at the MAC layer for subcarrier mapping at the PHY layer. Assume each of *n* subcarriers can carry only 1 bit (BPSK is used without coding), the total number of bits loaded to one OFDM symbol is *n*. We further assume the reliable group consists of the 1, 2, ... *n*/2 subcarriers, and the rest *n*/2 subcarriers belong to the unreliable group. To map the data bits into the subcarriers, we simply need to divide the data bits into groups with *n* bits in each. Within each data group, the first *n*/2 will be loaded into the reliable group and the rest *n*/2 will be mapped to the unreliable group. For video data, they are first queued in either I-frame queue or P-/B-frame queue based on the frame type. The data bits from both queues are then interleaved into the same OFDM symbol.

In a practical system, however, the loading process involves four more steps in digital domain - scrambling, forward error correcting (FEC) encoding, interleaving and modulating. Each of these can change the value, the order, or the combination of the both of the bit stream. For our purpose, we are concerned with the operations that change the *order* of bit stream because that essentially affects the bit-to-subcarrier mapping. In the next, we explain the necessary steps to counter the effect of these operations at the MAC layer.

**Impact of scrambler:** The purpose of scrambling is to eliminate the dependence of a signal's power spectrum upon the actual transmitted data, which avoids peak-to-average ratio (PAPR) that can degrade performance. The scrambler XORs each payload bit with a pseudo-random value, transforming potential long spans of constant values in payloads into randomized values. A reverse process at the receiver will recover the randomized values. Scrambler does change the values of bits, but neither changes the order of bits, nor inserts any extra bits, therefore it does not affect the mapping. No countermeasure is needed.

**Impact of FEC encoder:** FEC encoder can be categorized into systematic encoder and non-systematic encoder. The systematic encoder inserts *k* parity check bits for every the *j* payload bits. For non-systematic encoding, however, *j* data bits will be transformed into *j*+*k* bits without being able to tell which ones are parity bits and which are payload bits. For both types, FEC encoder inserts additional redundancy bits into the bit stream, and thus impacts the data-to-subcarrier mapping.

To fix this, the interleaving pattern of video bits should be adjusted based on the coding rate. If the FEC coding is enabled and the coding rate is 1/2, that means the encoder will insert 1 more redundancy bit for every payload bit. Suppose an OFDM symbol can still carry n bits, the total number payload bits loaded to each OFDM symbol should be n/2 and the other n/2 bits are reserved for parity bits added by FEC encoding. Among n/2 payload bits, n/4 bits of I-frame should be interleaved with n/4 data bits of P- or B-frame.

**Impact of interleaver:** Interleaving is referred as an operation at the PHY layer, thus is different from interleaving I-, and P-/B- frames at the MAC layer. Interleaving is used to further improve the performance of FEC coding. Many communication channels are not memoryless: errors typically occur in bursts rather than independently. If the number of errors within a code word exceeds the error-correcting code's capability, it fails to recover the original code word. Interleaving ameliorates this problem by shuffling source symbols across several code words, thereby creating a more uniform distribution of errors. The problem, however, is that it completely changes the order of bit stream, thus changes the mapping.

To fix, we propose to use a reverse process of interleaving - *deinterleaving* at the MAC layer to realign bit stream such that the bit stream can maintain its original order after being interleaved at the PHY layer. In this way, the data-to-subcarrier mapping is retained. The top of Figure 1 illustrates the operation of an interleaver. Without loss of generality, the input matrix in our example is simplified from a 6x8 matrix in a typical 802.11 system to a 3x4 matrix. The bit stream is first written into the input matrix by row. The interleaver, in wireless PHY, then reads bit stream out by column. The deinterleaver is introduced after bit stream has been placed properly but before fed into the PHY layer. Specifically, the deinterleaver first reshapes a 3x4 input matrix to a 4x3 matrix, and then reads bits out by column, as shown in Step 1 of Figure 1. In Step 2, the bit stream is read out by column. Note the change in the shape of the output matrix does not affect the order of bit stream, as bits are read out by row.

There is a problem, however. Deinterleaving can result in performance degradation since its effect is to disable interleaving at the PHY layer. To compensate this, we incorporate an additional MAC-layer process that shuffles bits stream within its subcarrier group. Together, we merge the two processes and term it as *shuffler*. Similarly, a reverse process - *De-shuffler* is introduced at the MAC layer of the receiver.

**Impact of Modulation:** Modulation determines the number of bits carried per subcarriers and thus the total number of bits contained per OFDM symbol. For example, BPSK, QPSK or16-QAM loads 1 bits, 2 bits, or 4 bits to each subcarrier respectively. Accordingly, we should decide the number of bits placed into each subcarrier group, and how subcarriers should be interleaved.

### C. When Frequency Diversity Meets Time Diversity

Wireless channel is highly dynamic. Our work explores the diversity in frequency domain, which is another knob to tune the video streaming quality. It is natural to jointly consider frequency diversity and time diversity.

**Traditional:** Input→Interleaver (PHY)→Output

$$\begin{bmatrix} 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \end{bmatrix} => \begin{bmatrix} 1 & 5 & 9 \\ 2 & 6 & 10 \\ 3 & 7 & 11 \\ 4 & 8 & 12 \end{bmatrix}$$

**FAVICS:**

Step1: Input→Deinterleaver (MAC)→M

$$\begin{bmatrix} 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \end{bmatrix} => \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \\ 10 & 11 & 12 \end{bmatrix} => \begin{bmatrix} 1 & 4 & 7 & 10 \\ 2 & 5 & 8 & 11 \\ 3 & 6 & 9 & 12 \end{bmatrix}$$

Step2: M→Interleaver (PHY)→Output

$$\begin{bmatrix} 1 & 4 & 7 & 10 \\ 2 & 5 & 8 & 11 \\ 3 & 6 & 9 & 12 \end{bmatrix} => \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \\ 10 & 11 & 12 \end{bmatrix}$$

**Fig. 1:** An example to demonstrate interleaver and deinterleaver.

Our previous strategy is that always loading important bits into the *m* subcarriers of the relatively reliable group. One problem with that is the *relativity*. It is possible that even the currently reliable group has a lower quality than the unreliable group at the previous or the next moment. Hypothetically, if we knew the channel status in the future, the problem could have been solved trivially via an optimized scheduling. In reality, however, the channel status is unpredictable.

We therefore propose a heuristic greedy algorithm to further improve the system performance. The transmitter records the average SNR $R_{avg}$ of all subcarriers in the last *n* frames. Every time it receives a new feedback from the receiver, it compares the new SNR value of reliable group $R_{new}$ with $R_{avg}$. If $R_{new}$ is larger than $R_{avg}$, I-frame should be loaded into the reliable subcarrier group; otherwise, the next payload will be filled up with P-, B-frame unless the P/B queue is empty. On the other hand, holding I-frame for too long will increase the latency. We thus set another threshold to limit the maximum number of packets transmitted back-to-back from the P/B queue. The process is described in Algorithm 2. Empirically, we choose *threshold* to be 5 and *n* to be 10.

There exists one possible improvement on this approach. The reliability of a subcarrier group is also affected by the frequency-selective fading. The more flat a subcarrier group is, the more reliable it is, provided the same SNR. Alternatively, the *average BER* across subcarriers can be used to measure the reliability of a subcarrier group [11]. In this work, however, we simplify the problem and assume that a higher SNR always indicates a better reliability regardless of its flatness, and leave the problem of interacting with bit rate adaptations for our future research.

### D. Overview of FAVICS System

This section explains the necessary modifications to frame format at the MAC layer and existing system architecture.

**Algorithm 2** Dealing with time diversity

**Input:** SNR of last n frames: $R_1, R_2, ..., R_n$, and SNR of the reliable group in the most recent frame: $R_{new}$

**Output:** whether I-frame is loaded to the next outgoing frame

load ← 0
$R_{avg}$ ← 0
**if** (txCount ≤ threshold) **then**
  $R_{avg}$ ← sum($R_1, R_2, ..., R_n$)/n
**end if**
**if** $(R_{new} > R_{avg})$ **then**
  load ← 1
  txCount ← 0
**else**
  txCount ← txCount+1
**end if**

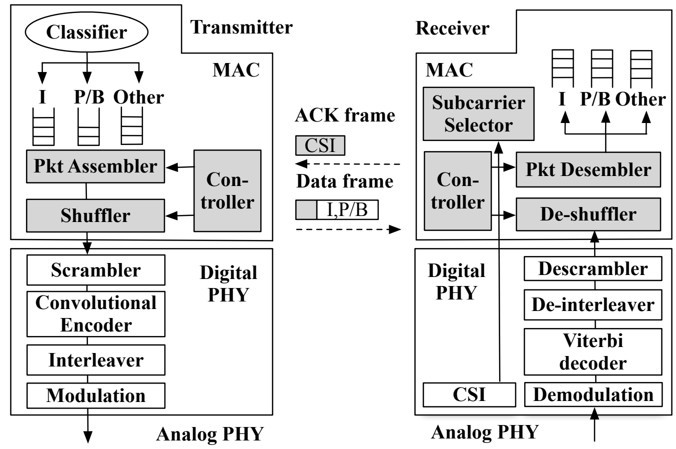



**Fig. 2:** System overview of FAVICS: shaded parts indicate newly added or modified components.

**Modifications to frame format:** A few modifications need to be made to the MAC layer frame header. Every time a receiver successfully receives a data frame, it identifies the reliable group and feed it back to the transmitter via an ACK frame. We first add a 8-bit field in ACK to include the sequence number of the first subcarrier of the reliable group, which is sufficient for maximum 256 subcarriers. In addition, to jointly deal with time diversity, two more octets are added. One is for the average SNR of the reliable group, and the other is for the average SNR of all subcarriers.

Because we only enable two priority groups, one extra length field (two octets) for I-frame is sufficient, and the length of P-or B- frame can be derived from the total length of a frame. However, the transmitter still needs to explicitly inform the receiver the mapping scheme (one octet) it uses to avoid the asynchronization problem, such as the loss of ACK frame. In total, we add three octets in ACK to feedback CSI, and add three octets in DATA header to inform data bit interleaving scheme.

**Modifications to MAC Layer:** We then describe modifications needed to a standard 802.11 a/g system to implement all features in FAVICS, and present it pictorially in Figure 2. All components in the figure are from the 802.11 a/g reference pipeline and the shaded parts indicate components newly added or components where some changes are needed.

At the transmitter, data traffic is classified into in three queues at the MAC layer - I-frame queue, P-/B-frame queue and other traffic queue. Our system allows for two priority levels, where only video traffic is considered to be prioritized. In a regular 802.11a/g pipeline, all data coming into the controller will be in a single queue and the maximum payload allowed is 1500 bytes. In FAVICS, we maintain the same total bytes for a single wireless frame, but allow the payload to carry a different number of bytes from I and P/B queues.

Base on the CSI information (subcarrier group and average SNR) feedback from ACK, the controller can then decide the interleaving pattern for the next frame. The payload frame will then be sent to the shuffler before passed down to the PHY layer. The frame then passes through the scrambler, the convolution encoder and the interleaver like in a regular 802.11 a/g pipeline. A similar, but reverse process would occur on the receive chain.

**Interaction with bit rate adaptation:** In general, any good rate adaptation scheme should ensure the property of UEP achieved via data-to-subcarrier mapping. We are aware of some state-of-the-art adaptation schemes, such as SoftRate [28] and Strider [10]. However, SoftRate requires information such as PHY layer confidence value that is not available in existing Wi-Fi systems, and Strider requires modifications to wireless PHY to enable the transformation from convolutional code to constellation map. We therefore choose to implement a rate selection scheme based on SNR in FAVICS [5]. As suggested by a recent research [26], the SNR-based approach can perform similarly to SoftRate in a relative static scenario where the channel coherence time is larger than 1 ms.

**Approximate communication:** Even if a video frame contains some erroneous bits, it is still a good approximation to the original video frame. Since video transmission can tolerate a certain degree of errors, it is suggested that erroneous frames should be kept, rather than be dropped completely [24]. In FAVIC, we reserve an erroneous frame if its MAC header is correctly decoded at the receiver (but the payload contains errors) and the transmitter has exhausted all of its retransmissions. The second condition can be easily known by the receiver if an incoming frame has a different MAC layer sequence number than the erroneous frame has.

## IV. Evaluations of FAVICS

We divide the evaluation process into two steps. In the first step, our goal is to validate the feasibility of basic system model. Although it has been shown that significant frequency diversity widely exists in Wi-Fi networks [3], the gain is harvested over non-contiguous subcarriers. In contrast, we want to demonstrate the frequency diversity of the contiguous subcarrier group. In addition, the previous work improves the throughput of generic data transmissions, and ours is to show the diversity gain can dramatically improve the streaming quality. In the second step, we prototype FAVICS with all proposed techniques implemented, and evaluate its performance in a range of wireless scenarios.

### A. Experiment Settings

**Hardware:** We prototype FAVICS on a software defined radio platform - WARP [22]. The WARP board is equipped with a 240 MHz PowerPC 405 embedded CPU and 32k on-chip memory. We use an OFDM reference design v16.1. Similar to IEEE 802.11 a/g, its wireless PHY implements a scrambler, a convolutional coder and a standard 64 subcarriers (48 for data) OFDM module. In addition, its MAC also uses CSMA/CA. Unlike IEEE 802.11 a/g, its channel is 10 MHz rather than 20MHz, and neither does it include an interleaver. As only MAC/PHY are implemented on WARP board, it relies on a connected computer for the upper layer processing. The computer and WARP are connected via bridged Ethernet interfaces. Video streaming generated from the computer (streaming server) is first sent to the WARP board over bridged interfaces, and then transmitted to another WARP board over the air. The video traffic will finally be passed over to the application layer of the receiving computer (streaming client).

**Video streaming:** In our experiments, we use standard reference videos - Akiyo and Highway in CIF format that are available at the Xiph.org foundation [31]. Each video is first looped a few times to get a playback length of 30 seconds, and then encoded to MPEG-4 format with *ffmpeg* tool [1]. *VLC* is used to stream videos, through RTP/MPEG Transport Stream, with a playout buffer of 1 second is introduced at the receiver. For each experiment, we present the average of 10 rounds of measurements unless stated otherwise.

**Metrics:** Frequency diversity is measured by BER. To measure BER, we send 10 million OFDM symbols filled with randomly generated data bits. For each OFDM symbol received, we calculate the BER for different groups. The video quality is evaluated by the Peak Signal-to-Noise Ratio (PSNR) [23], which is defined as a function of the mean squared error (MSE) between all pixels of the decoded video. A PSNR below 20 dB refers to a bad video quality, whereas a PSNR above 37 dB is considered to be excellent. The differences of 1 dB or higher are visible.

**Parameters:** A typical 802.11 PHY layer includes a convolutional code to provide further protection to data bits. We have experimented with different coding rate (includes 1/2, 2/3, 3/4, 1) in align with modulation schemes (BPSK, QPSK, 16-QAM), but choose to use the combinations of QPSK, 16-QAM, and the coding rate of 1/2 and 1 due to the simplicity. In addition, all experiments are conducted over 5 GHz bands to minimize external interferences.

**Schemes compared:** We primarily compare FAVICS with a traditional frequency-oblivious communication system (abbreviated as Trad.), which uses the same bit rate adaptation as FAVICS, but is not aware of video semantics.

A recent work - Apex maps bits to constellation map to provide UEP for video contents [24]. Because of the similarity, it will be interesting to compare the performance of Apex with that of FAVICS directly. However, due to the challenges in implementation, Apex was evaluated based on trace-driven simulations, while ours is a real-time communication system. We therefore consider a simplified variant of the approximate communication system (abbreviated as Approx.), where erroneous frames received at the PHY layer are regarded as an approximation to the original data and allowed to be passed up to the high layers. For this purpose, the CRC of erroneous frames needs to be recalculated. Unlike Apex [24], Apporx. does not consider mapping bits to constellation map.

### B. Validating Frequency Diversity Gain for Video Streaming

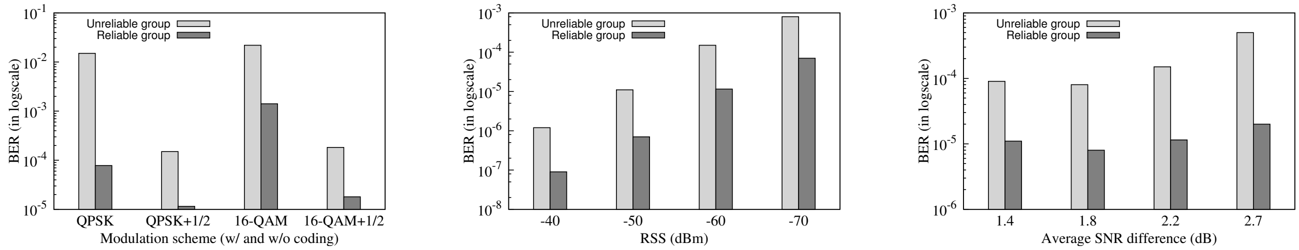
In particular, our experiments differ from those in [3] in three aspects. (i) We measure the frequency diversity at different level. While the previous work measures the SNR difference of individual subcarrier due to the adoption of the non-contiguous approach, we compare the reliability of contiguous subcarrier groups. (ii) We measure the frequency diversity by comparing the BER between subcarrier groups, rather than the SNR among subcarriers. (iii) The system gain from frequency diversity is measured by the PSNR of video, rather than by the throughput of data transmissions.

**Approach:** To show the difference of BER between subcarrier groups, the transmitter delivers a known bit stream to the receiver. At the receiver, the BER of the subcarrier groups can be calculated. Note that the specific subcarriers in each group is not static, and should be updated based on channel status. Yet, we always compare the BER between two groups.

To illustrate the BER difference can provide a significant performance gain to video streaming, we carry controlled experiments. In the controlled experiments, we can directly replicate the frequency diversity in wireless channel by adjusting the BER, and correlate that with the video quality. Specifically, the transmitter delivers video data to the receiver 3 meters away over a very reliable channel (the packet loss ratio is less than 0.01%). At the MAC layer of the receiver, we deliberately alternate certain percentage of payload bits. The percentage of alternation varies across I- and P-/B- frames, and should be based on the target BER.

**Varied modulations, with and without convolutional coding:** We first show that frequency diversity does provide UEP to the payload across different modulations regardless of whether convolutional coding is used. We plot the BER for different combinations of modulations and coding rate at an intermediate transmit power (RSS is -60 dBm) in Figure 3(a). Overall, convolutional coding improves the reliability significantly, compared with the cases without coding. Among all combinations, the contiguous subcarrier group with a better SNR consistently provides better protections to data bits. The difference in BER is at least of one order of magnitude, and in some case of two orders of magnitudes (QPSK). Due to the reliability of the QPSK combined with coding rate 1/2, this combination is used in the follows.

**Varied received signal strength:** We then examine the impact of received signal strength to UEP by moving the receiver to different locations. We calculate the BER when the RSS ranges from -40 dBm to -70 dBm. As shown in Figure 3(b), the reliable group can always provide about one order of magnitude lower BER than the unreliable group




(a) BER of varied modulations (b) BER of varied RSS (c) BER of varied frequency selectivity

**Fig. 3:** Impact of modulations, RSS or frequency selectivity on BER. Evaluated based on 10 million OFDM symbols transmitted.

does across all RSS levels. We thus conclude that frequency diversity exists regardless of the RSS values.

**Varied frequency selectivity:** We next present the BER performance when wireless channels exhibit different levels of frequency selectivity. The frequency selectivity is measured by the difference of average SNR between the two subcarrier groups. The larger difference in SNR indicates more frequency selectivity. To achieve different level of frequency selectivity, we change the direction and position of receiver's antenna. As shown in Figure 3(c), the BER of the two groups is even more imbalanced with the increasing level of frequency selectivity.

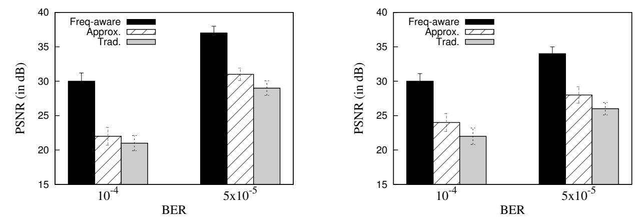
**Frequency diversity gain for video streaming:** We now emulate the BER behavior of channels and evaluate the potential gains for video streaming. Based on previous results, we choose two representative wireless scenarios where the BER of the unreliable group is $10^{-4}$ and 5x$10^{-5}$ respectively, and that of the reliable group is one order of magnitude lower. Figure 4(a) compares the performance of streaming Akiyo video with three different schemes - the frequency-aware approach, the traditional approach and the approximate communication. On average, the PSNR of the frequency-aware approach is 9 dB higher than that of the traditional approach at both BER levels. A similar case can be found in Figure 4(b) where Highway video is used.

Comparing the approximate communication with the traditional approach, we find the former gets about 2 dB high PSNR than the latter does. This confirms that the improvement of the frequency-aware approach is mostly attributed to the frequency diversity, rather than to the approximate communication. We thus validate that our basic approach is feasible and worthwhile for video streaming. However, the gain we showed so far is acquired in an ideal situation, where it implicitly assumes the UEP always exists and the feedback is always accurate. In the following, we implement the proposed schemes and measure the performance in realistic scenarios.

### *C. Evaluations of FAVICS*

In this subsection, we evaluate the performance of FAVICS from a variety of perspectives, and compare with the results of the traditional communication system.

**Harnessing time diversity:** We then evaluate the efficacy of the algorithm that jointly deals with time diversity and frequency diversity. First, we disable our enhancement technique and always load I-frames to relatively reliable subcarriers. Then, we enable the enhancement and load I-frames on relatively reliable subcarriers only if the SNR of that group is higher than the average SNR of all subcarriers of the past 10 frames. Comparing the results of two schemes (shown in Figure 5), we find that the streaming quality can be improved by 4 dB on average if the enhancement is used. Therefore, we always enable this enhancement in the following experiments.




(a) Streaming with Akiyo video (b) Streaming with Highway video

**Fig. 4:** Evaluating frequency diversity gain for video streaming via controlled experiments: frequency-aware approach vs. frequency-oblivious approaches.

**Dependency on video contents:** We next show the relative performance of FAVICS and the traditional approach for two different video clips, Akiyo and Highway, where the RSS of the wireless channel is around 60 dBm. As shown in Figure 6, FAVICS outperforms the traditional approach for both videos. The quality of Akiyo is slightly better than that of Highway because the former is less sensitive to packet loss.

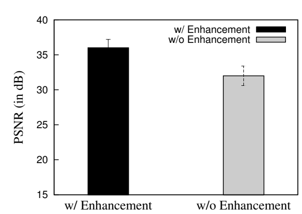



**Fig. 5:** Performance comparison when jointly considering time diversity (with Akiyo video).

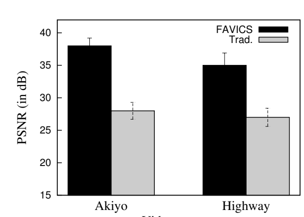



**Fig. 6:** Performance comparison with different video contents (Akiyo and Highway videos).

**Dependency on locations:** We then experiment how the system performance varies across different locations on the second floor of a two-story building at University of California Davis. The locations of transmitter and receiver not only impact how signal propagates over the time, but more importantly affect the selective fading at the spectral domain. We fix the location of the transmitter but move around the receiver within the building. The layout of the floor as well as the locations of transmitter and receiver are shown in Figure 7, where the square indicates the locations of the receiver and the circle is where the transmitter is placed. The streaming results across locations (L1∼L7) are presented in Figure 8. The relative performance difference between FAVICS and the traditional approach does not depend on the received signal strength. Rather it is the result of different levels of frequency diversity. For example, location L2 is closer to the transmitter than location L5, whose average PSNR is higher than that of L5. However, the frequency diversity gain at L2 is merely 5 dB, while the average PSNR at L5 is increased from 20 dB to 28 dB. Overall, the video quality is improved 5∼10 dB.

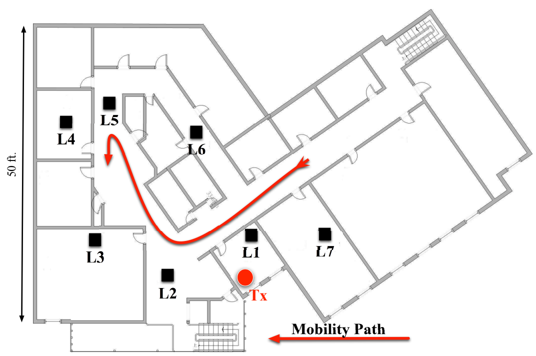



**Fig. 7:** FAVICS Indoor Measurement Layout

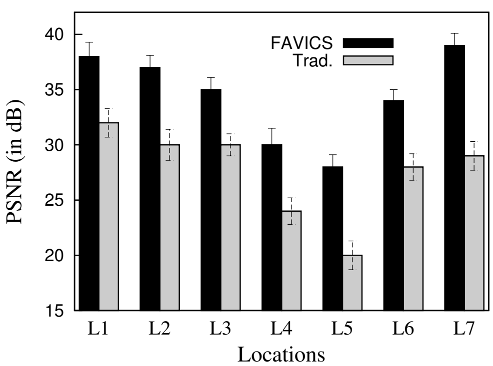



**Fig. 8:** FAVICS performance at different locations (with Akiyo video).

**Impact of mobility:** We next compare the performance of two approaches when the receiver is moving. The receiver is mounted on the top of a rolling table, and moved manually by an experimenter. The mobility path is indicated by a solid line in Figure 7. At the end of the path, if the video is still streamed, we turn around and continue the moving until it is finished. We also vary the speed from 0.5 meter/second to 1 meter/second. The speed is estimated based on the distance and the duration of the streaming, and assumed to be nearly constant during the tests. As shown in Figure 9, FAVICS outperforms the traditional approach by 6.5 dB. With the increase of speed, the video quality declines slightly because the feedback about channel status becomes less accurate.

**With external interference:** In reality, wireless channels often suffer from external interferences. We next test the performance of FAVICS when it coexists with an interfering source. We vary the level of interference by changing an

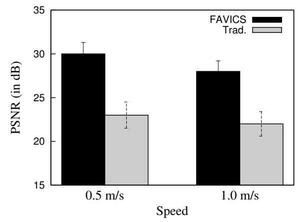



**Fig. 9:** Performance comparison with two different walking speed.

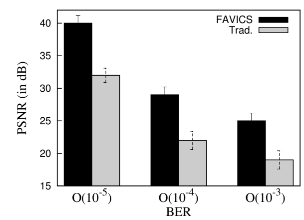



**Fig. 10:** Performance comparison when interference is presented.

USRP's transmit power and central frequency. USRP1 can only support up to 800 KHz, and WARP uses 10 MHz channels. To create an interfering scenario, we adjust the the transmit power of USRP as well as the distance between the two central frequency from 7 MHz to 9 MHz. In addition, we also raise the carrier sensing threshold of WARP, which allows WARP to deliver traffic even when the interference is presented. In this way, the subcarriers on the boundary of WARP's operational channel have lower SNR, while the other subcarriers have higher SNR. Due to the fluctuation of the transmit power of USRP, we can only estimate the order of WARP's BER with each configuration. As shown in Figure 10, both FAVICS and the traditional approach suffer from the increasing interference. However, FAVICS has a better interference resilience, and its PSNR is 7 dB higher than that of the traditional approach on average due to the careful placement of video bits.

## V. Related Works

A large body of research on frequency diversity has focused on exploiting frequency diversity in a multiuser scenario. Typically in an OFDMA network such as WIMAX, each user is dynamically assigned a subset of subcarriers with the best quality to itself, and thus the overall utility of all subcarriers can be maximized [4], [9], [16], [30]. They are, however, mostly based on theoretical analysis with limited simulation results. Ours differs from them in that we not only give more practical considerations in system design, but also present a wide range of empirical results to validate the proposed techniques.

To harness frequency diversity over a large bandwidth (100 MHz), FARA proposes to load different amount of bits based on sub-band quality [21], which requires varied bit rates across subcarriers. For Wi-Fi networks using 20 MHz channels, Halperin et al. empirically show the existence of frequency diversity [11] and Li et al. explore it for retransmissions [17]. In addition, Bhartia et al. propose to load important data bits (e.g. packet header is more important than payload) into reliable subcarriers [3]. We are inspired by this work to explore the frequency diversity for wireless streaming. Apart from that work, FAVICS is concerned by the quality of wireless streaming, and is additionally considering limiting feedback, processing overhead and striving to work with existing wireless PHY. Nevertheless, the performance of FVICS can be further enhanced by the scheme in [3] if the importance of bits is exploited at a finer granularity (e.g. load the frame header of P-/B-frames along with I-frame data into reliable subcarriers.)

FAVICS is also related to a few other state-of-the-art wireless video communication systems. RECOG enables video streaming over cognitive radio system by carefully redesigning the spectrum sensing and QoS modules, but does not touch upon the video-subcarrier mapping [27]. Both FlexCast and SoftCast suggest to use a non-standard video codec to improve the quality of mobile video [2], [14]. Further, ParCast jointly considers the source coding and the frequency diversity, but takes non-trivial modifications to video codec and wireless PHY [19]. Thus it cannot run in real-time due to the high complexity in implementations. Using standard video codec, Apex provides UEP to video contents via mapping video frames into different constellation points. To be beneficial, this approach requires wireless PHY to be aware of video semantics and requires a channel with a high SNR to support dense constellation (16-QAM or above). FAVICS has none of these onerous requirements. It is designed to work with standard video codec, existing wireless PHY, and benefit at a wide range of SNR.

Many previous research tries to provide UEP to video contents through tuning PHY layer parameters. This includes adjusting the PHY bit rate in unicast transmissions [7], [15] and in multicast transmissions [25], or varying the maximum retransmission limits per packet with video content [18], or adding different amount of FEC coding to different video payload [29], [32] as well as adapting bit rate and channel width simultaneously [20]. Different from those works, ours explore frequency diversity to provide UEP for video contents.

## VI. Conclusion

In this work, we present the design, implementation and evaluation of FAVICS, a wireless video communication system to harvest frequency diversity gain. In particular, we propose a series of techniques to enable FAVICS: to identify reliable subcarriers with low overhead and to interleave data bits with low latency; to work with existing Wi-Fi like system without modifing wireless PHY; to be able to jointly deal with time diversity along with frequency diversity. We prototype an end-to-end system based on WARP that can stream video real-time over wireless medium. Our extensive evaluations verify the efficacy and robustness of FAVICS, which demonstrates 5$\sim$10 dB improvement on the PSNR of videos across a range of wireless scenarios.

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