

Opportunistic Error Correction for WLAN Applications

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Abstract—The current error correction layer of IEEE 802.11a WLAN is designed for worst case scenarios, which often do not apply. In this paper, we propose a new opportunistic error correction layer based on Fountain codes and a resolution adaptive ADC. The key part in the new proposed system is that only packets are processed by the receiver chain which have encountered “good” channel conditions. Others are discarded. With this new approach, around $\frac{2}{3}$ of the energy consumption can be saved compared with the conventional IEEE 802.11a WLAN system under the same channel conditions and throughput.

Index Terms—Fountain codes, resolution adaptive ADC, OFDM, IEEE 802.11a.

I. INTRODUCTION

THE wireless channel is a very hostile environment. Therefore, it is a challenge to communicate both reliably and with a high throughput. In this paper, we investigate a novel error correction layer based on Fountain codes, Orthogonal Frequency-Division Multiplexing (OFDM) and an opportunistic Analog-to-Digital (AD) conversion to mitigate the effects of a wireless channel at a lower power consumption compared to traditional solutions.

In the current generation of wireless LAN equipment (based on IEEE 802.11a [1]), the Forward Error Correction (FEC) layer is based on Rate Compatible Punctured Codes (RCPC). These codes have good performance for random bit-errors and less performance for burst bit errors. For that reason, an interleaver is applied to randomize the burst errors of the wireless channel. On the other hand, the wireless channel is changing in time. This means that some packets are received with a “good” channel and others by a “bad” channel. The error correction layer based RCPC has been designed in such a way, that for most channel realizations, the Bit-Error Rate (BER) is zero. For a small part of the channel, bit errors will occur and retransmission is necessary. Although this solution works well in practical systems, it is not optimal for two reasons:

- Packets which have encountered “bad” conditions are still processed by the entire receiver chain.
- The error correction layer is based on worst case scenarios. This means that for most packets, the code rate and hence capacity could be increased.

In this paper we propose a new error correction layer, which does not have these disadvantages.

The outline of this paper is as follows. We propose two techniques to lower power consumption: Fountain codes and

a resolution adaptive AD Converter (ADC). First, Fountain codes are discussed, which is followed by the resolution adaptive ADC. Then, a description is given of the IEEE 802.11a system model and includes our proposed modifications. Finally, the simulation results are described, which compare the conventional 802.11a system with our modifications. The paper ends with conclusions and future work.

II. FOUNTAIN CODES

At the end of last century, a new class of error correction codes were invented, called *Fountain codes* [2]. The encoder of a Fountain code is a metaphorical fountain that produces a stream of encoded packets. Now, anyone who wishes to receive the encoded file holds a bucket under the fountain and collects enough packets to recover the original file. It does not matter which packets are received, only a minimum amount of packets have to be received correctly.

At each clock cycle, labeled by n , the encoder chooses randomly several packets, and computes the bitwise sum of these source packets to generate the corresponding transmitted packet. Not only a random selection of packets has been made, also how many packets are used, is random. In addition, the encoder generates K bits G_{kn} , to indicate which packets are selected.

So, the encoded packet at clock cycle n is:

$$t_n = \sum_{k=1}^K s_k G_{kn} \quad (1)$$

in which t_n is the encoded packet at the n^{th} clock cycle, s_k the k^{th} source packet and G the generator matrix. The Fountain code can supply us with a stream of packets, according to equation 1. In practical situations, however, only a fixed number of packets are generated. At the receiver side enough packets (N) have to be received for successful decoding. In order to recover the source packets, we need to know the generator matrix whose columns are corresponding to these received packets. So, we could assume the matrix G is generated by a deterministic random-number generator and the receiver has an identical generator that is synchronized to the encoder’s [2]. Alternatively, the transmitter could pick up a random key, k_n , which is used to generate the set of K random bits at each clock cycle. The random key is put in the head of the transmitted packet and the receivers can also use this random key for decoding. After receiving N packets, the receiver can get the corresponding generator matrix G which is used for decoding. This is shown in Figure 1.

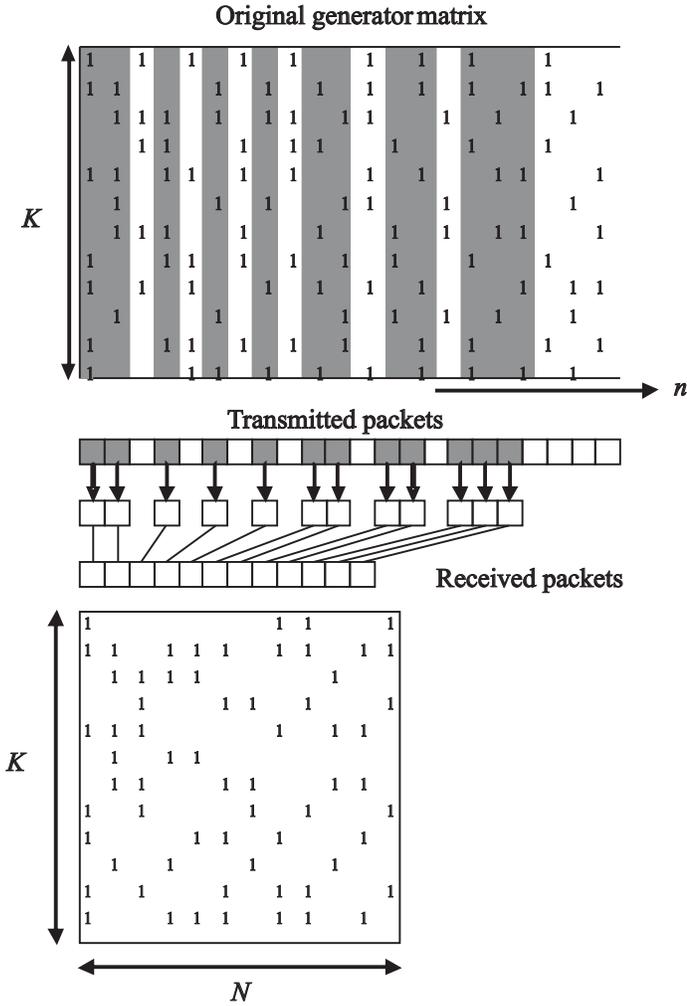


Fig. 1. The generator matrix of a fountain code (top). When the packets are transmitted, some are not received, shown by the grey shading of the packets and the corresponding columns in the matrix. We can realign the columns to define the generator matrix, from the point of view of the receiver (bottom), taken from [2].

In practical systems, Fountain codes are used in combination with other error correction algorithms, often Low-Density Parity-Check (LDPC) codes [3]. So, Fountain codes are first applied. In the next stage, to each group of Fountain encoded packet a Cyclic Redundancy Check (CRC) is added and encoded with a LDPC code. It will use the CRC, to determine whether a packet has been received correctly.

In this paper, we propose to transmit on each sub carrier of the OFDM system, a separate Fountain code packet. The general idea is, that if a sub carrier has a "bad" channel, it will be discarded. Only "good" sub carriers are decoded. If enough packets have been received, the receiver stops. The key problem is to choose the suitable parameters. Here, we have designed the system in such a way, that it has the same throughput as a traditional WLAN 802.11a system. More details can be found in Section IV.

III. RESOLUTION ADAPTIVE ADC

Wireless channels in OFDM systems are fading channels and modelled as frequency selective channels [4], [5]. An

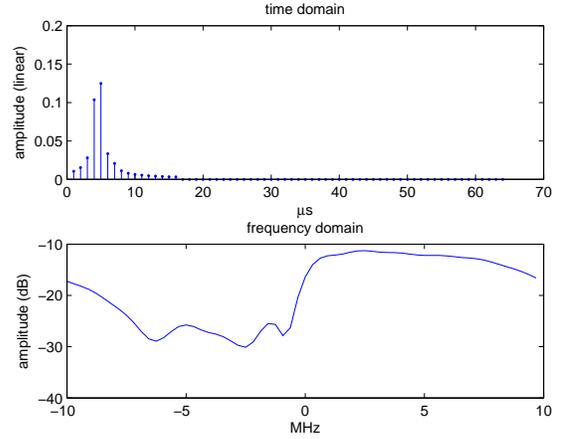


Fig. 2. Frequency selective channel

example is depicted in Figure 2. If a "bad" channel¹ is encountered, the required dynamic range of the ADC is higher than for a "good" one². In addition, the ADC power consumption can be almost 50% of the total baseband power consumption [6]. This means that there is a need for a resolution adaptive ADC. A CMOS implementation of such an ADC is described in [7]. In this implementation, the power consumption scales linear with the number of quantization levels.

In OFDM receivers the demodulation of the sub carriers is performed in the frequency domain. For that reason, it is not known, how many ADC bits are necessary for proper decoding. In [8], the authors have derived a relation between the quantization noise in the time and frequency domain. However, only results were shown for non-fading channels. In this section, we present a scheme to design an optimum low-resolution ADC for the frequency selective channels.

Because the quantization noise depends on the signal, we first analyze the statistical characteristic of the ADC input r_n . The channel is supposed to be noiseless, so the output at the n^{th} moment r_n is defined as:

$$r_n = \sum_{l=0}^{L-1} h_l x_{n-l} \quad (2)$$

where L is the number of channel taps, h_l the channel taps and x the transmitted signal. We assume that the quantization noise is dominant so the channel noise is ignored in this paper. From [8], we know that x_n is a complex Gaussian-distributed random variable with zero-mean and a variance of 1. The elements in vector $[x_0, x_1, \dots, x_{N-1}]$ are mutual independent.

According to the *central limit theorem* [9], the sum of a sequence of independent, identically distributed random variables tends to be Gaussian-distributed, so the PDF of r_n can be defined as:

$$f(r_n) \approx \frac{1}{\pi} e^{-\frac{|r_n|^2}{\sum_l |h_l|^2}} \quad (3)$$

¹A "bad" channel means a large difference in energy between sub carriers i.e. a large dynamic range of the ADC is required.

²A "good" channel on the other hand is when e.g. flat fading occurs.

In other words, $r_n \sim \mathcal{CN}(0, \sum_l |h_l|^2)$.

The ADC output y_n is expressed by:

$$y_n = \mathcal{Q}(r_n) = \sum_l h_l x_{n-l} + n_n \quad (4)$$

where n_n is the quantization noise in the time domain. From [8], we know that n_n is uniform distributed with zero mean and a variance of $\frac{\Delta^2}{6}$, where Δ is the uniform quantization step.

After the OFDM demodulation, we have Y_k as:

$$\begin{aligned} Y_k &= \frac{1}{\sqrt{N}} \sum_n y_n e^{-j\frac{2\pi}{N}nk} \\ &= \frac{1}{\sqrt{N}} \sum_n \sum_l (h_l x_{n-l} + n_n) e^{-j\frac{2\pi}{N}nk} \\ &= \frac{1}{\sqrt{N}} \sum_n x_{n-l} e^{-j\frac{2\pi}{N}(n-l)k} \sum_l h_l e^{-j\frac{2\pi}{N}lk} \\ &\quad + \frac{1}{\sqrt{N}} \sum_n n_n e^{-j\frac{2\pi}{N}nk} \\ &= \sqrt{N} H_k X_k + N_k \end{aligned} \quad (5)$$

where N_k is the quantization noise in the frequency domain. In [8], the authors have proved that N_k is a Gaussian distributed random variable with zero mean and a variance of $\frac{\Delta^2}{6}$. Thus, for each sub carrier, the variance of quantization noise is the same, but the Signal-to-(quantization)-Noise Ratio (SNR) is different due to different fading which is defined as:

$$\text{SNR}_k = \frac{|H_k|^2}{\frac{\Delta^2}{6}} \quad (6)$$

where H_k is the fading over the k -th subcarrier. As we know, error correcting codes are applied to mitigate the effects of quantization and each code has a certain SNR threshold when BER is at a certain order (e.g. 10^{-4}) or lower. So, Δ can be determined once the error correcting code is chosen and the channel is perfect estimated. In practical systems, the ADC resolution is finite. This means that for the same channel, the required dynamic range of the ADC is larger for higher code rates.

If some clipping is allowed, the number of quantization levels N_q is given by [8]:

$$N_q = 2 \left\lceil \frac{C}{\Delta} \right\rceil \quad (7)$$

where C is equal to $3\sigma_{r_n}$.

The power consumption of the ADC is proportional to the number of quantization levels (N_q). The latter is related to the Effective Number Of Bits (ENOB) by:

$$N_q = 2^{\text{ENOB}} \quad (8)$$

Thus, N_q is a measurement for the power consumption:

$$P = \sum_{i=0}^{M_c-1} \alpha_i N_{qi} \mathcal{M} \quad (9)$$

where M_c is the number of channel realizations, α_i is the percentage of the i -th channel realization where useful information is transmitted, N_{qi} is the number of quantization levels

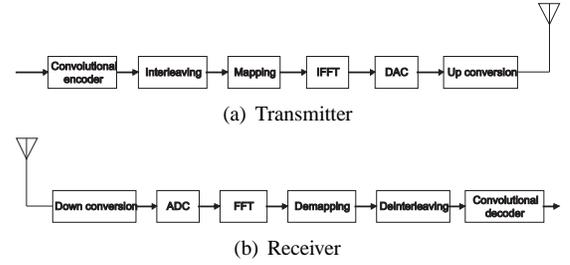


Fig. 3. Conventional 802.11a transmitter and receiver

used in the i -th channel realization, and \mathcal{M} is the number of samples per MAC frame.

IV. SYSTEM MODEL

In this section, the system model of a IEEE 802.11a transceiver is discussed as shown in Figure 3. It is a simplified model with focus on the (de)modulation en (en/dec)oding of the bit stream. This means that we assume that there is no adjacent channel interference. In addition, we assume that we have perfect channel knowledge.

In Figure 3, the source bits are encoded by convolutional encoder (RCPC) and interleaved. This results in a bit group called *channel bits*. The channel bits are converted into complex symbols (BPSK/QPSK/16-QAM/64-QAM) by the mapping function which are transmitted over N subcarriers. An inverse FFT (IFFT) function is applied to generate the time domain signal. This time signal is converted to the analog domain by Digital-to-Analog Converters (DACs) and up converted to Radio Frequencies (RF). In the receiver, the reverse process takes place. First, the RF signal is mixed to a complex baseband signal and quantized by ADCs. The output signal is then converted to the frequency domain by the FFT function and de-mapped into channel bits. The channel bits are de-interleaved and decoded by the convolutional decoder to get the source bits.

Although this solution works well in practical systems, it is not optimal. First, because packets that have encountered a “bad” channel condition are still processed by the entire receiver chain. In addition, the error correction layer is based on worst case scenarios. This means that for most packets, the code rate and hence capacity could be increased.

In Figure 4, we propose a new error correction layer that mitigates both problems. It is based on LDPC and Fountain codes. The key idea is to generate additional packets by the Fountain encoder. First, the source packets are encoded by the Fountain encoder. Then, a CRC checksum is added to each Fountain encoded packet and LDPC encoding is applied. Each encoded group is transmitted on one sub carrier of the OFDM system. At the receiver side, we assume the channel estimation and synchronization are perfect. If the SNR of the sub carrier is equal to or above the threshold which is 12 dB for the used LDPC, the received Fountain encoded packet will go through LDPC decoding, otherwise it will be discarded. This means that the receiver is allowed to discard several sub carriers (i.e. packets) to lower the dynamic range of the ADC and hence the power consumption. After the LDPC decoding,

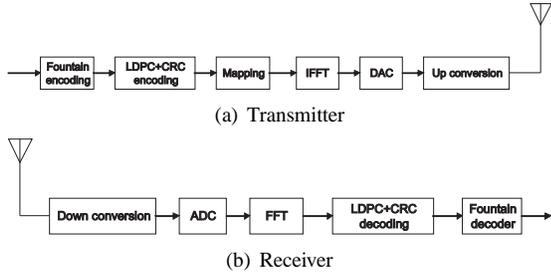


Fig. 4. Proposed 802.11a transmitter and receiver

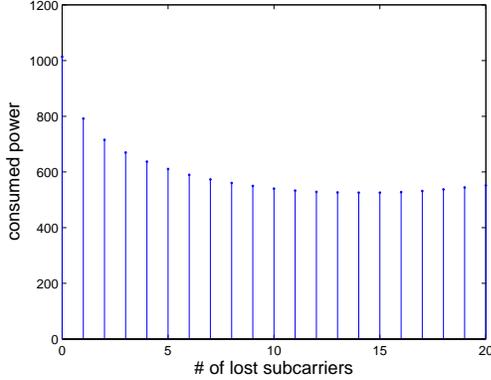


Fig. 5. Power consumption versus the number of lost sub carriers for a Fountain code with a packet size of 168 bits.

the CRC checksum is used to discard erroneous packets. As only packets with a high SNR are proceeded by the RX, this will not happen very often. In Figure 5 the relation is depicted between power consumption (dynamic range) and the number of discarded sub carriers. In each case the same amount of information was transmitted and the sub carriers with the lowest energy were discarded. When 14 sub carriers are discarded, the minimum power consumption is reached.

In the next section, we compare both systems for the same bit rate.

V. PERFORMANCE ANALYSIS

In this section we compare three scenarios. Channel *model A* [10] is used in our simulations and we simulate at least 1 million bits. The first scenario, Scenario I, is a conventional IEEE 802.11a system with mode 16-QAM and code rate $\frac{1}{2}$. This mode has a throughput of 24 Mbit/s (source bits). As the standard allows 10% packet loss [1], the effective throughput is $0.9 \cdot 24 = 21.6$ Mbit/s. Moreover, we assume that conventional ADCs are used. In Scenario II, the conventional ADCs are replaced by resolution adaptive ADCs. Finally, in Scenario III, we designed the new opportunistic error correction layer, which has the same effective throughput as Scenario I.

In our simulations, we use the parameters in Table I. The “SNR in frequency domain” is the minimal SNR for each sub carrier. If this value is met, the Packet Error Rate (PER) will be less than 10%, as required by the standard [1]. Symbols are transmitted in bursts (i.e. MAC frame) and in 802.11a, 500 OFDM symbols are packed into one burst.

	Scenario 1	Scenario 2	Scenario 3
ADC	normal	res. adapt.	res. adapt.
FEC	RCPC	RCPC	LDPC + Fount. codes
Code rate	0.5	0.5	0.66
Modulation	16-QAM	16-QAM	16-QAM
N_c	48	48	48
N	64	64	64
N_s	500	500	500
Effective throughput	21.6 Mbit/s	21.6 Mbit/s	21.6 Mbit/s
SNR			
in freq. domain	9.0 dB	9.0 dB	12.0 dB

TABLE I
SYSTEM SETUP COMPARISON FOR THREE SCENARIOS (N_c - THE NUMBER OF DATA CARRIERS, N - THE NUMBER OF SUBCARRIERS, N_s - THE NUMBER OF OFDM SYMBOLS PER MAC FRAME)

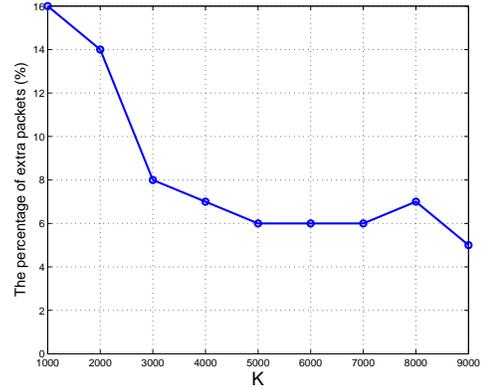


Fig. 6. The overhead of Fountain codes (LT codes, $c = 0.03$, $\delta = 0.3$)

From Figure 5, one can derive that the minimal power consumption for Scenario III will be reached if about 14 subcarriers can be discarded. So, the LDPC and CRC checksum have to be designed in such a way, that both the total throughput is equal to Scenario I and about 14 sub carriers can be discarded by the receiver.

So, we replace the error correction layer by a 7-bit CRC checksum and a LDPC code (175,255) which has a code rate of 0.66. For the Fountain code part, we use a Luby Transform (LT) code with parameters $c = 0.03$ and $\delta = 0.3$. The resulting Fountain code packets are transmitted on separate sub carriers and over multiple MAC frames. On average 13 sub carriers can be discarded by the receiver, which is near the optimal value of 14.

Fountain codes always need some extra packets for successful decoding. The theoretical overhead of LT codes is present in [2], but it is not suitable for practical system. Figure 6 shows the practical overhead of LT codes for $c = 0.03$ and $\delta = 0.3$. The overhead becomes smaller for a larger number of source packets as shown in Figure 6. For 5000 source packets (of which each contains 168 source bits), the overhead is 6%. This means that the receiver needs to receive at least 5300 Fountain code packets for successful decoding. Although larger packets decrease the overhead, it also results in more delay. In case of 5000 packets, the delay is acceptable and around 40 ms.

Figure 7 shows the consumed power (per 1000 source

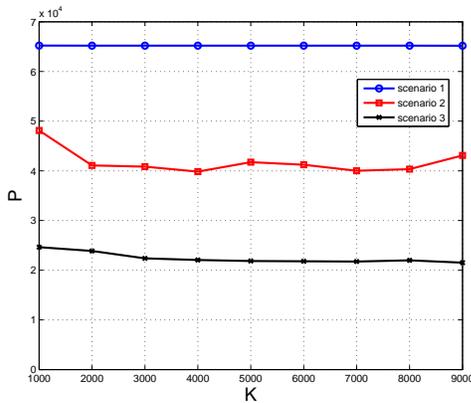


Fig. 7. The power consumption (defined in equation 9) per 1k source bits.

bits) for each scenario versus the Fountain Code block length K . For each simulation point 1000 Fountain code bursts are transmitted. The power consumption in Scenario I is constant for each K since the conventional ADC is designed for worst case. In Scenario II, the power consumption is about 62% of the power consumed in Scenario I. The difference in the power consumption for different K in this scenario is due to the channel randomness. In Scenario III, the power consumption for different K is inversely proportional to the overhead of LT codes. The average power consumption for receiving 1k source bits in Scenario III is about 54% of the average power consumed in Scenario II and about 33% of the average power consumed in Scenario I.

Thus, the resolution adaptive ADC can save around 38% power and the new opportunistic error correction layer can save an additional 29% power consumption.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we propose a new opportunistic error correction layer for IEEE 802.11a based on Fountain codes and a resolution adaptive ADC. The ADCs in a receiver can consume up to 50% of the total baseband energy, so it is advantageous to lower its power consumption. The resolution adaptive ADC can save around 38% energy consumption comparing to the conventional ADC. Fountain codes together with LDPC plus CRC codes can allow the power consumption to be decreased by an additional 29%. So, the new opportunistic error correction layer can reduce the power consumption by $\frac{2}{3}$ compared with the conventional IEEE 802.11 system.

Here, we assume that we have perfect channel knowledge, so our ADCs can be adapted to the minimum resolution. Further research focusses on channel estimation and its influence on our new error correction scheme. In addition, we will investigate the influence of adjacent channel interference.

Currently, we use LT codes as Fountain codes. More efficient Fountain codes are available such as Raptor codes [2], which have a lower overhead. So, future work will also concentrate on lowering the overhead and delay of Fountain codes.

ACKNOWLEDGMENTS

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