ALOHA WITH COLLISION RESOLUTION: PHYSICAL LAYER DESCRIPTION AND SOFTWARE DEFINED RADIO IMPLEMENTATION

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ABSTRACT
A cross-layer scheme, namely ALOHA with Collision Resolution (ALOHA-CR), is proposed for high throughput wireless communications in a cellular scenario. Transmissions occur in a time-slotted ALOHA-type fashion but with an important difference: simultaneous transmissions of two users can be successful. The physical layer required to achieve this functionality is described and the statistical properties of the user delays are determined so that the probability of user separation is maximized. An implementation of ALOHA-CR on the Wireless Open Access Research Platform (WARP) testbed containing software defined radio nodes is discussed and experimental results are presented.

keywords: multi-user system, blind source separation, MIMO systems, collision resolution, software defined radio

1. INTRODUCTION
The way collisions in wireless networks have traditionally been treated lowers throughput and wastes power and bandwidth. A collision is a result of simultaneous transmissions of more than one users, and in theory can be resolved via some form of diversity, such as frequency or time diversity (FDMA, TDMA), use of bandwidth expansion (CDMA), or use of multiple receive antennas. However, these approaches might not be ideal in a wireless network due to the burstiness of the wireless traffic, limited battery power, or receiver physical size limitations. Wireless network-friendly approaches to achieve diversity include the NDMA protocol [1], ALIANCES [2, 3] and ZigZag decoding [4]. In these protocols, collisions are resolved by combining collided packets and several retransmissions. In [5, 6] it was proposed that, at least in theory, colliding packets can be resolved without any retransmissions by exploiting carrier frequency offsets (CFOs), user delays, and/or user pulse-shape diversity.

This work builds upon the main idea of [5, 6]. In order to improve the packet/user separability we introduce small intentional delays at transmission time. The properties of the intentional user delays are determined so that the probability of user separation is maximized. Further, we propose a novel cross-layer scheme for a cellular uplink scenario that can be summarized as follows. Transmissions occur in a time-slotted ALOHA-type fashion but with an important difference: simultaneous transmissions of two users can be successful. A second-order collision is resolved at the base station by oversampling the received collision signal and exploiting the information in its polyphase components along the lines of [5, 6]. If there is only one user present, its packet is recovered with some probability, depending on the state of the channel. If there are more than two users in the collision, the packets are discarded and the users are asked to retransmit at a later time.

The physical layer is analyzed and tested on a software defined radio (SDR) [7] testbed. A host of interesting issues that arose during the SDR implementation are discussed. In [8] the system throughput and queuing delay analysis is derived and validated against experimental data obtained on the SDR testbed. Both analysis and experiments suggest that ALOHA-CR leads to significant increase in throughput and reduction of service delays.

2. ALOHA-CR: PHYSICAL LAYER
The channel between transmitter and receiver is assumed to be flat fading. Moreover, the channel is quasi-static, i.e., the channel remains unchanged over the duration of a packet.

If within a given time slot K users transmit, the baseband signal received at the BS corresponding to a K-fold collision, equals

\[ y(t) = \sum_{k=1}^{K} a_k x_k(t - \tau_k) + w(t), \]

where \( a_k \) denotes the channel coefficient between the \( k \)-th user and the BS; \( \tau_k \) is a random delay associated with the user \( k \); \( w(t) \) represents noise; and \( x_k(t) \) is the \( k \)-th user signal, i.e.,

\[ x_k(t) = \sum_{i} s_k(i)p(t - iT_s) \]

where \( s_k(i) \) is the \( i \)-th symbol of user \( k \); \( T_s \) is the symbol interval; and \( p(t) \) is a pulse shaping function with main lobe support \([-T_s, T_s]\). The mainlobe of neighboring pulses overlap by 50%.

The users in the collision can be separated as follows [5, 6]. Each received symbol is upsampled by a factor of \( P \), with

This work has been supported by Office of Naval Research under grant ONR-N-00014-07-1-0500, and National Science Foundation under grant CNS-0916947
sampling locations at \( t = iT_s + mT_s/P, m = 1, 2, \cdots, P \). The \( m \)-th polyphase component of the sampled output is

\[
y_m(i) = \sum_{k=1}^{K} a_k h_{mk}(i) * s_k(i) + w_m(i),
\]

where \( \ast \) denotes convolution, and \( h_{mk}(i) \) equals

\[
h_{mk}(i) = p(iT_s + mT_s/P - \tau_k);
\]

for \( i = -2, -1, 0, 1, 2, \ldots \). Forming the vector \( y(i) \) by appending the polyphase components of the received signal, \( y_m(i), m = 1, \ldots, P \), we get

\[
y(i) = A s(i) + w(i);
\]

where \( A = HD; H = [h_1^T, h_2^T, \cdots, h_P^T]^T; h_m = [h_{m1}(0) h_{m1}(-1), \ldots, h_{mK}(0) h_{mK}(-1)], D = \text{diag}( [a_1, a_1, \cdots, a_K, a_K] ) \) and

\[
s(i) = \begin{bmatrix} s_1(i) & s_1(i+1) & \cdots & s_K(i) & s_K(i+1) \end{bmatrix}^T.
\]

Equation (4) represents a typical \( P \times 2K \) instantaneous MIMO problem that can be solved in a blind fashion. In the implementation that follows we use the JADE algorithm [9] to separate the users (for details see [6, 9]).

\section{Introducing intentional user delays}

According to eq. (4) if \( \tau_k \)'s are close to each other, the columns of \( A \) will be highly correlated, resulting in high condition number for \( A \). Since naturally occurring delays are usually small, we propose that before transmission, each node introduces an intentional delay. Let \( \tau_k \) be the sum of the naturally occurring delay and the intentional delay. In this work, only collision of order two will be resolved, thus we focus on the two user case. Let us express the delay difference between two users as \( \tau = \alpha + \delta \), where \( \alpha \) is the intentional delays difference between users \( i \) and \( j \), and \( \delta \) is the naturally occurring delays difference. Let \( f_\delta(x) \) be the pdf of the natural delays differences, and further assume that \( f_\delta(x) \) is symmetric around the origin.

**Proposition 1:** Let the intentional delays be uniformly distributed over some interval \([0, T] \). If \( T = T_s \), the probability of the collision being non-resolvable achieves a local minimum, independent of \( f_\delta(x) \).

The proof is omitted due to lack of space. For detail please see [10].

\section{Use of successive interference cancelation (SIC) [11]}

After blind source separation, the contribution of the strongest user signal can be reconstructed and deflected from the received signal. This usually provides a better estimate for the weak user. One way to determine which is the strongest user is to look for the signal that has the smallest variance around the known constellation.

\section{On dealing with a collision of unknown order}

In theory, one could use pilots to determine the number of users present in a collision. However, this detection problem can be prone to errors especially at low signal-to-noise ratio cases. As currently we can successfully resolve second order collisions, instead of attempting to estimate the collision order, we propose to always treat the received signal as a second-order collision. If it is a collision free packet, after applying blind source separation and identifying the strongest user, as explain above, the remainder will contain meaningless information, for example, it would not pass a checksum test. If the collision order is higher than two, the proposed method will not work and the received packet will be discarded. By this method we can guarantee the collision free packets are successfully received and second-order collisions are resolved.

\section{Determining sampling points}

In order to determine the beginning of the packet, frame synchronization is required. For synchronization purposes, users are assigned distinct pseudo random sequences (pilots). The base station keeps a record of all pilot sequences in use in the network. When the packet arrives, the base station uses the beginning part of the received signal to perform correlation with every entry of the code book. A peak in the correlation of the received signal with code \( i \) indicates the presence of user \( i \). The peak location provides the beginning of the packet of user \( i \), while the peak value provides the corresponding channel coefficient. This can be repeated for all possible users, however, in practice the following approach works better. The strongest user is identified as the one that produces the largest peak in the correlation. Then, the user pilot signal is reconstructed based on estimated channel coefficients and delays, and is subsequently deflated from the pilot portion of the received signal along the lines of SIC. The CFO effect is ignored at this point because of the short duration of the pilot segment.

For synchronization purposes, the best pulse shaping waveform for the pilots is the raised root cosine (RRC) function, as this function maximizes the SNR at the output of the matched filter while it eliminates ISI at the sampling points.

\section{Frequency offsets and phase tracking}

In a practical system there are always CFOs between transmitters and receivers. Those will propagate in the separated symbols and can be mitigated using a phase locked loop (PLL) device, from where a CFO estimate can be obtained.

\section{Blind versus pilot-based user separation}

Since a real communication system always uses pilots for synchronization purposes, one would think that these pilots could be used to estimate the channel matrix \( A \) in (4), which then could be used to recover the information bearing symbols. However, the fact that different pulse shape waveforms are used for pilots and information bearing symbols renders that approach impossible. In order to minimize intersymbol interference between neighboring symbols of a user, IOTA pulse shaping is used for the payload symbols. Thus, the estimate of matrix \( A \) based on the pilots would be different with that corresponding to the payload (based on (4)). \( A \) depends on the pulse shape function. Pilots can be exploited as follows to obtain an estimate of \( A \). We can first estimate the channel coefficients \( a_k \) and user delay \( \tau_k \) based on the pilot symbols,
and subsequently combine them with the IOTA pulse shape function and sampling points, (see (3)) to get the estimate of channel matrix $\mathbf{A}$. Following the estimation of $\mathbf{A}$ the symbols can be recovered via least-squares. We term this approach as training method. In section 4, we compare the training method to the blind approach, in which the matrix $\mathbf{A}$ is considered to be unknown. As it will be seen in that section, the estimation errors in channel coefficients and user delays render the training method inferior to the blind one.

3. SDR IMPLEMENTATION

The user packet is structured as shown in Fig. 1. The SDR implementation was carried out in the following steps. The transmitter - The payload contained 414 bits (32 bits for the user ID and 382 random bits). Convolutional coding with rate $1/2$ was applied to get 828 bits. The coded bits were then interleaved. Specifically, the interleaver writes the input sequence in a matrix in row-wise fashion and then reads it in column-wise. Differential quadrature phase shift keying (DQPSK) was used to modulate the data. The IOTA pulse shape waveform with time support $[-2T_s, 2T_s]$ was chosen for the payload. A 32-bit m-sequence was added at the beginning as a sequence of pilots; it was BPSK modulated and RRC pulse shape waveform was used for the transmission of the pilot symbols. A code book of m-sequences was generated, which was kept at the BS and linked to the user IDs. The sampling rate of the board was $40$ Msamples/sec and 32 samples/symbol were taken, yielding data rate of $1.25$ Msymbols/sec. A random number of zero samples, chosen uniformly in $[0, 32]$, was added in the beginning of each packet as means of introducing user delays. The signal was first up-converted to $5$ MHz and sent to the transmission buffer. The board used channel 8 of the IEEE 802.11 standard to transmit the signal, with carrier frequency $2.414$ GHz.

The receiver - The signal was read from the receiver buffer where it was already down-converted to $5$ MHz. Subsequently it was down-converted to baseband. All entries of the code book were used to perform correlations with the header of the received signal. The entry which gave the largest correlation peak was chosen to indicate who the corresponding user was. For the following discussion, suppose that this is user $u_1$ ($u_1$ could be any of the users present in the system). The delay and channel coefficient of user $u_1$ was estimated based on the location and value of the peak, respectively. The chosen m-sequence was deflated from the pilot portion of the received signal. All entries of the code book were used to perform correlation with the pilot portion of the deflated signal. The entry that gave the largest correlation peak indicated the second user, $u_2$, and the corresponding delay and channel coefficient was estimated. Note that if there was only one user, the remaining signal after deflation would be just noise.

The received signal was up-sampled by 4, with sampling points $[57, 62, 67, 72]$ in each received pulse. The resulting 4 polyphase components were input to the JADE [9] algorithm for source separation. The output of the JADE algorithm was input to a PLL. The results were 4 sequences, i.e., $s_{u_1}(i), s_{u_1}(i+1), s_{u_2}(i), s_{u_2}(i+1)$, within phase and delay ambiguities. Let $s_u(.)$ be the strongest signal, i.e., the sequence that has the smallest variance around the known constellation. The symbols corresponding to $s_u(.)$ were demodulated. The use of DQPSK modulation allowed for removal of phase ambiguity. The demodulated output was passed through a de-interleaver and decoder, to get 414 decoded bits. The result could be either $s_u(i)$ or $s_u(i+1)$. If we misinterpreted $s_u(i)$ for $s_u(i+1)$, the de-interleaver would give a meaningless output. We used the user ID part in the beginning of the decoded output to do correlation with the corresponding entry of the user ID book in order to determine whether the recovered signal was $s_u(i)$ or $s_u(i+1)$, and also whether the recorded signal corresponded to user $u_1$ or user $u_2$. Note that although we use correlation with the user IDs to determine the user, we cannot use this information to estimate the channel. This is because the received packet is interleaved and coded, thus the beginning part of the frame is a random sequence until decoding. Next, we used the detected $s_u(i)$ to obtain the corresponding channel estimate using cross-correlation with the IOTA pulse. Finally, we deflated the corresponding signal from the received mixture.

![Fig. 1. Packet structure](image)

4. TESTBED MEASUREMENTS

The proposed approach was implemented on the WARP testbed [7]. In WARP, Matlab can be used to create a set of data, modulate it, apply the designed pulse shaping function, and transfer the data to the radio card. On the receiver side, WARPLab allows for data to be processed in Matlab immediately after it has been down-converted by the radio frequency integrated circuit (RFIC) on the radio card.

The experimental configuration consists of a single host computer which controls three nodes (two transmitters and
one receiver). The separation between each transmitter and receiver is 10m; the separation between the two transmitters is about 10m. The host computer acts as the BS and controls all the nodes in order to provide the correct synchronization between the transmitters and the receiver. All the nodes transmit narrowband signals simultaneously with symbol rate 1.25M sym/sec, both using the same carrier frequency 2.447 GHz (channel No.8 of 802.11b WiFi channel).

For each time slot both nodes transmit with probability 1. We next show the testbed performance of the ALOHA-CR using blind source separation followed by SIC, described in Section 2 (denoted in the figures as blind), ALOHA-CR using training based source separation followed by SIC, described in Section 2 (denoted in the figures as training).

We consider the raw BER performance (BER before decoding) of the proposed scheme. In this scenario, the location of transmitter and receiver, and the antenna gains are fixed. By varying the amplitude of the input signal we can look at the BER performance at different SNR levels. For each SNR level, 600 packets were transmitted. The SNR difference of user 1 and user 2 was within 3dB; 94% of them were within 1dB.

For comparison purposes only, in this BER evaluation we only include the delay differences in the range \([T_s/2 - T_s/8, T_s/2 + T_s/8]\). When the delay differences are smaller, all methods yield high BER and their performance is the same. The BER performance of the blind approach, as captured by the testbed, is shown in Fig. 2, where the BER approaches \(10^{-3}\) at an SNR of about 20dB. The performance of the training method is also shown in Fig. 2. One can see that there is about 3dB performance advantage of the blind over the training method when the SNR is smaller than 20dB, and this advantage further increases at higher SNR level. The inferior performance of the training method is due to the sensitivity of least-squares at low SNR, distortion of the pulse shape by antenna, and possible drifting of the sampling points.

Computer simulations were also conducted to produce the BER for this case. In the simulation the channel coefficients, \(a_k, k = 1, 2\), were taken to have amplitude one and random phase. It was assumed that the channel remains the same within each block. The delays and CFOs were set equal to the values observed during the testbed experiments. The estimation results were averaged over 100 independent channels, and 10 Monte-Carlo runs for each channel. In Fig. 2 one can see that there is only 1dB gap between the testbed measurements and the computer simulations.

5. CONCLUSIONS

We have proposed ALOHA-CR, which is a novel cross-layer scheme for high throughput wireless communications in a cellular scenario. Based on the user delay, this scheme can re-

![Fig. 2. BER performance of different separation scheme](image-url)