A NEW APPROACH TO ACHIEVE MULTIPLE PACKET RECEPTION FOR AD HOC NETWORKS

A. G. Orozco-Lugo[1], G. M. Galván-Tejada[1], M. M. Lara[1] and D. C. McLernon[2]
[1]Centro de Investigación y de Estudios Avanzados del IPN, Sección de Comunicaciones
Av. IPN No. 2508, Colonia San Pedro Zacatenco, CP. 07360, México D.F., México.
[2]Institute of Integrated Information Systems, School of Electronic and Electrical Engineering
University of Leeds, Leeds LS2 9JT, United Kingdom.
E-mails: aorozco@mail.cinvestav.mx, ggalvan@mail.cinvestav.mx, mlara@mail.cinvestav.mx, d.c.mclernon@ee.leeds.ac.uk
Tels: +(52) 5550613800 exts. 6350, 3767 and 3768, +(44) 113 3432050

Abstract: An algorithm for the recovery of multiple packets is proposed in this paper. The algorithm exploits the fact that every transmitter sends an implicit training sequence along with the information to accomplish multiple user equalization and interference suppression in the challenging scenario of an asynchronous random access ad hoc network. The proposed method has the advantage of allowing the transmission of complex data over time-dispersive multipath channels. A simulation example is presented that corroborates the interference suppression capabilities of the algorithm.

I. Introduction

Multiple packet reception (MPR) is a way to resolve collisions and enhance throughput in random access wireless networks. MPR gives to the receiving node the capability to separate multiple transmissions and promises vast improvements in network performance [1]. Moreover, it opens up the possibility for the development of new medium access control (MAC) protocols that could take advantage of the new characteristics of the physical layer [2], [3]. Digital signal processing is at the heart of an MPR receiver, where new approaches to achieve signal separation and interference suppression might be needed. Much work has been done in the areas of equalization, interference mitigation and source separation algorithms in the past years, and it is possible to take advantage of all this knowledge for its application to the emerging arena of massive networks with packet switching capability.

Related work to the one to be presented here can be described as follows. In [4] an algorithm for the blind separation of multiple users in non time-dispersive (flat) channels using modulation induced cyclostationarity (MIC) is presented. In [5] it is shown that using the MIC approach, simpler and more robust methods of channel estimation, for the single user case, can be devised compared to the case where cyclostationarity is induced at the receiver via oversampling [6], [7]. Another important application of MIC is given in [8] where a method to perform channel identification for two users in time-dispersive channels is proposed. On the other hand, the work in [9] shows that, with the aid of an implicit training sequence, accurate channel estimation can be obtained in the single user case using only first-order statistics of the data. This work, however, considers neither the possibility of the receiver having a dc-offset nor the fact that synchronization of the implicit training sequence at the receiver is essential if the channel is going to be estimated without ambiguity[1]. Some other works on the same lines are [10], [11] and [12]. The latter reference presents a more realistic channel model having potentially more practical value, and do propose a method to solve the dc offset problem. However, synchronization of the implicit training sequence is assumed. Another recent approach can be found in [13] where the transmission format is similar but the transmitter possesses multiple antennas. Our own work in [14] uses a similar methodology, but additional material is added to jointly deal with the synchronization and the dc-offset problems. In addition, conditions are derived for the implicit training sequences that allow unbiased channel estimation with an error variance independent of the channel characteristics. While a considerable amount of research as been done in the area of source separation and equalization, where [4]-[13] are some examples, its application to the problem of packet separation in ad hoc networks is recent and is up to know considered only in [15] and [16]. The method in [15] can handle complex data but assumes synchronization and cannot be used over time-dispersive multipath channels. The method in [16] does not need synchronization and can be used over time-dispersive multipath channels, but cannot handle complex data.

In this paper we propose a new method to recover multiple packets in an asynchronous random access wireless mobile *ad hoc* network (MANET) that does not have the limitations of the previous approaches. The method is attractive because it is neither necessary to know the number of active sources, nor their received powers, nor the characteristics of their propagation channels. Moreover, it is not necessary to know the starting time of their packet transmissions, so that the proposed method is able to handle the asynchronous transmissions that most likely will appear in ad hoc networks. The new technique to be presented builds upon two approaches previously proposed by some of the authors of this paper. The first approach is a blind interference cancellation technique based on modulation induced cyclostationarity (MIC), where the transmitted sequences are modulated by polynomial phase sequences (PPS) [16]. This method can be used to separate multiple asynchronous packet transmissions that have undergone time-dispersive multipath propagation. The restriction is that the transmitted information symbols should be real valued, so precluding the use of high rate two-dimensional constellations. The second approach is a single user channel estimation method that exploits the availability of an implicit training (IT) sequence [14]. This approach serves to reliably estimate a single user time-dispersive channel with

[1] In fact this paper did consider the issue but the solution proposed there to tackle the problem is not correct. (See [14]).

estimation error variance independent of the modulation format. Combining the transmission formats of these two techniques, we realize that it is now possible to achieve intersymbol interference (ISI) and random access interference (RAI) cancellation for a wireless MANET while at the same time allowing all the users to transmit using arbitrary complex constellations, thus getting over the main restriction of the work in [16]. On the other hand, the results to be presented in this paper can be considered an improvement over the approaches in [9]-[14], in the sense that the signal transmission format is similar but here multiple users can be handled. Moreover, both the synchronization and the dc offset problems are now easily solved.

The paper is organized as follows. Section II presents the system model, where the transmission model is described. Section III introduces the proposed algorithm. Simulation results that illustrate the multipacket separation capability of the method are presented in Section IV. Finally, conclusions are given in Section V.

II. System Model

A discrete-time baseband model for the system under consideration is shown in Fig. 1. There are P independent transmitters that could be sending packets which arrive asynchronously at the receiver. In order to provide the receiver with MPR capability, a K-element antenna array is used. The packets contain complex valued information data $b_i(k)$ $(i=1,\ldots,P)$, with $E\{b_i(k)\}=0$, $E\{|b_i(k)|^2\}=\sigma^2_{b_i}$. Every transmitter employs a quadratic polynomial phase implicit training sequence, defined as $c_i(k)=\gamma_i e^{j2\pi[fk^2+\alpha_i k]}$ where $f=1/T_f$ and $\alpha_i=i/D$ $(i=1,\ldots,D-1)$ with D, T_f and γ_i design parameters. In order to be able to achieve complete ISI and RAI removal, we should choose T_f a prime number such that $T_f \geq M+Q-1$ (with M and Q to be defined later), and D should be chosen to be relatively prime to T_f [16]. This implicit training sequence is arithmetically added to the information sequence so that the transmitted signals are now $s_i(k)=b_i(k)+c_i(k)$. Note that the total transmitted power is divided between information and training and so a data power loss factor equal to $\sigma^2_{b_i}/(\sigma^2_{b_i}+\gamma_i^2)$ occurs [14]. The transmitted signals become mixed in a multiple-input multiple-output (MIMO) system with matrix impulse response $\mathbf{H}$ that models the situation where P transmitted signals travel through a time-dispersive multi-path channel and arrive at each of the K receiving antennas. The noisy outputs of the MIMO system are denoted by $x_m(k)$ $(m=1,\ldots,K)$. The receiver uses a space-time equalizer to suppress the ISI and RAI that could result in this environment. The structure of the space-time equalizer is depicted in Fig. 2. It uses one finite impulse response linear filter (with Q coefficients) per antenna, which operates at the symbol rate. The outputs of all these filters are added together to obtain the equalized signal. The mathematical expressions linking the important variables are given by

$$x_m(k)=\sum_{i=1}^{P}\sum_{\ell=0}^{M-1}h_{i,m}(\ell)\big(b_i(k-\ell)+c_i(k-\ell)\big)+n_m(k) \quad ; \quad m=1,\ldots,K \tag{1}$$

$$y(k)=\sum_{m=1}^{K}\sum_{\ell=0}^{Q-1}w_m(\ell)x_m(k-\ell) \tag{2}$$

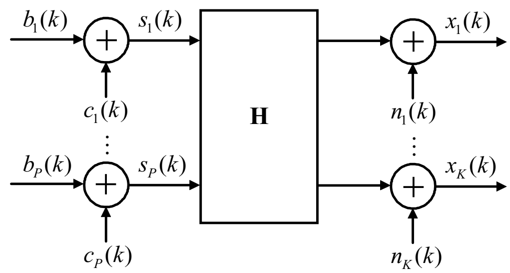

Fig. 1. System model

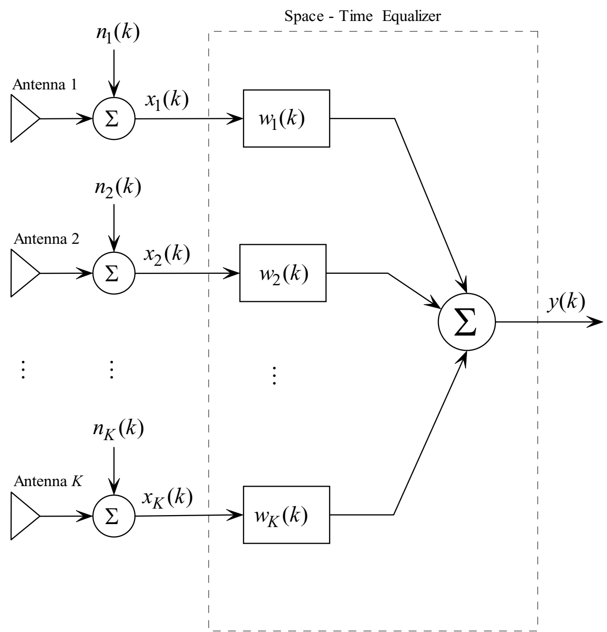

Fig. 2. Space-time equalizer

where $h_{i,m}(\ell)$ stands for the channel impulse response from transmitter i to receiving antenna m at time instant ℓ, and M is the channel dispersion length between any transmitter-receiver antenna pair. Moreover, $w_m(\ell)$ stands for the impulse response of the linear filter associated with antenna m as shown in Fig. 2. Note that in practice different transmitter-receiver antenna pairs could have a different value of M, and so the M in (1) stands for the largest value. This is not a problem, because for channels whose dispersion is lower than M some of the coefficients in their channel impulse responses will be zero. Equations (1) and (2) can be expressed in matrix notation as:

$$\mathbf{x}(k)=\sum_{i=1}^{P}\mathbf{H}_i\mathbf{s}_i(k)+\mathbf{n}(k) \tag{3}$$

$$y(k)=\mathbf{w}^{\mathrm{H}}\mathbf{x}(k) \tag{4}$$

where $\mathbf{s}_i(k)=\mathbf{b}_i(k)+\mathbf{c}_i(k)$ in (3). Note that the dimensions of the variables involved are as follows: $\mathbf{H}_i$ (dim. $(K\times Q)\times(M+Q-1)$), $\mathbf{x}(k)$ (dim. $(K\times Q)\times 1$), $\mathbf{b}_i(k)$ (dim.

$\left(M+Q-1\right)\times 1$), $\mathbf{c}_i(k)$ (dim. $\left(M+Q-1\right)\times 1$), $\mathbf{n}(k)$ (dim. $\left(K\times Q\right)\times 1$) and $\mathbf{w}$ (dim. $\left(K\times Q\right)\times 1$). Furthermore,

$$\mathbf{x}(k)=\left[x_1(k),\ldots,x_1(k-Q+1),\ldots,x_K(k),\ldots,x_K(k-Q+1)\right]^{\mathrm{T}} \quad (5)$$

$$\mathbf{s}_i(k)=\left[s_i(k),s_i(k-1),\ldots,s_i(k-Q-M+2)\right]^{\mathrm{T}} \quad (6)$$

$$\mathbf{w}=\left[w_1(0),\ldots,w_1(Q-1),\ldots,w_K(0),\ldots,w_K(Q-1)\right]^{\mathrm{T}} . \quad (7)$$

The proposed quadratic PPS implicit training sequences $c_i(k)=\gamma_i\, e^{j2\pi\left[fk^2+\alpha_i k\right]}$ have the following important properties:

P1) *Periodicity:* The sequences have a common period equal to DT_f .

P2) *Zero Mean Property:* All the sequences have zero mean.

P3) *Orthogonality:* The periodic correlation between any given pair of sequences satisfy

$$\sum_{k=0}^{DT_f-1} c_i(k-\lambda)c_p^*(k-\tau)=\begin{cases} DT_f\gamma_i^2 e^{j2\pi\left[\frac{p\tau-i\lambda}{D}\right]} & ; \quad i=p,\lambda=\tau \bmod T_f \\ 0 & ; \quad \text{otherwise}\end{cases} \quad (8)$$

III. Proposed Algorithm

To recover a particular packet coming from a specific user r the following algorithm is proposed. The objective function that we will seek to minimize is

$$J=\frac{1}{N-L}\sum_{k=L}^{N-1}\left|y(k)-c_r(k-d)\right|^2 \quad (9)$$

which is intuitively appealing giving the data transmission format. In (9), N is the length of the observation window, $L=Q-1$ and d is some integer representing the equalization delay. Note that there is no need for synchronization because the equalizer will automatically extract the transmitted symbol that matches the equalization delay. For a deeper explanation of this issue see [17]. In order to find a closed form expression for the space-time equalizer coefficients that minimize the previous objective function, we proceed as follows. Using (4) in (9),

$$J=\frac{1}{N-L}\sum_{k=L}^{N-1}\left|\mathbf{w}^{\mathrm{H}}\mathbf{x}(k)-c_r(k-d)\right|^2 , \quad (10)$$

$$\Rightarrow J=\mathbf{w}^{\mathrm{H}}\mathbf{R}\mathbf{w}-\mathbf{a}_r^{\mathrm{H}}\mathbf{w}-\mathbf{w}^{\mathrm{H}}\mathbf{a}_r+\gamma_{r_r}^2 \quad (11)$$

where

$$\mathbf{R}=\frac{1}{N-L}\sum_{k=L}^{N-1}\mathbf{x}(k)\mathbf{x}^{\mathrm{H}}(k) \quad (12)$$

and

$$\mathbf{a}_r=\frac{1}{N-L}\sum_{k=L}^{N-1}c_r^*(k-d)\,\mathbf{x}(k) . \quad (13)$$

Now, to find the space-time equalization vector $\mathbf{w}$ that minimizes J , it is necessary to have

$$\frac{\partial J}{\partial \mathbf{w}^*}=\mathbf{R}\,\mathbf{w}-\mathbf{a}_r=0\Rightarrow \mathbf{w}=\mathbf{R}^{-1}\mathbf{a}_r \quad (14)$$

Equation (14) gives the solution for the space-time equalizer in the proposed method. Note that $\mathbf{w}$ depends only on the received vector $\mathbf{x}(k)$, and on the implicit training sequence $c_r(k)$ of the desired user. In a MANET, the implicit training sequence of the desired user cannot be assumed known due to the highly mobile and random access nature of the network. However, the requirement of knowing $c_r(k)$ can be exchanged by the existence of a codebook of training sequences known to all nodes, as explained in [16]. Moreover, note that the algorithm operates in a decentralized fashion because it does not recover the users jointly. This is highly advantageous in a random access MANET because it is not known before hand how many and which specific users are transmitting on a given observation window. Note also that due to the zero mean property of the implicit training sequences, any dc offset that could be present can be estimated using first-order statistics and removed before running the proposed algorithm. This is so because the equalizer estimation is not based on first-order statistics. So the dc offset problem is very easy to solve in the current context. Also note that after equalization, the training sequence should be subtracted to decode the data. It can be shown that the proposed algorithm has an asymptotic performance equal to the one of the optimum minimum mean square error processor due to the properties P1-P3 of the implicit training sequences. The proof of this will be presented elsewhere.

IV. Simulation Results

A simulation that shows the performance of the proposed technique is presented in this section. For the simulation we consider a circular antenna array with six equally spaced elements and a radius equal to one wavelength of the nominal frequency $f_c=2.4$ GHz. The symbol period for all sources is $T=1\,\mu\text{s}$, and the packet size is the same for all users. A number of 50 Monte Carlo trials are performed for averaging purposes in the experiment. The performance measure used for the simulation is the signal to interference plus noise ratio (SINR), where signal means the information data of the desired user.

Three transmitters respectively using 16QAM, 8PSK and QPSK data modulation formats send packets that arrive asynchronously to the receiver. The signals coming from the sources are received at SNR equal to 35, 25 and 20 dB respectively. Raised cosine pulse shaping filters with a roll-off factor equal to 0.3 are used by all transmitters in order to limit the bandwidth. Implicit training sequences are added to the information data of every transmitter with parameters $f=1/11$ and $\alpha_i=i/13$, $\left(i=1,2,3\right)$. Every transmitted signal arrives to the receiver via three paths with angles of arrival, relative amplitudes and transmission delays as given in Table I. For every Monte Carlo trial, several realizations are carried out where the packet length is varied from 100 to 900 hundred symbols in steps of 200 symbols. The observation window is twice the packet size. The packets of the different users arrive to the receiver at positions, with respect to the receiver observation window, equal to N divided by 6, 3 and 2 for users 1, 2 and 3 respectively. Simulation results are presented in Fig. 3 for user 1 only, but similar behavior is observed for others users.

The simulation results show that the algorithm is able to suppress the interference in this realistic scenario of a time-dispersive channel and asynchronous packet interference. They also show that the SINR does not improve much after certain value of the packet size. This is because the algorithm is stochastic and so it is affected by the finite amount of data available to perform the calculation of the space-time equalizer coefficients.

Table I. Multiple channel parameters
θ_i : Angle of arrival for the *i*-th path; τ_i : Delay for the *i*-th path;
β_i : Amplitude for the *i*-th path

User 1			
i	θ_i	τ_i (µs)	β_i
1	30	0	1.0
2	-15	0.52	0.7
3	10	1.35	0.5
User2			
i	θ_i	τ_i (µs)	β_i
1	-45	0	0.2
2	30	0.34	0.8
3	-20	1.23	0.8
User 3			
i	θ_i	τ_i (µs)	β_i
1	-60	0.47	0.5
2	-20	0.71	1.0
3	50	1.33	0.3

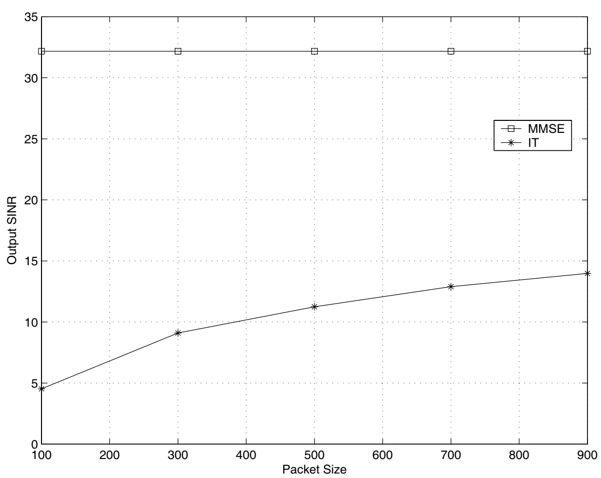

Fig. 3. Performance for user 1 as packet size varies

V. CONCLUSIONS

An algorithm to recover multiple packets in an asynchronous random access wireless ad hoc network has been proposed. The algorithm is based on the use of quadratic polynomial phase implicit training sequences which are arithmetically added to the information sequence of the various users. The imposed signal structure is exploited at the receiver by the space-time equalization algorithm to suppress ISI and RAI from other users. The main advantage of this algorithm, as compared with other similar approaches, is that it allows the use of bi-dimensional modulations for multiple users in a time-dispersive multipath channel. Simulations were presented that show that the proposed method indeed allow the separation of multiple packets with useful output SINR at the expense of expending some power for the transmission of the implicit training sequence, but without the need for extra bandwidth to send separate training.

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