Initial Acquisition and Synchronization Based on Nonparametric Reception Techniques for IoT

Dmitry Osipov¹,²
¹Kharkevich Institute for Information Transmission Problems of the RAS 127051, 19 bld. 1 Bolshoy Karetny Lane, Moscow, Russian Federation
²HSE University, 20 Myasnitskaya Str., Moscow, 101000, Russian Federation
d_osipov@iitp.ru

Abstract. Internet of Things (IoT) is one of the most important emerging techniques for the future generation communication systems. Recently a new approach to IoT physical layer design based on FH OFDMA and nonparametric reception techniques has been proposed. This approach offers a number of benefits including: high interference proofness and thus high user capacity, elimination of the channel estimation and equalization techniques and thus reduced overhead, low complexity of both transmission and reception techniques. However initial acquisition and synchronization methods design for such systems remains a challenging problem. In existing IoT solutions this problem is solved by employing signals with special properties. This paper advocates a different approach: initial acquisition and synchronization methods development based solely on the same signalling and reception techniques that are used for information transmission and the use of low-rate codes with low complexity decoding.

1. Introduction

As the number of IOT connected devices grows drastically each year the problem of developing novel physical layer techniques for future generation IOT systems becomes crucial. Lately a novel approach based on FH OFMA and nonparametric reception techniques developed in [1-3] has been proposed. The approach in question does not use CSI and thus results in interference-proof systems with low overhead. However to the best of the author’s knowledge initial acquisition and synchronization methods based on nonparametric reception techniques have not been developed yet. In modern communication systems it is typical to solve the initial acquisition problem by employing sequences with special (autocorrelation) properties as a prefix [4-5] or by using blind methods based on the properties of the signal [6-7]. The aim of this paper is to demonstrate the feasibility of the development of the initial acquisition and primary (coarse) synchronization methods based on the same signalling, reception and decoding techniques that are used for data transmission in a multi-band multi-tone DHA FH OFDMA system [8,9](to be described in short in the next section).

2. Transmission and reception in a multi-band multi-tone DHA FH OFDMA system

In a multi-band multi-tone DHA FH OFDMA system [8] within the scope of the transmission procedure the information to be transmitted is encoded with an \( C(n,k) \) code. Each symbol of the resulting (say \( i \) th) codeword \( \vec{v}^i = [v_0^i, v_1^i, \ldots, v_{n-1}^i] \) is then mapped into a weight 1 column vector of
length $q$. The matrix corresponding to the transmitted signal can be represented in the following form

$$X^i = \begin{bmatrix} x_0^i, x_1^i, \ldots, x_{n-1}^i \end{bmatrix}$$

where $Z$ is an all zero $n \times rQqN$ matrix and is the $g$th copy of the matrix $B^i$.

Each column of the matrix $X^i$ is then permuted independently (permutations $\pi_0, \pi_1, \ldots, \pi_{n-1}$ are chosen equiprobably from the set of all possible permutations.) This operation corresponds to the dynamic hopset allocation. In what follows it will be assumed that $K$ users transmit OFDM symbols in the way discussed above i.e. at each time instant $K \cdot N_r$ tones are transmitted via the same channel.

Let us now consider the reception process. Within the scope of this process $n$ OFDM symbols are to be received. A matrix $F^i = \begin{bmatrix} f_0^i, f_1^i, \ldots, f_{n-1}^i \end{bmatrix}$ corresponds to each transmitted codeword $\tilde{v}^i$ (here $\tilde{f}_j^i$ is the column vector corresponding to the $j$th OFDM symbol (and thus the $j$th symbol of this codeword)). The receiver applies inverse permutations to each column of the matrix $F^i$ the obtained matrix being given by $Y^i = \begin{bmatrix} y_0^i, y_1^i, \ldots, y_{n-1}^i \end{bmatrix}$ where $y_j^i = \pi_j^{-1}(f_j^i)$ and $\pi_j^{-1}()$ stands for the inverse permutation for the permutation $\pi_j()$. Each element of the first $q$ rows of the matrix $Y^i$ is then squared. The elements of the resulting matrix $Y^i$ are given by the following equation

$$Y^i(j, k) = (\chi_j^i(k))^2$$

where $\chi_j^i(k)$ is the $k$th element of the column vector $\tilde{y}_j^i$. The column-wise permutation at the transmitter side corresponds to the hopping procedure and thus the inverse permutations correspond to dehopping. Since inverse permutations are applied at the receiver side the first $q \cdot N_r$ rows of the matrix $Y^i$ (and thus corresponding rows of the matrix $Y^i$) correspond to the first $q \cdot N_r$ rows of the transmitted matrix $X^i$.

As for the detection it is convenient to consider detection as a two stage process: within the scope of the first stage reliability estimates for each possible value of each symbol are computed. Within the scope of the second stage that is referred to as “decoding” stage the obtained reliability estimates are combined in order to make a decision on the transmitted codeword. In the traditional $\alpha$ detector the reliability estimates are computed in the following way: let us designate the $\alpha$-th obtained by sorting (the $\alpha$-th column of the matrix) in the descending order by $\alpha_j$. Each element of the reliability matrix is given by:

$$D(j, k) = \begin{cases} 1 & D(j, k) \geq \alpha_j \\ 0 & D(j, k) < \alpha_j \end{cases}$$

In traditional (single-tone single-band) DHA FH OFDMA [3] the reliability value for each (say $m$-th) codeword is computed in the following form
in a multi-band multi-tone DHA FH OFDMA proposed in [8] the reliability matrix $D_i$ from each (say $i$ th subband) is calculated and the combined matrix $\hat{D}$ is calculated via

$$\hat{D} = \wedge D'$$

where $\wedge$ stands for element-wise logical AND operation.

The reliability value for each (say $m$ -th) codeword is computed in the following form

$$S_m = \sum_{j=1}^{\tilde{q}} \sum_{\kappa=1}^{q} \hat{D}(j,\kappa)B^*(j,\kappa)$$

The decoding boils down to choosing the set $S'$ where

$$S' = \arg \max_{i \in \mathcal{C}} S_i$$

### 3. Initial acquisition in a DHA FH OFDMA system: the proposed approach

The basic idea behind the proposed approach is to transmit several copies of the low-rate code in several parallel subbands in a similar way as discussed in the previous section (the only difference will be discussed shortly hereinafter). The receiver is to process the received signal in a sliding window fashion similarly to what is done in traditional initial acquisition procedures. Thus at each (say $i$ th) time instant the receiver is to process OFDM symbols $x_{i-N+1},x_{i-N+2},\ldots,x_i$. However in contrast to traditional methods in our case the initial acquisition procedure is based on constant decoding attempts. In particular at each time instant the receiver performs decoding in parallel subbands as discussed above combing then the decisions taken in each subband. In our case the combining method is similar to the one proposed in [8]. Let us consider some essential aspects of the proposed approach in more detail.

Since the initial acquisition is the first step of establishing a reliable communication link the receiver cannot obtain information about the instantaneous hopset and thus unlike the case for the data transmission frequency hopping cannot be dynamic in this case. Hence conventional FH and static hopset allocation are to be used. Since at each time instant the receiver is to perform $N_r$ parallel decodings the reception and decoding techniques are to have latency and complexity as low as possible. Thus we choose $\alpha$ detector that (to the best of the author’s knowledge) has the lowest latency and complexity (for the same parameters) among all the nonparametric detectors proposed so far. For the same reason we choose repetition code as a low-rate code for the proposed procedure. Although any code with a sufficiently low rate is suitable for our task the reliability metrics computed for the codewords in the previous time instant can be partially reused for the case of the repetition code (it is this property along with the low complexity of both encoding and decoding which makes repetition code ideal for the task.) Thus within the procedure proposed each user randomly chooses a number from a range $\{1,\ldots,\tilde{q}\}$ and transmits $N_r$ copies of the corresponding codeword of the repetition code via $N_r$ parallel subbands (each subband consists of $\tilde{q}$ subcarriers.) We assume that several devices can try to establish communication with the receiver and thus some of them can start their transmission at the same time instant (OFDM symbol). Moreover in what follows we assume that the subbands in use are allocated within the very same frequency band that is used for data transmission. Thus the detector (decoder) in each subband is influenced both by the signals transmitted.
by the $K_n$ devices trying to establish a reliable communication with the receiver by transmitting $\tilde{N}_r$ tones (per single OFDM symbol) each and by the $K$ users that have successfully established a reliable communication with the receiver and are transmitting $N_r$ tones (per single OFDM symbol) in a DHA FH OFDMA manner. Please note that since the users transmitting data use permutations prior to transmission from the initial acquisition block (IAB) point of view, the tones transmitted by those users are randomly distributed via the whole frequency band available. Thus the IAB cannot decode the codeword in a traditional fashion i.e. choosing a single codeword or declaring decoding failure as a conventional $\alpha$ detector does. In contrast to the conventional detector employed in a single-tone DHA FH OFDMA [3] the decoder in use is a list decoder i.e. the output of the decoder is a list of codewords that were (presumably) transmitted. Finally let us summarize the essential features of the proposed initial acquisition mechanism

- The information for the initial acquisition is transmitted within the same frequency band that is used for the transmission of the data with DHA FH OFDMA by the $K$ active users transmitting $q$-ary codewords via $\tilde{N}_r$ non-overlapping subbands allocated in a dynamic (pseudorandom) fashion within the frequency band split into $Q$ subcarriers (each band consist of $q$ distinct non-overlapping subcarriers.)
- For this purpose $\tilde{N}_r$ non-overlapping subbands (distinct non-overlapping $\tilde{q}$ subcarriers each) that can be used for data transmission are allocated for the initial acquisition as well. Unlike the subbands used for data transmission those are allocated in a constant (“once and for all”) way.
- Whenever each of the $K_n$ users that want to establish reliable communication with the receiver feels ready to start the process in question he chooses (randomly) one of the $\tilde{q}$ subbands and transmits copies of the respective codeword of the $(N,1,\tilde{N})$ repetition code via all the $\tilde{N}_r$ subbands.
- The initial acquisition block (IAB) processes the incoming signal in a sliding window fashion ($\tilde{N}$ OFDM symbols each time) and for each (say $t$th) subband the respective component detector calculates the reliability matrix $D_t$.
- The IAB then computes the combined matrix $\hat{D}$ using (4), computes the reliability values using (5) and computes the list of the codewords as given by (6).

4. Simulation
In order to demonstrate the effectiveness of the proposed approach simulation has been carried out. Within the scope of the scenario under consideration the following parameters were considered:

$Q = 4096, \tilde{q} = 128, \tilde{N}_r = 2, N = 128$. The Signal-to-Noise Ratio per bit is given by

$$SNR = 10 \cdot \log_{10} \left( \frac{E_s}{\log_2 (\tilde{q}) E_n} \right)$$

where $E_s$ is the total signal power and $E_n$ is the noise power within the entire band.

We assume that $K$ active users transmit $\tilde{N}_r = 3$ tones each at each time instant (OFDM symbol) and $K_n$ new users try to establish a reliable communication with the receiver transmitting $\tilde{N}_r$ tones each. The channel model for both active and new users is described by the Pessimistic Path Loss Model (PPLM) introduced in [10]. The acquisition failure is registered if at least one of the new users transmission detections fail. Thus the Joint Acquisition Failure Rate (JAFR) is the probability that the acquisition of at least one new user fails. The dependencies of JAFR vs. different number of interfering signals $K\cdot\tilde{N}_r$ for a different number of connecting devices $K_n$ are shown on Figure 1 below.
Figure 1 Joint Acquisition Failure Rate (JAFR) vs. a different number of interfering signals $K \cdot N_r$ for a different number of connecting devices $K_n$.

As can be seen the proposed approach ensures relatively low values of JAFR and JAFR is almost constant with the number of interfering signals. Thus the proposed approach can enable initial acquisition with a relatively low probability of failure even if the number of users already transmitting is great. Please note that no false positive detections were registered during the simulation.

Future development of the initial acquisition should include feedback from the receiver in the form of acknowledgment. Whenever a user fails to receive an acknowledgment he tries to retransmit in an ALOHA-like fashion. Another challenging problem is the simulation within the time domain in order to take into account the effects within the time domain (such as carrier frequency offset (CFO)). These problem fall out of the scope of this work and are subject for future research.

Acknowledgment
This work has been supported in part by the Russian Foundation for Basic Research, project no. 18-07-01409 a

References
[1] Viswanathan R and Gupta S 1985 IEEE Trans. Comm. 33 pp 178-84
[2] Kreshchuk A and Potapov P 2017 El. Notes in Discr. Math. 57 pp 139-145
[3] Osipov D 2014 Proc. Int. Work. on Mult. Access Comm. (Halmstad) (Cham:Springer) pp 29-34
[4] Shi K and Serpedin E 2004 IEEE Trans. Wireless Comm. 3 pp 1271-1284
[5] Schmidl T M and Cox D C 1997 IEEE Trans. on Comm. 45 pp 1613-1621
[6] Tanda M 2004 IEEE Trans. Comm. 52 pp. 1609-1612
[7] Bolcskei H IEEE Trans. Comm. 49 pp. 988-999
[8] Osipov D 2019 Proc. Int. Cong. Ultra Modern. Comm.(Dublin) (IEEE) pp 1-5
[9] Osipov D 2019 Proc. XVI Int.Symp. Probl. of Redund. in Inf. and Contr.Syst.(Moscow) (IEEE) pp 36-41
[10] Osipov D 2019 Journ. of Phys.: Conf. Ser. 1163 012047