CODE-BLIND RECEPTION OF FREQUENCY HOPPED SIGNALS OVER MULTIPATH FADING CHANNELS

Xiangqian Liu
Dept. of Elec. and Comp. Engr.
University of Louisville
Louisville, KY 40292
Email: x.liu@louisville.edu

Nicholas D. Sidiropoulos
Dept. of Elec. and Comp. Engr.
University of Minnesota
Minneapolis, MN 55455
Email: nikos@ece.umn.edu

Ananthram Swami
Communication & Networks Br.
Army Research Lab
Adelphi, MD 20783
Email: a.swami@ieee.org

ABSTRACT

A noncoherent reception scheme is developed for joint blind estimation of hop timing, hop frequency, and direction-of-arrival (DOA) of frequency hopped signals over multipath fading channels. Based on the principle of dynamic programming and 2-dimensional harmonic retrieval, the method does not require knowledge of users' hop codes, and it remains operational even with multiple (unknown) hop rates, frequency offsets, and asynchronism. The model is based on FSK, but the scheme is also evaluated with GMSK modulation and shown to be robust.

1. INTRODUCTION

Frequency hopped spread spectrum (FHSS) has been widely studied and mainly used for military applications, such as in SINCGARS, due to its low probability of detection and interception, power-control issues in a peer-to-peer setting, good near-far properties, etc. Recently, it has also been adopted in commercial wireless communications standards, such as IEEE 802.11 and Bluetooth. Blind reception of FHSS signals is technically challenging since not only the hopping codes (hopping sequences), but the directions of arrival of the signals, the bin-width, the hop rate, timing, symbol rate, etc., may all be unknown in a realistic setting.

Most of the existing methods for synchronization and signal recovery in frequency hopping systems assume knowledge of the actual hopping codes at the receiver, which makes them unusable in non-cooperative environments or in the presence of unknown carrier frequency offset. In these scenarios, hop timing and other unknown parameters must be estimated blindly from received FH signals. Several methods have been proposed for blind/semi-blind hop timing and frequency estimation. For example, assuming known hop rate, channelized receivers have been proposed for semi-blind hop timing estimation for the *single* user case [6], as well as the *multiuser* case [1]. However, the performance of those receivers degrades rapidly if the channelization is imperfect, or users have different hop rates.

In [4, 5], hop timing and frequency estimation methods based on the principle of dynamic programming were developed for blind tracking of multiple frequency hopped signals, either using serial procedure [5] or parallel procedure [4]. These methods do not assume knowledge of hop codes or hop frequency grids, and do not rely on channelization, and hence are robust to frequency offset.

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However, all aforementioned methods assume single TX-RX propagation for each frequency hopped user. When the hopping bandwidth is greater than the channel coherence bandwidth, channel effects due to multipath propagation cannot be ignored. Blind receiver design for frequency hopping systems over multipath channels is nontrivial since multipath reflections create fictitious sources in the spatial dimension, as well as unknown delay spread in the temporal dimension. Few results have been found available in the literature on the blind parameter estimation for FH signals in multipath channels, e.g., [2], which need to work on packet-invariant data set.

In this paper, we propose a blind reception scheme for joint maximum likelihood (ML) estimation of hop timing, carrier frequency, and DOA of frequency hopped signals over multipath channels. Hop codes, hop rates, and multipath time delays of the users are assumed to be unknown. Each user may have distinct hop timing and rate. Furthermore, hop frequencies of different users may be chosen from different sets of candidate frequencies. Our proposed method is based on the principle of dynamic programming (DP) and 2-D harmonic retrieval (2-D HR). The model assumes FSK modulation, but the algorithm is also evaluated with GMSK modulation in the simulations.

2. PROBLEM FORMULATION

Consider a frequency hopping communication scenario where there are d users in the system. The receiver utilizes a uniform linear array (ULA) of M antennas. Suppose the signal of the k-th user arrives at the ULA from r_k distinct paths due to multipath propagation, each with DOA α_{kl}, (frequency dependent) path attenuation β_{kl}, and time delay τ_{kl}, where $l = 1, \ldots, r_k$.

The baseline separation of the ULA is Δ wavelengths. The array steering vector in response to a signal from direction α_{kl} can be written as

$$\mathbf{a}(\theta_{kl}) = \left[1, \theta_{kl}, \ldots, \theta_{kl}^{M-1}\right]^T, \quad \theta_{kl} = e^{j2\pi\Delta\sin(\alpha_{kl})}. \quad (1)$$

At time t, the baseband representation of the $M \times 1$ received signal vector at the ULA output is

$$\mathbf{x}(t) = \sum_{k=1}^{d}\sum_{l=1}^{r_k} \mathbf{a}(\theta_{kl})\beta_{kl}^p e^{j\omega_c\tau_{kl}} s_k(t-\tau_{kl}) + \mathbf{w}(t), \quad (2)$$

where $s_k(t) = e^{j(\omega_k^p t + \phi_k)}$, ω_c is the center carrier frequency, and ω_k^p and ϕ_k^p are the baseband frequency and initial phase of the transmitted signal from the k-th user during its p-th hop. Note that the p-th hop frequency and the baseline separation Δ (measured in wavelength units) are both functions of time; for notational clarity, we do not explicitly denote this dependence. The transmitted signals can be fast or slow frequency hopping, with M-ary FSK modulation. Here the carrier shifts due to hopping or symbol modulation are treated as conceptually equivalent, albeit of different magnitude. $\mathbf{w}(t)$ is complex white Gaussian noise with variance σ^2.

Suppose received signal (2) is sampled at an (over-)sampling rate of $1/T$, then we have

$$\begin{aligned}\mathbf{x}(n) &= \sum_{k=1}^{d}\sum_{l=1}^{r_k} \mathbf{a}(\theta_{kl})\beta_{kl}^{p} e^{j\omega_c\tau_{kl}} s_k\left(nT-\tau_{kl}\right)+\mathbf{w}(nT)\\ &= \sum_{k=1}^{d}\sum_{l=1}^{r_k} \mathbf{a}(\theta_{kl})\widetilde{\beta}_{kl}^{p} e^{j\omega_k^p nT}+\mathbf{w}(nT) \qquad (3)\end{aligned}$$

for $n = 1, \ldots, N$, where

$$\widetilde{\beta}_{kl}^{p} = \beta_{kl}^{p} e^{j(\omega_c\tau_{kl}+\omega_k^p\tau_{kl}+\phi_k^p)}. \qquad (4)$$

Here we assume that the delay spread for a given user is small so that time delay can be approximated by phase shift, which is a reasonable assumption in practice. This does not require synchronism across different users. Eqn. (3) can also be written in matrix form

$$\mathbf{X} = [\mathbf{x}(0) \ \cdots \ \mathbf{x}(N-1)]. \qquad (5)$$

Assuming that the total number of paths of all users is known or estimated, the objective of blind reception is to recover DOAs, hop timings, frequencies of all users from $\mathbf{X}$ without knowledge of hop codes, rates, and multipath time delays.

3. A 2-D HR PERSPECTIVE VIEW

For simplicity of exposition, let us focus on a FH system where there are two users, with r_1 paths and r_2 paths, respectively. As shown in Fig. 1, the original transmitted signals $s_1(t)$ and $s_2(t)$ may have different hop rates and hop timings, and n_i, $i = 1, \ldots, K-1$, are the hop instants ($n_0 = 0$). We assume that during one received data block, the total number of hops for all users (but not all paths) is bounded above by $K-1$ (such a bound could be deduced from the spectrogram of the data, and need not be tight).

Between any two *system wide* consecutive hop instants, e.g., n_i and n_{i+1}, there are only two temporal frequencies involved. During such a time segment, the received data is

$$\begin{aligned}\mathbf{X}_i &= [\mathbf{x}(n_i) \ \ \mathbf{x}(n_i+1) \ \ \cdots \ \ \mathbf{x}(n_{i+1}-1)]\\ &= \mathbf{A}_i\mathbf{B}_i\mathbf{S}_i + \mathbf{W}_i, \qquad (6)\end{aligned}$$

where

$$\begin{aligned}\mathbf{A}_i &= [\mathbf{a}(\theta_{11}) \ \cdots \ a(\theta_{1r_1}) \ \ a(\theta_{21}) \ \cdots \ a(\theta_{2r_2})],\\ \mathbf{B}_i &= \mathrm{diag}\big(\widetilde{\beta}_{11}^{p}, \ \ldots, \ \widetilde{\beta}_{1r_1}^{p}, \ \widetilde{\beta}_{21}^{q}, \ \ldots, \ \widetilde{\beta}_{2r_2}^{q}\big),\\ \mathbf{S}_i &= [\mathbf{s}_1 \ \cdots \ \mathbf{s}_1 \ \mathbf{s}_2 \ \cdots \ \mathbf{s}_2]^T : \ \ (r_1+r_2)\times(n_{i+1}-n_i),\\ \mathbf{s}_1 &= \left[e^{j\omega_1^p n_i T} \ \cdots \ e^{j\omega_1^p (n_{i+1}-1)T}\right]^T,\\ \mathbf{s}_2 &= \left[e^{j\omega_2^q n_i T} \ \cdots \ e^{j\omega_2^q (n_{i+1}-1)T}\right]^T,\end{aligned}$$

and $\mathbf{W}_i$ is the noise matrix. Here we assume user 1 and user 2 are in their p-th and q-th hops respectively during this time segment.

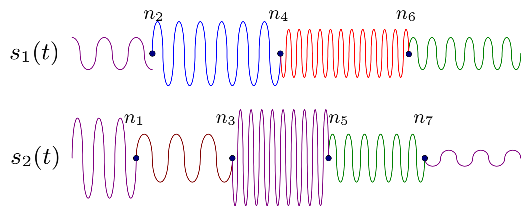

Fig. 1. Frequency hopped signals transmitted from two users.

From (6), it is seen that multipath propagation creates fictitious sources in the spatial dimension and delay spread in the temporal dimension, which manifest themselves as DOAs and phase shifts in $\mathbf{A}_i$ and $\mathbf{B}_i$, respectively.

The estimation of DOAs, time delays, and frequencies from $\mathbf{X}_i$ in (6) is in fact a 2-D HR problem, and there are $r_1 + r_2$ frequency components along each of the spatial and temporal dimensions. Notice that there are identical frequencies in the temporal dimension. If a total number of d users are active in the system, a similar 2-D harmonic mixture model can be obtained except that the number of frequency components in such a time segment along each dimension is $\sum_{k=1}^{d} r_k$. Recently, improved identifiability result and algorithms regarding 2-D HR have been developed (see [3] and references therein). We will use the MDF algorithm in [3] for this purpose since it achieves the best known identifiability bound and performs well for a wide range of SNR, but most importantly, it can deal with such a 2-D harmonic mixture wherein identical frequencies exist along one dimension. Note that estimates of elements of the triple $\left(\theta_{kl}, \omega_k^p, \widetilde{\beta}_{kl}^p\right)$ are associated automatically by the MDF algorithm (see [3]).

4. CODE-BLIND RECEPTION OF FH SIGNALS

The key idea behind our proposed code-blind reception scheme is that between any two hypothesized *system-wide* hops, the data follow a 2-D harmonic model. Hence for a hypothesized set of hops (that is, including all hops of all users in the system), 2-D HR methods can be used to estimate model parameters, and subsequently calculate model fit. If one operates under an upper bound on the total (system-wide) number of hops, then system stage can be defined as the number of remaining hops, and state can be defined as the sample instant, hence dynamic programming can be used to find the optimal hop sequence and associated model parameters per dwell. Note that this is different from assuming a bound on the number of hops on a per user basis – the complexity of the latter is exponential in the number of co-channel users.

In particular, let us define vectors of hop instants, hop frequencies, DOAs, and complex amplitudes as

$$\begin{aligned}\mathbf{n} &= [n_1, \ldots, n_K], \quad \boldsymbol{\omega} = \left[\omega_1^1, \ldots, \omega_1^P, \omega_2^1, \ldots, \omega_2^Q\right],\\ \boldsymbol{\alpha} &= \left[\alpha_{11}^1, \ldots, \alpha_{1r_1}^1, \ldots, \alpha_{11}^P, \ldots, \alpha_{1r_1}^P, \alpha_{21}^1, \ldots, \alpha_{2r_2}^Q\right],\\ \boldsymbol{\beta} &= \left[\widetilde{\beta}_{11}^1, \ldots, \widetilde{\beta}_{1r_1}^1, \ldots, \widetilde{\beta}_{11}^P, \ldots, \widetilde{\beta}_{1r_1}^P, \widetilde{\beta}_{21}^1, \ldots, \widetilde{\beta}_{2r_2}^Q\right],\end{aligned}$$

where $P-1$ and $Q-1$ are the total numbers of hops of user 1 and user 2 in the block, respectively. Now, the joint maximum likelihood estimation of $\mathbf{n}$, $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, and $\boldsymbol{\omega}$ from $\mathbf{X}$ amounts to minimizing

$$J(\widehat{\mathbf{n}}, \widehat{\boldsymbol{\alpha}}, \widehat{\boldsymbol{\beta}}, \widehat{\boldsymbol{\omega}}) = \sum_{i=0}^{K-1} \|\mathbf{X}_i - \widehat{\mathbf{X}}_i\|_F^2 \qquad (7)$$

over $\widehat{\mathbf{n}}, \widehat{\boldsymbol{\alpha}}, \widehat{\boldsymbol{\beta}}, \widehat{\boldsymbol{\omega}}$, where $\widehat{\mathbf{X}}_i$ is the reconstructed 2-D harmonic mixture based on parameter estimates (i.e., DOAs, complex amplitudes, and carrier frequencies) obtained by applying the MDF algorithm to (6) for a given time segment defined by hypothesized $\widehat{n}_i$ and $\widehat{n}_{i+1}$, assuming a 2-D harmonic mixture model for the received data during this segment. Thus from the MDF estimates for the data block in $\widehat{n}_i$ and $\widehat{n}_{i+1}$, we form

$$\widehat{\mathbf{X}}_i = \widehat{\mathbf{A}}_i \widehat{\mathbf{B}}_i \widehat{\mathbf{S}}_i. \tag{8}$$

Define $\Lambda_i[n_{i-1}, n_i]$ as the cost function for the time segment $n_{i-1} \le n < n_i$

$$\Lambda_i[n_{i-1}, n_i - 1] = \|\mathbf{X}_{i-1} - \widehat{\mathbf{X}}_{i-1}\|_F^2. \tag{9}$$

Furthermore, to solve the minimization problem in (7) by the dynamic programming method, we define

$$\Gamma_h(L) = \min_{\substack{n_1,\ldots,n_{h-1} \\ n_0=0, n_h=L+1}} \sum_{i=1}^{h} \Lambda_i[n_{i-1}, n_i - 1], \tag{10}$$

where $0 < n_1 < \cdots < n_{h-1} < L$. Eq. (10) can be viewed as the minimization problem of finding the best fit for a subset of the data of size $M \times (L+1)$ when a total number of $h-1$ hops is allowed. Hence $\Gamma_K(N-1)$ is the minimum of $J(\widehat{\mathbf{n}}, \widehat{\boldsymbol{\alpha}}, \widehat{\boldsymbol{\omega}}, \widehat{\boldsymbol{\phi}})$. From (10), a recursion for the minimum can be developed as (see [5])

$$\Gamma_h(L) = \min_{n_{h-1}} \Big(\Gamma_{h-1}(n_{h-1} - 1) + \Lambda_h[n_{h-1}, L]\Big). \tag{11}$$

where $2h - 1 \le n_{h-1} < L$. This says that for a data matrix of size $M \times (L+1)$, the minimum error for h segments (i.e., $h-1$ hop instants) is the minimum error for the first $h-1$ segments that end at $n = n_{h-1} - 1$, and the error contributed by the last segment from $n = n_{h-1}$ to $n = L$. The solution of the minimization of (7) is for $h = K + 1$ and $L = N - 1$, which gives the joint ML estimation of hopping instants, DOAs, frequencies, and complex amplitudes of all users.

Assuming that the minimum length of a segment is two samples, the procedure to compute the solution by DP and 2-D Harmonic Retrieval (DP-2DHR) is summarized in Table 1. Note that frequencies and complex amplitudes of different segments pertaining to a particular path can be associated via their corresponding DOA parameters, since for a single segment, frequency, amplitude, and DOA parameters pertaining to one path are paired up automatically by the MDF algorithm. In addition, different paths pertaining to a particular user will result in different DOAs but identical hop frequency sequence and hop timing (recall that time delay is treated as phase shift), hence paths can be associated to users by hop sequences, which is a clustering problem and can be solved by, e.g., calculating the pair-wise distance among all hop sequences.

The complexity of the DP-2DHR algorithm is $\mathcal{O}(N^5)$. In practical FH systems, frequencies hop at a regular rate, so it is enough to estimate two parameters: hop timing and hop period. These can be obtained by applying dynamic programming to a relatively short portion of a long data record, while DOA, amplitude, and frequency estimation for the remaining data can be accomplished by applying the MDF algorithm to pre-decided hop-free data blocks delimited by *system-wide* adjacent hop instants, provided that the number and directions of multiple paths do not change over the time interval of interest. This will reduce the complexity significantly.

Table 1. The DP-2DHR Algorithm

1. **Initialization**
   $h = 1$, compute $\Gamma_h(L)$ for $L = 1, \ldots, N - 2K + 1$ using (9) and (10), where $\widehat{\mathbf{X}}_0$ is a reconstructed 2-D harmonic mixture matrix based on DOAs, amplitudes, and frequencies estimated by applying the MDF algorithm to data matrix $\mathbf{X}(:, 0 : L)$.
2. **Recursion**
   Using (11), for $2 \le h \le K - 1$, compute $\Gamma_h(L)$ with $L = 2h - 1, \ldots, N - 2K + 2h - 1$; for $h = K$, compute $\Gamma_h(L)$ with $L = N - 1$.
   For each L, denote the value of n_{h-1} that minimizes $\Gamma_h(L)$ as $n_{h-1}(L)$, and denote the corresponding $\widehat{\boldsymbol{\alpha}}_{h-1}$, $\widehat{\boldsymbol{\beta}}_{h-1}$, $\widehat{\boldsymbol{\omega}}_{h-1}$ as $\widehat{\boldsymbol{\alpha}}_{h-1}(L)$, $\widehat{\boldsymbol{\beta}}_{h-1}(L)$, and $\widehat{\boldsymbol{\omega}}_{h-1}(L)$, respectively.
3. **Backtracking**
   The maximum likelihood estimates of hop instants are obtained by using the backward recursion, i.e., $\widehat{n}_i = n_i(\widehat{n}_{i+1} - 1)$, for $i = K - 2, K - 3, \ldots, 1$, initialized by $\widehat{n}_{K-1} = n_{K-1}(N - 1)$. Similarly, the corresponding DOA, amplitude, and frequency estimates of each segment can be obtained by their respective backward recursions.

5. DISCUSSION AND SIMULATION

The proposed method is developed based on an FH-FSK data model, but it may be applied for signal parameter estimation in other FH multipath propagation scenarios as well, which are summarized in the following cases.

i) Slow frequency hopping (SFH) with FSK modulation: Frequency changes due to baseband modulation are usually much smaller than those due to carrier frequency hopping. Hence symbol rate and hopping rate can be obtained from the result of DP, and consequently symbol recovery is possible.

ii) SFH with PSK modulation: During one hop dwell, frequency is constant, but the complex amplitudes are different from symbol to symbol due to phase modulation (recall that for one hop dwell, the effect of phase shift on the complex amplitudes due to time delay is constant). Hence symbol rate and hopping rate are still distinguishable from the result of DP.

iii) SFH with GMSK modulation: GMSK signal is not a pure exponential in one symbol period. However, narrow band GMSK signal can be approximated by exponentials for the purpose of joint DOA and hop timing estimation.

iv) Fast frequency hopping (FFH): The DP-2DHR method is applicable for hop timing and hop frequency sequence estimation. However, addition information (e.g., symbol period) is needed for symbol detection.

In simulation, we tested the blind reception of FH signals transmitted from two users, each hopping with different hop timing and rate. Suppose one user has two paths at DOA=$[6^\circ,\ 14^\circ]$ with the second path delayed $0.25\ \mu$s, and the other one has a single path at DOA=25°. The ULA consists of $M = 6$ antennas, with separation

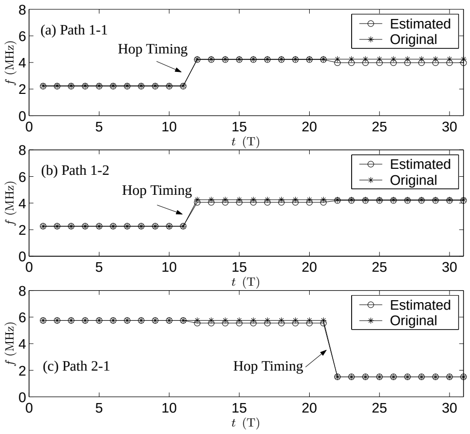

Fig. 2. Test 1 (FH-FSK): Hop timing and frequency estimation.

Table 2. Test 1 (FH-FSK): DOA estimation results for three paths.

	True DOA	Estimated DOA		
		1st Seg.	2nd Seg.	3rd Seg.
Path 1-1	6°	5.38°	5.98°	5.73°
Path 1-2	14°	12.56°	17.56°	13.9°
Path 2-1	25°	24.43°	24.67°	24.88°

of half a wavelength at center frequency $f_c = 1$GHz. A hopping band of 8MHz bandwidth is occupied by 32 frequency channels. At the receiver, the baseband signal is sampled at a rate of 8MHz, and $N = 32$ samples are collected at each antenna.

Test 1 (FH-FSK, SNR=12dB): In this test, each FH-FSK user hops once during the data block period; hence, there are three time segments with three temporal frequencies present in each (two are identical). Table 2 gives the results of DOA estimation for those three segments, and Fig. 2 depicts the corresponding hop timing and frequency estimation for the three paths, where "Path 1-2" denotes the 2nd path of user 1. We assume that mobility-induced changes in DOA are negligible within the analysis window (which is 4 μs long in this example). Thus, (varying hop) frequencies are associated with different paths via their corresponding (window invariant) DOA parameters. The results show that DOA, hop timing and frequency estimates are close to the respective true values. Fig. 2 also indicates that path 1 and 2 pertain to the same user since they have identical hop timing and frequency sequence.

Test 2 (FH-GMSK, SNR=15dB): In this test, the two users are GMSK modulated. Typical results shown in Fig. 3 implies that the DP-2DHR algorithm is able to deal with GMSK modulations despite the associated model mismatch.

Test 3: We define *timing estimation error* as a situation where an estimated hop instant deviates from its true value by more than 10% of the symbol period. The probability of timing estimation error P_e is obtained via Monte Carlo simulation of the FH-FSK case. For each realization, hop timings are randomly generated, and frequencies are also randomly selected from the 32 candidate bins. Fig. 4 plots P_e vs. SNR, which indicates that the DP-2DHR algorithm performs well for a wide range of SNR values, given the fact that the signals are tracked in a situation where hop code, rate, timing, and multipath delay are all unknown.

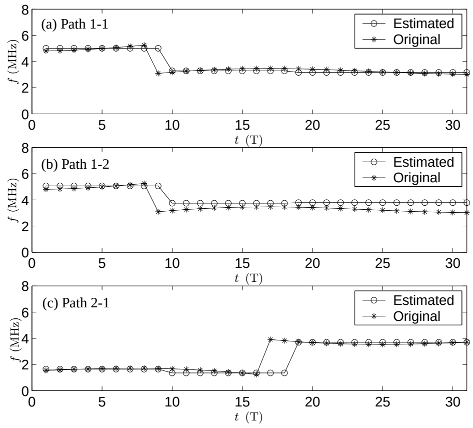

Fig. 3. Test 2 (FH-GMSK): Hop timing and frequency estimation.

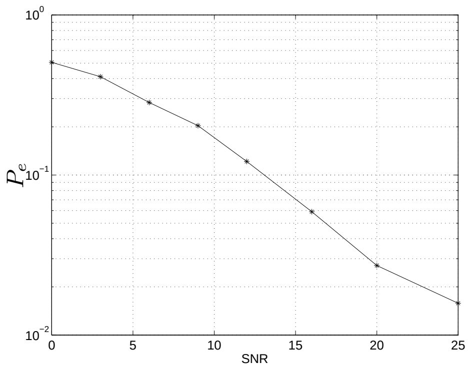

Fig. 4. Probability of timing estimation error vs SNR.

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