Selection Criteria for Frequency Hopping Pattern Set

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Abstract: In this contribution we propose a set of criteria for evaluating the quality of a set of Frequency Hopping patterns that can be used in Slow-Frequency-Hopping Spread Spectrum physical layer implementations. We also propose that such a set, once created, be incorporated in the 802.11 standard for use by anyone who wishes to produce compliant implementations of SFH based systems.

Introduction

Consider the operation of an autonomous network system with multiple Access Points interconnected by a Distribution System. There are several possibilities for physical layer implementation. In this contribution we assume a physical layer based on Slow Frequency Hopping Spread Spectrum communication under U.S. FCC Part 15.247. The following general assumptions are made with respect to operation of a multicell network.

- There exists a predetermined set F of FH patterns for use in the autonomous network.
- Each Access Point will follow its own FH pattern chosen from the predetermined set F.

The choice of set F is important. The set F will have a direct impact on the hop interference experienced by a cell due to the presence of adjacent cells that provide overlapping coverage. In this contribution we propose the following set of criteria for judging the quality of a family of FH patterns, F.

Criterion 1 (Equal Use of Channels)

Each channel frequency should be used equally often in each pattern. This requirement ensures that, on the average, the power transmitted on each channel frequency is the same. A consequence of this requirement is that the pattern length, n, has to be a multiple of the number of available channel frequencies, p. If the pattern length is equal to the number of channel frequencies, then each pattern is a permutation of the channel frequencies.

Criterion 2 (Direct Hits)

The following properties hold for systems under consideration.

- The FH patterns are permutation sequences of p channel frequencies. One period of a hopping pattern is called a *superframe*.
- All the hops within a superframe are of the same length.
- Superframes of adjacent Access Points are unsynchronized.

Any two patterns in the family should be on the same frequency channel (at the same time) as little as possible. This criteria is important to ensure that two transmitters with a common area of radio coverage have little interference with each other. The number of hits between two patterns is the number of positions in which their elements are equal.

As an example, consider Frequency Hopping with 5 frequencies and the following three patterns.

`Pattern 1: (1 2 3 4 5)  Pattern 2: (4 2 5 1 3)  Pattern 3: (5 4 3 2 1)`

Example 1: Suppose Patterns P1 and P3 are used in adjacent cells.

P1:	1	2	3	4	5	No. of hits (i.e., hops interfered)	
P3:	5	4	3	2	1	1	(initial phase)
	1	5	4	3	2	1	(after 1 cyclic shift)
	2	1	5	4	3	1	(after 2 cyclic shifts)
	3	2	1	5	4	1	(after 3 cyclic shifts)
	4	3	2	1	5	1	(after 4 cyclic shifts)

In the above example the interference is spread uniformly over time.

Example 2: Suppose Patterns P1 and P2 are used in adjacent cells.

P1:	1	2	3	4	5	No. of hits
P2:	4	2	5	1	3	1
	2	5	1	3	4	0
	5	1	3	4	2	2
	1	3	4	2	5	2
	3	4	2	5	1	0

In the above example the interference is not spread uniformly over time even though the mean value of hops interefered over time is the same as in Example 1.

A common technique for minimizing interference between overlapping adjacent cells in a fully synchronized network is based on *orthogonal* FH pattern sets (i.e., no hits between any pair of patterns). However, in unsynchronized networks, the phase relationships of FH patterns followed by adjacent Access Points will change over time. Interference of a pattern with respect to another pattern must take into account all possible phase relationships.

Given a pair of FH patterns, F_i and F_j, let $H_{ij}^{(k)}$ be the number of hits between Patterns F_i and F_j cyclically shifted k times.

$$H_{ij}^{(k)} = Cardinality\,\{\, l : f_i(l) = f_j(l+k),\ 0 \le l < n \,\}\,,$$

where the position index of the patterns is taken modulo n, i.e., $l + k \triangleq (l + k) \bmod n$.

Since we assume no synchronization between transmitters, the definition of hits is as follows:

Patterns F_i and F_j have h **hits** if

$$h = \max_{0 \le k < n} H_{ij}^{(k)}$$

A very desirable property for a set of FH patterns to satisfy is the following: The number of hits for any pair of FH patterns is one. Then, even in the worst-case situation, at most one hop interference will occur between any two FH patterns in the set. A set of FH patterns with constraints on the the number of hits will have predictable interference characteristics.

Criterion 3 (Adjacent Channel Interference)

Any two patterns in the family F should be on adjacent frequency channels (at the same time) as little as possible. This *Adjacent Channel Interference* criterion is important because the filters in radios typically allow some energy to leak in from adjacent frequency bands. Thus, to ensure that two transmitters with a common area of radio coverage have little interference with each other, they should minimize their Adjacent Channel Interference. The Adjacent Channel Interference between two patterns is the number of positions in which their elements differ by exactly one. In a similar manner to hits, we define the Adjacent Channel Interference, taking care of the lack of synchronization between transmitters, as follows:

Patterns F_i and F_j have *Adjacent Channel Interference* c if

$$c = \max_{0 \le k < n} Cardinality\,\{\, l : |\, f_i(l) - f_j(l+k)\,| = 1,\ 0 \le l < n \,\}$$

A desirable property for a set of FH patterns to satisfy is that the Adjacent Channel Interference for any pair of FH patterns is two. Then, even in the worst-case situation, at most two hops will be on adjacent channels for any two FH patterns in the set.

Criterion 4 (Temporal Frequency Diversity)

The adjacent elements of a pattern should not be close together. This *temporal frequency diversity* criterion is important because if the transceiver experiences interference on a channel, it is desirable that the channel frequency on the next hop be far from the channel with the interference. Specifically, this criterion is trying to minimize the effect of some interference that simultaneously affects a range of adjacent channel frequencies, e.g. microwave ovens, amateur radio operators. The temporal frequency diversity of a pattern is defined by the minimum difference between adjacent elements of the pattern.

Pattern F_i has temporal frequency diversity a if

$$a = \min_{0 \leq j < n} \mid f_i(j+1) - f_i(j) \mid$$

It is desirable to include a FH pattern $< f_1, f_2, \dots, f_n >$ in set F, only if $a \geq f_{sep}$, where, f_{sep} is the minimum desirable frequency separation between adjacent hopping channels.

Consider frequency hopping with 5 channels and $f_{sep} = 2$. $< 1\ 2\ 3\ 4\ 5 >$ is a FH pattern that does not satisfy the constraint while $< 1\ 3\ 5\ 2\ 4 >$ is a pattern that satisfies the diversity constraint.

Criterion 5 (Avoidance of Contiguous Bad Hops)

This final criterion regards the positions of the interference from *hits* and *Adjacent Channel Interference*. Any family of sequences will suffer some interference from these two sources. An objective is to ensure that the elements of a pattern experiencing hits and Adjacent Channel Interference from another pattern not be adjacent to each other. This is to ensure that even if communication is lost for one hop due to interference from another nearby transmitter, then communication is regained in the next hop and not lost for a number of adjacent hops.

The following is an illustrative example. Consider Frequency Hopping with 7 patterns with patterns P4 and P5 shown below.

P4:	6	5	4	3	2	1	0
P5:	3	1	6	4	2	0	5

Even though P4 and P5 have one hit, there exists a sequence of contiguous hops such that either there is a direct hit or Adjacent Channel Interference (*bad hops*). In the above example, sequence P4 (xxx321x) has three contiguous hops that interfere with P5 (xxx420x).

It is desirable to choose a FH pattern set such that for any pair of patterns Pi, Pj and any relative phase, sequences of ($\geq$ 3) contiguous bad hops are not possible.

Summary

It is proposed that a good set of FH patterns possess the five properties described above.

- Equal use of different channels.
- Upper limits on number of direct hits.
- Upper limit on adjacent channel interference.
- Maximum temporal frequency diversity.
- No contiguous sequence of hops affected by hits or adjacent channel interference.

Suppose a good FH pattern set FHPSET that satisfies the above properties is created. Autonomous networks cannot be expected to *explicitly* coordinate with each other. *Implicit* coordination between colocated networks will result if all networks assign FH patterns from the same good set FHPSET satisfying all the desirable properties. The extent of interference can be made predictable and will be a function of the number of adjacent overlapping cells (belonging to either the same network or other autonomous but colocated networks). The good set FHPSET should become part of the 802.11 standard.