Project	**IEEE 802.16 Broadband Wireless Access Working Group** <http://ieee802.org/16>
Title	**Self-organizing Fractional Frequency Reuse for 802.16m Systems**
Date Submitted	**2008-11-10**
Source	Kim Olszewski ZTE USA, Inc. 10105 Pacific Heights Blvd, Suite 250 San Diego, CA 92121 E-mail: kolszewski@zteusa.com
Re:	802.16m-08/040 - Call for Comments and Contributions on the 802.16m System Description Document (SDD). **TGm SDD: SON**
Abstract	This contribution proposes the usage of methods for self-organizing fractional frequency reuse within IEEE 802.16m systems. An approach is also described.
Purpose	To review and adopt the proposed text in the next revision of the SDD.
Notice	This document does not represent the agreed views of the IEEE 802.16 Working Group or any of its subgroups. It represents only the views of the participants listed in the “Source(s)” field above. It is offered as a basis for discussion. It is not binding on the contributor(s), who reserve(s) the right to add, amend or withdraw material contained herein.
Release	The contributor grants a free, irrevocable license to the IEEE to incorporate material contained in this contribution, and any modifications thereof, in the creation of an IEEE Standards publication; to copyright in the IEEE’s name any IEEE Standards publication even though it may include portions of this contribution; and at the IEEE’s sole discretion to permit others to reproduce in whole or in part the resulting IEEE Standards publication. The contributor also acknowledges and accepts that this contribution may be made public. by IEEE 802.16
Patent Policy	The contributor is familiar with the IEEE-SA Patent Policy and Procedures: <http://standards.ieee.org/guides/bylaws/sect6-7.html#6> and <http://standards.ieee.org/guides/opman/sect6.html#6.3> Further information is located at <http://standards.ieee.org/board/pat/pat-material.html> and <http://standards.ieee.org/board/pat>

Self-organizing Fractional Frequency Reuse for 802.16m Systems

Kim Olszewski
ZTE USA, Inc.

1 Introduction

There are four basic approaches for interference mitigation within OFDMA-based cellular networks. Specifically, the following four approaches that complement each other and can be combined:

1. Interference randomization or averaging via subcarrier frequency hopping.
2. Interference avoidance by fixed or adaptive allocation of OFDMA frequency reuse patterns.
3. Interference estimation and cancellation via advanced signal processing techniques.
4. Interference mitigation by transmit and receive beamforming or precoding.

This contribution addresses the second approach with a focus on its implementation for self-organizing networks operating in a TDD mode. Fixed or adaptive fractional frequency reuse (FFR) provides a means to mitigate interference especially cell edge interference. To support FFR a set of orthogonal OFDMA subchannels is divided into several frequency partitions or subbands. In a typical FFR implementation mobile stations (MSs) near a cell center are allowed to operate in a frequency partition that is comprised of all OFDMA subchannels. In contrast, MSs at a cell edge are only allowed to operate in a frequency partition that uses use a fraction or subset of the available OFDMA subchannels. For cell edge MSs disjoint or orthogonal frequency partitions are allocated so that MSs in adjacent cell edges will simultaneously operate on a different subset of OFDMA subchannels. Cell-edge MSs are allowed a smaller number of OFDMA subchannels but gain inter-cell interference mitigation (see Figure 1).

There are several approaches as how to map or distribute mobile stations to a set of frequency partitions. For example, the simplest one consists of randomly picking frequency partitions from a set of available frequency partitions. For self-organized networks frequency partitioning should involve little or no inter-BS coordination as described in Section 20.1.1.2 of the SDD. This contribution proposes baseline SDD text and describes an FFR approach for self-organized networks that encompasses spectrum profiling by MSs and self-organizing frequency partitioning by BSs.

2 Proposed SDD Text

The proposed text below addresses FFR for self-organizing IEEE 802.16m networks. Some detail of an approach for supporting self-organizing FFR is described in the remaining sections of this contribution.

18.x Self-organizing Fractional Frequency Reuse

Self-organizing FFR is distributed process divided between a base station and the mobile stations within its cell. For self-organizing FFR two basics steps are required: spectrum profiling by mobile stations and self-organizing frequency partitioning by base stations.

18.x.1 Spectrum Profiling by Mobile Stations

Spectrum profiling may be defined as the process of characterizing spectrum comprising a frequency partition set $\mathcal{F} = \{F_1, F_2, ..., F_r\}$ and maintaining an awareness of channel state and interference conditions within $\mathcal{F}$. MSs assess and characterize their local spectrum situation for each F_i in $\mathcal{F}$. Spectrum profiling provides BSs information on the characteristics (dynamic channel and interference conditions) of a frequency partition set $\mathcal{F} = \{F_1, F_2, ..., F_r\}$. A base station may specify time instances for spectrum profiling or they may occur at periodic time intervals (e.g. P-SCH, midambles, etc). MSs provide acquired spectrum profile data concerning $\mathcal{F}$ to their serving BSs via spectrum profiling messages.

18.x.2 Self-Organizing Frequency Partitioning by Base Stations

Self-organizing frequency partitioning may be based on a combination of inputs gathered from spectrum profiling messages provided by MSs spatially distributed within a BS's cell. Self-organizing frequency partitioning is the process of mapping MSs to frequency partitions F_i in $\mathcal{F}$. For self-organizing FFR, frequency partitioning is realized independently by each BS, no inter-BS communications are required.

3 Frequency Partition Sets for FFR

- Let N_{FFT} (a power of 2) denote the number of orthogonal subchannels associated with an OFDMA symbol. The frequency set associated with an OFDMA symbol is defined as

  $$\mathsf{F} = \{f_k\}_{k=0}^{N_{FFT}-1} = \{f_k\}_{k=-N_{FFT}/2}^{N_{FFT}/2-1} \tag{1}$$

  Here f_k denotes a subcarrier frequency. The N_{FFT} orthogonal subchannels are centered at the discrete frequencies in F, each having a bandwidth of $1/N_{FFT}T_S$ where T_S denotes the system sample period
- Set F contains the frequencies of all N_{FFT} subchannel signals associated with an OFDMA symbol.
- We define a frequency or subband partitioning associated with an FFR implementation as

  $$\mathcal{F} = \{F_1, F_2, ..., F_r\} \tag{2}$$

  where integer $1 \leq r \leq N_{\text{used}}$ and $N_{\text{used}} < N_{FFT}$ denotes the number of used subcarriers.
- Each frequency partition F_i in $\mathcal{F}$ consists of N_i contiguous or non-contiguous subcarrier frequencies taken from F.
- Frequency partitions $F_1, F_2, ..., F_r$ may be overlapping or orthogonal (disjoint) meaning that the equality $N_{\text{used}} = \sum_{i=1}^{r} N_i$ holds.

4 Spectrum Profiling by Mobile Stations

- A spectrum profiler portrays the spectrum characteristics of a frequency partitioning $\mathcal{F} = \{F_1, F_2, ..., F_r\}$ using physical layer measurements such as the following:
  1. Estimates of the received signal to interference plus noise power ratio P_{SINR} for each F_i in $\mathcal{F}$.
  2. Estimates of interference (narrowband, wideband, impulsive and mixed) plus noise power P_{IPN} for each F_i in $\mathcal{F}$.
  3. Estimates of received signal power P_S for each F_i in $\mathcal{F}$.

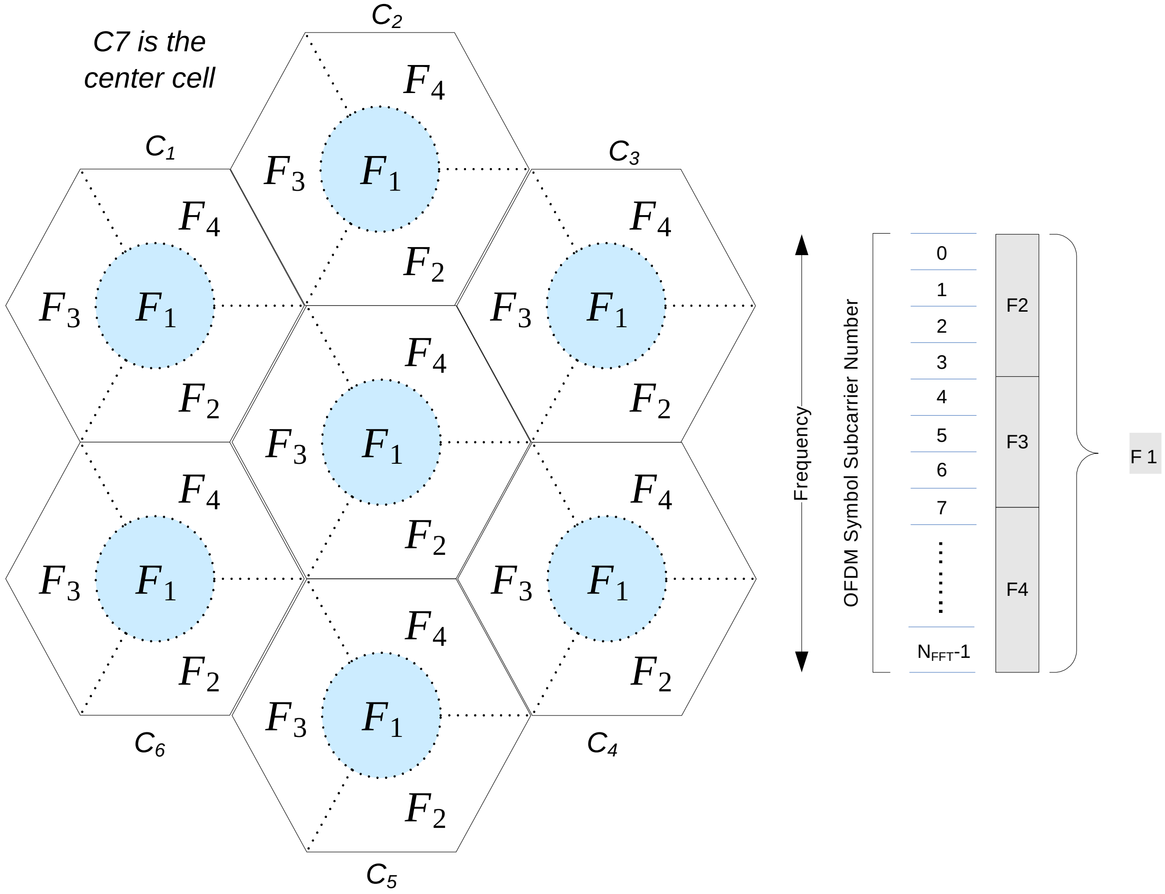

Figure 1: Example cluster of cells illustrating fractional frequency resuse with a frequency partition set defined as $\mathcal{F} = \{F_1, F_2, F_3, F_4\}$. Each F_i, $i \neq 1$, is associated with a cell sector in the example.

4. Decision bits that indicate whether a frequency partition F_i in $\mathcal{F}$ is favorable for MS radio operation at a desired data rate.

- A spectrum profiler may provide these measurements at periodic (e.g. superframe of frame-based) or random time intervals and in accordance with a specified scanning or search algorithm. The search algorithm may change based on application needs.

4.1 Signal Processing for Spectrum Profiling

Figure 2 shows a conceptual block diagram of a Spectrum Profiler. Referring to Figure 2 the components are now described.

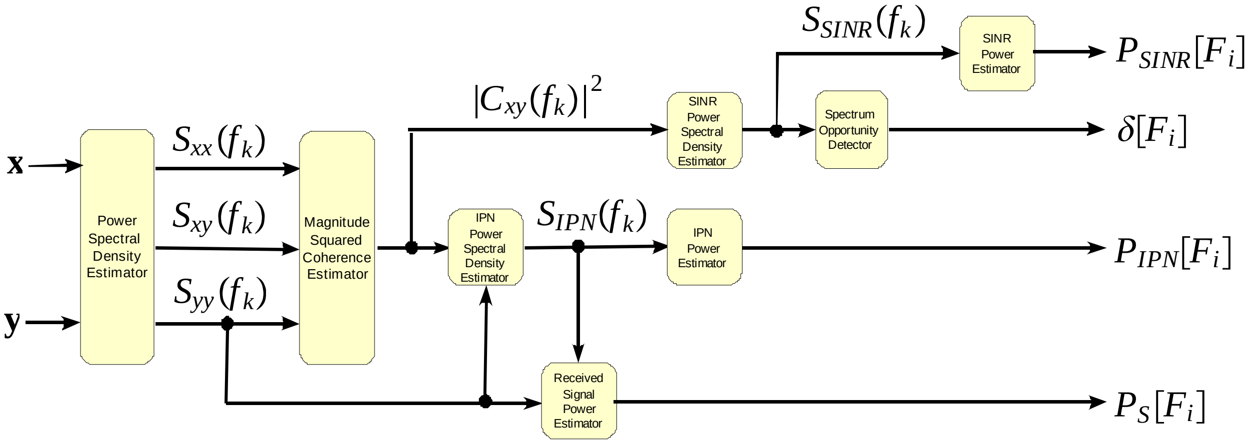

Figure 2: Conceptual block diagram of a Spectrum Profiler.

4.1.1 Power Spectral Density Estimator

- Let $\mathbf{x}$ denote a known wideband reference sequence such as a preamble or a midamble and $\mathbf{y}$ the received channel and interference corrupted version of $\mathbf{x}$. The length of the sequences is N_{FFT} which equals a power of two.

- Let T_S denote sampling period and recall the OFDMA symbol frequency set

$$\mathsf{F} = \{f_k\}_{k=0}^{N_{FFT}-1} = \{f_k\}_{k=-N_{FFT}/2}^{N_{FFT}/2-1} \tag{3}$$

  Discrete subcarrier frequency

$$f_k = \frac{k}{N_{FFT}T_S} = \frac{2k}{N_{FFT}} f_{\mathrm{NF}} \tag{4}$$

  lies within the baseband spectral band $B = [0, f_{\mathrm{NF}}]$ where $f_{\mathrm{NF}} = 1/2T_S$ is the Nyquist frequency.

- Given $\mathbf{x}$ and $\mathbf{y}$ the Power Spectral Density (PSD) Estimator computes the FFT-based PSD estimates

$$\{S_{xx}(f_k)\}_{k=-N_{FFT}/2}^{N_{FFT}/2-1}, \ \{S_{yy}(f_k)\}_{k=-N_{FFT}/2}^{N_{FFT}/2-1} \text{ and } \{S_{xy}(f_k)\}_{k=-N_{FFT}/2}^{N_{FFT}/2-1} \tag{5}$$

  for each subcarrier frequency f_k in F. The estimates can be easily computed using Welch's method.

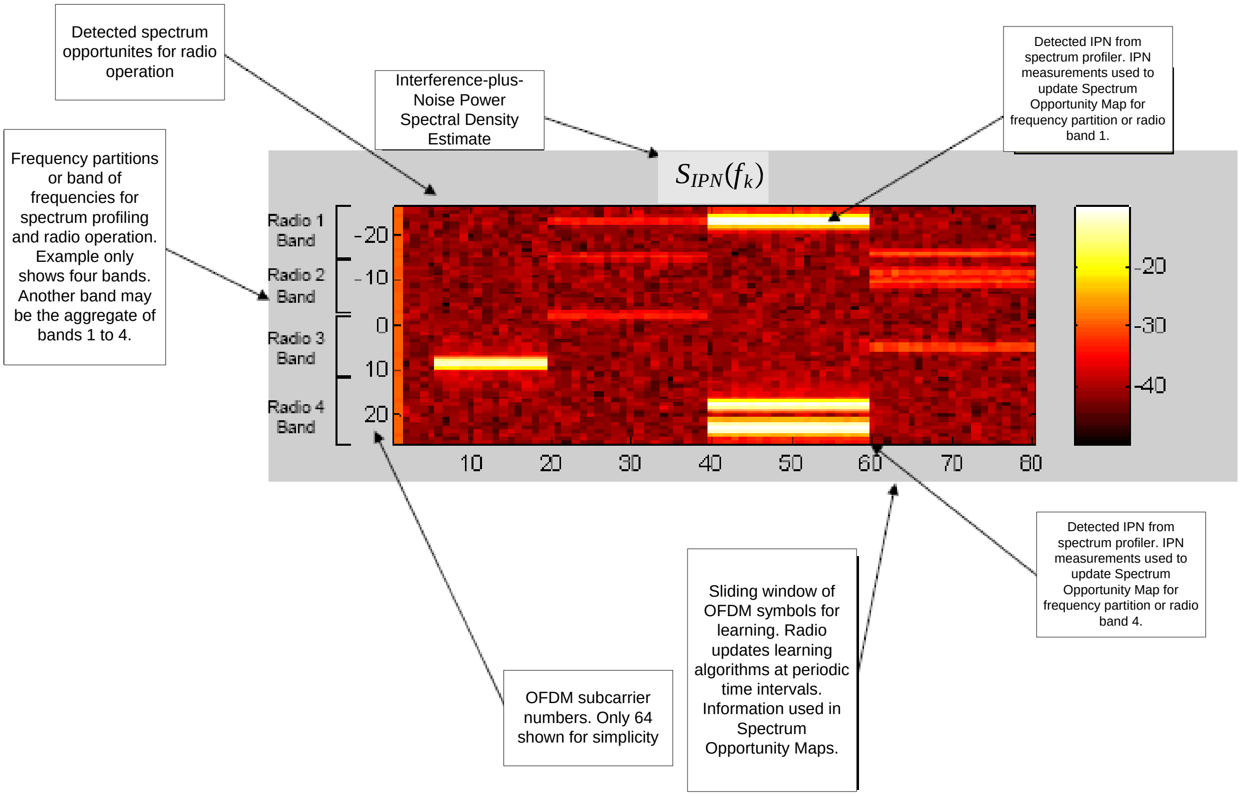

Figure 3: A spectrogram computed by the Spectrum Profiler. A spectrogram is a frequency vs. time vs. power display where the frequency is represented on y-axis and time on the x-axis. The power is expressed by the color.

- To improve performance PSD estimates should be smoothed or averaged. For example, let $t > 0$ denote the preamble or a midamble number and $S_{yy}(f_k, t)$ the PSD estimate of $\mathbf{y}$ computed from the tth preamble or a midamble. A simple exponentially weighted smoothing algorithm such as the following may be easily implemented:

$$\tilde{S}_{yy}[t] = \tilde{S}_{yy}[t-1] + \alpha \left(S_{yy}(f_k, t) - \tilde{S}_{yy}[t-1] \right) \tag{6}$$

  The parameter $0 \leq \alpha \leq 1$ controls the degree of smoothing. When α approaches 1 smoothing increases and when α approaches 0 smoothing decreases.

4.1.2 MS-Coherence Estimator

- Given the PSD estimates

$$\{S_{xx}(f_k)\}_{k=-N_{FFT}/2}^{N_{FFT}/2-1}, \ \{S_{yy}(f_k)\}_{k=-N_{FFT}/2}^{N_{FFT}/2-1} \text{ and } \{S_{xy}(f_k)\}_{k=-N_{FFT}/2}^{N_{FFT}/2-1} \tag{7}$$

  the Magnitude-Squared (MS) Coherence Estimator computes

$$\left\{ |C_{xy}(f_k)|^2 \right\}_{k=-N_{FFT}/2}^{N_{FFT}/2-1} \tag{8}$$

  where

$$0 \leq |C_{xy}(f_k)|^2 = \frac{|S_{xy}(f_k)|^2}{S_{xx}(f_k) S_{yy}(f_k)} \leq 1 \tag{9}$$

  denotes the magnitude-squared coherence estimate at discrete frequency f_k.

- The MS-Coherence estimate $|C_{xy}(f_k)|^2$ quantifies the similarity or dependence between sequences $\mathbf{x}$ and $\mathbf{y}$.
- The MS-Coherence estimate $|C_{xy}(f_k)|^2$ is a normalized cross-spectral density that measures the linear dependence (correlation) between the N_{FFT} spectral components of $\mathbf{x}$ and those of $\mathbf{y}$.
- If the spectral components of $\mathbf{x}$ and $\mathbf{y}$ are uncorrelated (e.g., $\mathbf{x}$ is an independent noise process not derived from $\mathbf{y}$), then $|C_{xy}(f_k)|^2$ is theoretically zero at all frequencies f_k.
- Time-domain cross-correlations between $\mathbf{x}$ and $\mathbf{y}$ also provide sequence similarity measures but $|C_{xy}(f_k)|^2$ may be more useful for spectrum profiling because:
  1. $|C_{xy}(f_k)|^2$ provides similarity measures at discrete subcarrier frequencies f_k
  2. $|C_{xy}(f_k)|^2$ is independent of any time delay between sequences $\mathbf{x}$ and $\mathbf{y}$.
  3. $|C_{xy}(f_k)|^2$ simplifies the mathematical formulation of a signal detector implementation.

4.1.3 SINR, IPN and Received Signal Power Estimators

- MS-coherence estimates are appropriate for spectrum profiling since they may be used to also provide SINR and interference estimates.
- Given MS-coherence estimates the SINR Estimator computes the ratio of received signal-of-interest power to received interference-plus-noise power:

$$S_{SINR}(f_k) = \frac{|C_{xy}(f_k)|^2}{1 - |C_{xy}(f_k)|^2} \tag{10}$$

  See references for mathematical details.

- Given MS-coherence estimates and $S_{yy}(f_k)$ the interference-plus-noise (IPN) Power Spectral Density Estimator computes the PSD of the received IPN:

$$S_{IPN}(f_k) = \left(1 - |C_{xy}(f_k)|^2\right) S_{yy}(f_k) \tag{11}$$

  See references for mathematical details.

- As defined above a frequency partitioning associated with an FFR implementation is

$$\mathcal{F} = \{F_1, F_2, ..., F_r\} \tag{12}$$

  where integer $1 \leq r \leq N_{\text{used}}$ and $N_{\text{used}} < N_{FFT}$ denotes the number of used subcarriers. Each frequency partition F_i in $\mathcal{F}$ consists of N_i contiguous or non-contiguous subcarrier frequencies taken from F.

- The SINR Power Estimator computes the received signal-of-interest to interference-plus-noise (IPN) power ratio over a frequency partition F_i in $\mathcal{F}$ from the summation

$$P_{SINR}[F_i] = \frac{1}{N_i} \sum_{f_k \in F_i} S_{SINR}(f_k) \tag{13}$$

- The IPN Power Estimator computes the received interference-plus-noise power over a frequency partition F_i in $\mathcal{F}$ from the summation

$$P_{IPN}[F_i] = \frac{1}{N_i} \sum_{f_k \in F_i} S_{IPN}(f_k) \tag{14}$$

- The PSD estimate $S_{yy}(f_k)$ may be written as

$$\begin{aligned} S_{yy}(f_k) &= S_{ss}(f_k) + S_{IPN}(f_k) \qquad (15) \\ &= |H(f_k)|^2 S_{xx}(f_k) + S_{IPN}(f_k) \end{aligned}$$

  and the received signal PSD estimate as

$$S_{ss}(f_k) = S_{yy}(f_k) - S_{IPN}(f_k) \tag{16}$$

  The Received Signal Power Estimator computes the received interference-plus-noise power over a frequency partition F_i in $\mathcal{F}$ from the summation

$$P_S[F_i] = \frac{1}{N_i} \sum_{f_k \in F_i} S_{ss}(f_k) \tag{17}$$

4.2 Some Estimator Computation Notes

- Sequence $\mathbf{x}$ should designed so that $S_{xx}(f_k)$ is constant and non-zero for all f_k. If $S_{xx}(f_k)$ is zero $|C_{xy}(f_k)|^2$ will be singular and corrupt subsequent signal processing operations.
- If $\mathbf{x}$ is known and constant $S_{xx}(f_k)$ can be computed off-line and stored in memory.
- Estimate $S_{xy}(f_k)$ can be computed efficiently from $S_{xx}(f_k)$ and $S_{yy}(f_k)$. Thus for each received frame only $S_{yy}(f_k)$ (which is required for OFDMA systems) needs to be computed using Welch's method.

- Performance of the spectrum profiler depends upon implementation factors:
  - Receiver characteristics such as sensitivity
  - Spectrum profiler window size equal to N_{FFT}
  - Average and peak values within the window
  - Spectrum profiling scan rate
  - Thresholds on discriminating interference/noise from signals

4.3 Spectrum Opportunity Detector

- A spectrum opportunity may be defined simply as a band or frequency partition F_i in $\mathcal{F}$ favorable for MS radio operation at a desired data rate. A spectrum opportunity exists if a radio can transmit using some combination of its operating parameters.
- For any discrete frequency f_k in a frequency partition $F_i \in \mathcal{F}$ it can be shown that the MS-Coherence estimate can be written as

$$|C_{xy}(f_k)|^2 = \frac{|S_{xy}(f_k)|^2}{S_{xx}(f_k)S_{yy}(f_k)} = \frac{\sigma_x^2}{\sigma_x^2 + S_{IPN}(f_k)/|H(f_k)|^2} \tag{18}$$

  where $S_{xx}(f_k) = \sigma_x^2$, $H(f_k)$ denotes the channel transfer function at f_k and $S_{IPN}(f_k)$ the PSD of the received interference-plus-noise (IPN).
- From the above equation it is easily seen that a MS-Coherence estimate aggregates information on both channel quality and interference-plus-noise.
- From the above equation it is easily seen that as $S_{IPN}(f_k)/|H(f_k)|^2$ increases (decreases) $|C_{xy}(f_k)|^2$ decreases (increases).
- We can therefore use $|C_{xy}(f_k)|^2$ as a measure to detect spectrum opportunities for each f_k in a frequency partition $F_i \in \mathcal{F}$.
- The problem of detecting spectrum opportunities can be formulated as a statistical hypothesis test with null and alternative hypotheses $\mathcal{H}_0$ and $\mathcal{H}_1$.
- For each f_k in a frequency partition $F_i \in \mathcal{F}$ a spectral opportunity may detected using the hypothesis test:

$$\begin{aligned} \mathcal{H}_0 &: |C_{xy}(f_k)|^2 = 0 \text{ (Spectrum opportunity does not exist)} \\ \mathcal{H}_1 &: |C_{xy}(f_k)|^2 > 0 \text{ (Spectrum opportunity exists)} \end{aligned} \tag{19}$$

- The following table summarizes the possible decisions and errors:

Truth	Decision Accept $\mathcal{H}_1$	Decision Reject $\mathcal{H}_1$
$\mathcal{H}_0$	Type I Decision Error	Correct Decision
$\mathcal{H}_1$	Correct Decision	Type II Decision Error

(20)

4.3.1 Decision Test Statistic and Error Probabilities for Spectrum Opportunity Detection

- Let the random variable

$$T(f_k) = (m-1)\frac{|C_{xy}(f_k)|^2}{\left(1 - |C_{xy}(f_k)|^2\right)} = (m-1)S_{SINR}(f_k) \tag{21}$$

  denote a test statistic at discrete frequency f_k in a frequency partition F_i in $\mathcal{F}$.

- Let τ denote a critical value or a decision threshold for $T(f_k)$ at a discrete frequency f_k in a frequency partition $F_i \in \mathcal{F}$.

- The probability of a Type I decision error (spectrum opportunity false alarm) is defined as

$$P_{\mathrm{FA}} = \Pr\left\{\text{Accept } \mathcal{H}_1 | \text{Truth } \mathcal{H}_0\right\} = \Pr\left\{T(f_k) \geq \tau | \text{Truth } \mathcal{H}_0\right\} \tag{22}$$

- The probability of a Type II Decision Error (missed spectrum opportunity detection) is defined as

$$P_{\mathrm{MD}} = \Pr\left\{\text{Accept } \mathcal{H}_0 | \text{Truth } \mathcal{H}_1\right\} = \Pr\left\{T(f_k) < \tau | \text{Truth } \mathcal{H}_1\right\} \tag{23}$$

- The difference $1 - P_{\mathrm{MD}}$ is the probability of detecting a spectrum opportunity.

- A design requirement for a Spectrum Opportunity Detector is to minimize the missed detection probability P_{MD} for a false alarm probability P_{FA} as small as possible.

4.3.2 Probability Distribution of the Decision Test Statistic

- Under $\mathcal{H}_0$ test statistic $T(f_k)$ has an F distribution $F_{1-P_{\mathrm{FA}}}(2, 2(m-1))$ with 2 numerator and $2(m-1)$ denominator degrees of freedom. Probability P_{FA} is chosen from the interval $[0, 1]$.

- Positive integer $m > 0$ denotes the number of segments used to compute $|C_{xy}(f_k)|^2$ (e.g. when computing $|C_{xy}(f_k)|^2$ using Welch's method m segments of a sequences $\mathbf{x}$ and $\mathbf{y}$ are used to compute m periodograms that are averaged).

4.3.3 Decision Function for Spectrum Opportunity Detection

- The decision function for the Spectrum Opportunity Detector is defined as

$$\delta(f_k) = \begin{cases} 1 & \text{if } T(f_k) \geq \tau = F_{1-P_{\mathrm{FA}}}(2, 2(m-1)) \\ 0 & \text{otherwise} \end{cases} \tag{24}$$

- Given a specified false alarm probability of P_{FA} the Spectrum Opportunity Detector rejects the null hypothesis $\mathcal{H}_0$ at a discrete frequency f_k in a frequency partition $F_i \in \mathcal{F}$ when $\delta(f_k)$ outputs a 1.

- Decisions $\delta(f_k)$ may be combined to detect a spectrum opportunity in a frequency partition F_i in $\mathcal{F}$. For example, using equal weighted decision combining (majority voting) the Spectrum Opportunity Detector may uses the decision function

$$\delta[F_i] = \begin{cases} 1 & \sum_{f_k \in F_i} \delta(f_k) > \left\lceil \frac{N_i}{2} \right\rceil \\ 0 & \text{otherwise} \end{cases} \tag{25}$$

  Other decision combining methods may also be used. For example, other spectrum profiler values (e.g. $P_S[F_i]$) may be used to weight decisions $\delta[F_i]$. The approach is up to the implementer.

4.3.4 Computation of the Detector Threshold Value

- Given a false alarm probability P_{FA} and the number of signal segments used to compute $|C_{xy}(f_k)|^2$ the inverse of the F distribution function $F_{1-P_{\mathrm{FA}}}(2, 2(m-1))$ can be used to compute a detector threshold value τ.
- Computations for a number of τ values can be computed off-line and results stored in look-up tables indexed by false alarm probabilities P_{FA}.

4.4 Some Applications for a Spectrum Profiler

- A Spectrum Profiler can be used for increasing spectrum efficiency, dynamic spectrum planning, frequency hopset adaptation, and rate adaptation.
- A Spectrum Profiler may be used as a key component for the following radio applications:
  - Link data rate adaptation
  - Transmit power control
  - Noise/interference avoidance
  - Interference mitigation
  - Channel access control
  - Efficient bandwidth utilization
  - Coexistence management with other radios and equipment
- Some measurements that may be provided by a Spectrum Profiler are the following:
  - For each frequency partition F_i in $\mathcal{F}$ received power levels and average usage durations may be estimated.
  - Interference duty cycles, interference traffic patterns and spectrum usage patterns may be estimated. For example, in a lightly loaded network duty cycles may be slow.
  - Dynamic histogram construction for estimating the probability of a spectrum opportunity occurring at a specified frequency partition F_i in $\mathcal{F}$. Let $\Pr(F_i)$ denote the probability that a frequency partition F_i in $\mathcal{F}$ provides a spectrum opportunity. Decisions $\delta[F_i]$ may be used to generate estimates of $\Pr(F_i)$ by averaging binary decision values $\delta[F_i]$ over a window of time (e.g. a sequence of superframes or frames). Dynamic histogramming can be implemented by combining the $\Pr(F_i)$ values for each frequency partition. More specifically, for the partition set $\mathcal{F} = \{F_1, F_2, ..., F_r\}$ a plot of the values $\Pr(F_i)$, $i = 1, 2, \ldots, r$, versus partition set index numbers will give the probability that each F_i in $\mathcal{F}$ provides a spectrum opportunity for an MS. Probabilities $\Pr(F_i)$ may also be used by networked BSs or MSs as feature vectors for frequency usage pattern recognition algorithms.
  - Change-point detection is an area of statistical inference and signal processing that links together control theory, estimation theory and hypothesis testing. Simply stated a change-point in an observed random signal is defined as the moment in time when some probabilistic characteristics of the signal change. Probabilistic changes in a random signal can be additive or multiplicative. Additive changes imply changes in the mean of a random signal. Multiplicative changes result when a random signal is transformed by a linear or nonlinear map resulting in spectral, variance or correlation changes in the signal. The change-point detection problem is to detect a change-point in a signal via a statistical hypothesis test, estimate an unknown parameter or parameters

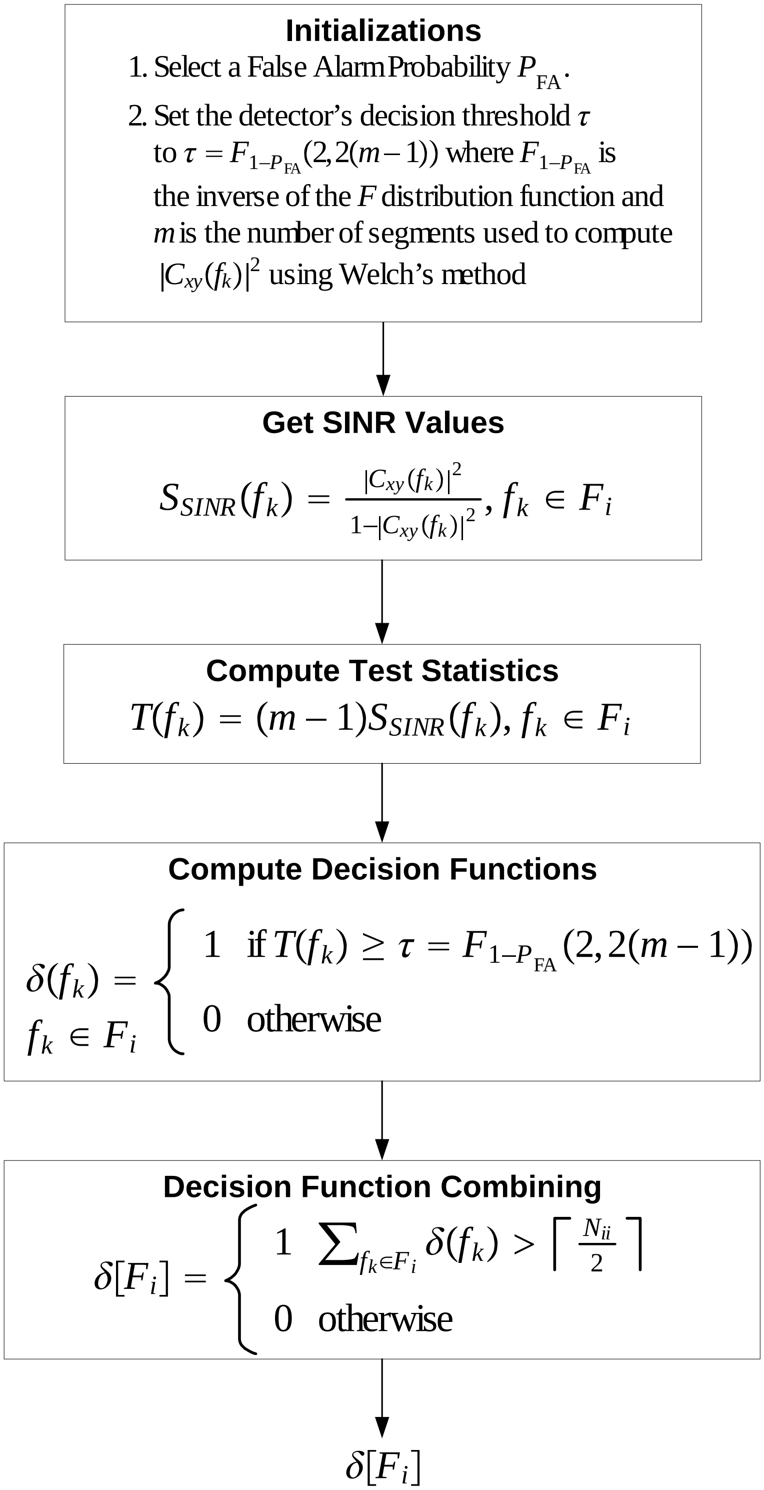

Figure 4: Example steps for spectrum opportunity detection.

of interest that the change-point depends on and to invoke a control or action based on the change-point detected and the parameter estimation. Change-point detection algorithms can be designed based on values provided by a Spectrum Profiler.

5 Self-Organizing Frequency Partitioning by Base Stations

- The basic concept of frequency partitioning is to map each MS to one of r frequency partitions within $\mathcal{F} = \{F_1, F_2, ..., F_r\}$.
- During a spectrum profiling interval (e.g. P-SCH or preamble, midamble) each MS obtains spectrum profiling data for one or more frequency partitions F_i in $\mathcal{F} = \{F_1, F_2, ..., F_r\}$.
- The MSs transmit their spectrum profile data to their serving BS in an uplink spectrum profile message. An example of a spectrum profile message derived from spectrum profiling data is as follows:

Message Fields

MS_ID	$\delta[F_i]$, $F_i \in \mathcal{F}$	$P_{SINR}[F_i]$, $F_i \in \mathcal{F}$	$P_S[F_i]$, $F_i \in \mathcal{F}$	$P_{IPN}[F_i]$, $F_i \in \mathcal{F}$
8 bits	r bits	$r \cdot 8$ bits	$r \cdot 8$ bits	$r \cdot 8$ bits

Example Format of Spectrum Profiling Message

- Given a spectrum profile message the serving BS invokes a frequency partitioning algorithm such as a clustering algorithm.
- Figure 1 shows a cell cluster comprised of seven hexagonal cells C_i, $i = 1, 2, \ldots, 7$.
- Frequency partitions in the cell cluster are denoted by F_i, $i = 1, 2, 3, 4$. Frequency partitions F_i, $i = 1, 2, 3, 4$ may be simultaneously used by MSs in each cell.
- Frequency partition F_1 is comprised of all available OFDMA subchannels. MSs near the cell center should operate in F_1.
- Frequency partitions F_i, $i = 2, 3, 4$, are orthogonal and use a fraction or subset of the available OFDMA subchannels. MSs at a cell edge operate in these frequency partitions.
- Clustering is a form of unsupervised learning that for the present application concerns the mapping of MSs to frequency partitions (clusters). A clustering algorithm may be used by a BS to map its MSs to frequency partitions F_i, $i = 1, 2, 3, 4$.
- A metric is required to quantify the correlation or similarity between received spectrum opportunity decisions and candidate frequency partitions F_i. There are many metrics that may be implemented. The outputs $\delta[F_i]$ (F_i, $i = 1, 2, 3, 4$) of the Spectrum Opportunity Detector may be used. These values may be also be combined with or weighted by Spectrum Profiler estimates such as $P_{SINR}[F_i]$, $P_S[F_i]$, and $P_{IPN}[F_i]$.
- There are a variety of clustering algorithms that may be implemented for frequency partitioning. The following is a simple example used only to describe an approach.

Cell C_i Frequency Partitioning for Self-Organizing FFR

```
1. Initializations:
    (a) Let $F_1$ denote the cell-center frequency partition and $F_i$, $i = 2, ..., r$, the cell-edge frequency partitions. Define the frequency partition set $\mathcal{F} = \{F_1, F_2, ..., F_r\}$.
2. Get an MS's spectrum profiling message that contains its spectrum opportunity decisions $\delta[F_i]$ for all subcarrier frequencies in the frequency partition set $\mathcal{F} = \{F_1, F_2, ..., F_r\}$.
3. if $\delta[F_1] == 1$
        Map the current MS to the cell-center partition $F_1$.
   else
        Compute $I = \min_i \{\delta[F_i] \cdot P_{IPN}[F_i]\}_{i=2}^{r}$
        Map the current MS to the cell-edge partition $F_I$.
   end
4. Return to Step 2
```

- Some notes concerning the example:
    1. For each iteration of the algorithm an MS is assigned to the cell-center partition frequency partition F_1 or the frequency partition F_i, $i = 2, ..., r$, that minimizes its interference.
    2. If the cell-center frequency partition F_1 can support a spectrum opportunity a MS is first mapped to this partition.
    3. Cell-edge MSs are mapped to frequency partitions F_i, $i = 2, ..., r$. Neighboring base stations that operate in the same manner will avoid mapping their cell-edge MSs to these frequency partitions. This is turn will improve the cell-edge frequency partitions.

6 References

1. Shkumbin Hamiti, "The Draft IEEE 802.16m System Description Document", IEEE 802.16m-008/003r5

2. Priestley, M.J., *Spectral Analysis and Time Series*, Academic Press, San Diego, 1996.

3. P. J. Brockwell and R. A. Davis, *Time Series: Theory and Methods*, 2ed., New York: Springer-Verlag, 1991.

4. Bendat, J. S., and A. G. Piersol, 1993, *Engineering Applications of Correlation and Spectral Analysis*, 2nd ed., John Wiley & Sons.

5. A. Papoulis, *Probability, Random Variables, and Stochastic Processes*, McGraw-Hill, NY, 1984.

6. Technical Report from Wireless World Initiative New Radio (WINNER), "Spectrum Aspects: Methods for efficient sharing, flexible spectrum use and coexistence," Oct 2004.

7. Stolyar, A.L. "Viswanathan, H., Self-Organizing Dynamic Fractional Frequency Reuse in OFDMA Systems," INFOCOM 2008. The 27th Conference on Computer Communications. 13-18 April 2008, page(s): 691-699.