Dynamic Spectrum Allocation in Low-Bandwidth Power Line Communications

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***Abstract*—The application of frequency-agile communications techniques, or Dynamic Spectrum Allocation (DSA), have proven to be effective for adaptive communication in many scenarios. In particular, DSA finds primary application in wireless systems, such as cognitive or software-defined radio. In this work, we implement a form of DSA which uses weighted statistical analysis of channel parameters and a heuristic decision process. This algorithm selects and prioritizes the most favorable subcarriers for multicarrier, frequency-division transmission while avoiding arbitrary spectral obstructions in occupied channels. We validate this technique in the context of "Smart Grid" communication, which provides a very useful means of exercising the capability of the algorithm.**

***Keywords*-Dynamic spectrum allocation, DSA, cognitive radio, power line communcations, Smart Grid, Frequency Division Multiplexing, FDM**

I. INTRODUCTION

This paper presents an algorithm designed to analyze a transmission channel and prioritize appropriate subcarriers for use in subsequent transmissions. The algorithm forms a subset of the processing required to achieve "Dynamic Spectrum Allocation" (DSA) in a communication system. The collection of DSA techniques ranges from simple, efficient, and non-robust energy measurements [1]–[4] to sophisticated, resource-intensive, and robust pattern matching algorithms [5]–[7]. In most cases, DSA algorithms are used in wireless communications systems where spectrum is overused, or has been allocated by regulatory means [8].

In this work, we use a combination of subband energy measurements, statistical characterizations, and heuristic decision making to produce a robust channel selection algorithm which can be used for DSA in cognitive radio or other transmission schemes where bandwidth is scarce, such as power line communications (PLC). The algorithm selects and prioritizes the subcarriers while avoiding spectral obstructions in occupied channels. Since the approach uses particular statistical metrics to sort and rank channel parameters, we use the description "Mean-based Spectral Moment Algorithm", or MSMA. The MSMA algorithm is intended to be a component of a larger, more complicated multicarrier communication system. As a result, discussion of specific modulation schemes, access control algorithms, protocol structures, or other higher-layer topics is beyond the scope of this paper. However, we refer to basic modulation techniques during the evaluation of the algorithm.

A particularly interesting use of MSMA may include application in a "Smart Grid" communication system, comprising a low-bandwidth management network for metering, utility monitoring and pay-per-use electrical power [9]. To clearly distinguish this application, we present MSMA in the context of low-bandwidth, low-frequency communication on a power line channel.

The remaining sections of this paper discuss various aspects of adaptive channel allocation, the MSMA algorithm, and the power line as a communications channel. Section II discusses challenges and features of the power line channel which can be leveraged by MSMA. Section III describes the MSMA algorithm, and Section IV presents simulation results for the MSMA algorithm in a power line channel. Finally, Section V discusses conclusions and proposes future work on the MSMA algorithm.

II. CHALLENGES OF POWER LINE COMMUNICATIONS

The concept of communicating over existing power infrastructure is not new. Several well-known systems and technologies allow local, home based communication between devices and so on [10]. There is a clear distinction, however, between these existing systems and the application of the MSMA algorithm in a PLC scenario. The main objective of the MSMA algorithm is to facilitate one-way, upstream communication between end hardware (meters, charging stations), grid hardware (transformers, troubleshooting equipment) and the serving substation. In this scenario, attenuation and noise constraints in the channel are important concerns, but effective navigation around established power quality regulations are perhaps more significant. Power quality requirements can be found in national and international standards [11], [12] which impose limits on parameters related to voltage/current fluctuations, harmonic distortion, transients, and noise. Most of these limits focus on measurements at the "point of common coupling," or the intersection between utility and consumer terminals [13]. In addition to these regulatory limitations, the natural characteristics of the power line channel offer a very interesting and difficult challenge.

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This application focuses on transmitting data “upstream” in the distribution grid, from end-user applications to the substation, without relays or amplifiers or transformer bypasses. The network properties of the distribution grid severely limit the frequency range that may be used. The main factor contributing to the frequency limitation seems to be related to the frequency response or admittance of the transformers used in power distribution. A simple model of this admittance characteristic shows a sharp notch passband around the fundamental (50-60Hz) and a “high admittance lobe” from approximately 200 Hz to 2 kHz [14]. This high-admittance lobe varies depending on the quantity, type, and even the brand of the transformers present in the distribution grid, and the band-edges of the lobe are time variant. Thus, for a communication signal to effectively transit the distribution grid and not interfere directly with the fundamental, it must be within this high-admittance lobe. This limitation reduces the methods of modulation and the effective bandwidth of low-frequency PLC.

Power line systems also experience varying attenuations and phase distortions for signals within them. Upon investigating the conditions of the power line it can be seen that it has constantly changing topology and, in fact, is a time variant system. This makes it exceedingly difficult to deal with the many changes that can occur in order to locate a suitable frequency band for communication. Further increasing the complexity of the problem is the fact that there are a large number of connected devices which cause interference, and which present time-varying loads. This complex channel topology creates a unique challenge and a good proving ground for frequency-agile communication schemes.

III. The MSMA Algorithm

The goal of any adaptive communication algorithm is to analyze channel conditions and send data as efficiently as possible while minimizing error. Depending on conditions in the channel, techniques to maximize transmission quality vary widely, but most methods attempt to exploit consistent, unique characteristics of the channel to maximize desirable output. In the case of the power line, the presence of a large amount of energy at the fundamental frequency (60Hz in the U.S., for example) is well-known. The remaining frequency space of the channel is cluttered by reduced-amplitude harmonics of the fundamental (typically odd), as well as a significant amount of transient noise. This noise can be temporal or pseudo-stationary as well as broadband and relatively uncorrelated [15].

The concepts behind policy based cognitive radio systems can be leveraged for adaptive powerline communication [16]. Constant monitoring of the channel and continuous adaptation to avoid interference with the primary channel user is very important, as powerline conditions are extremely dynamic. Additionally, routing aware channel selection algorithms, such as those proposed for IEEE 802.11s mesh networks [17] can be leveraged effectively for powerline communications. As in cognitive radio, such active selection algorithms constantly scan and monitor channel conditions, but the mesh algorithm uses uplink and downlink airtime cost as a key decision making factor.

Similar to cognitive radio systems or mesh network routing algorithms, the MSMA algorithm is a technique for analyzing a given frequency spectrum, discovering a number of potential transmit channels, using calculated statistics to rank these potential transmit channels, and producing a vector of suggested transmission carrier frequencies to be used by the transmission subsystem(s).

To achieve this outcome, the MSMA algorithm attempts to exploit the regulated nature of power-line harmonic peaks, transmitting inside the low interference areas of the powerline spectrum. The MSMA algorithm also places high values on potential transmit bands inside the “high admittance lobe” of the distribution grid, ranking potential channels with a weighted combination of mean, variance, and fit within transformer admittance limits. After calculating appropriate ranking values for subcarriers, potential channels can be sorted, and carrier frequencies and amplitude values selected to transmit in the “best” areas of the channel. Figure 1 shows a high-level flow diagram of the processing implemented by the MSMA algorithm.

There are several important conditions that must be met for this application of the MSMA algorithm. The most important condition is that transmission must not interfere with any powerline harmonics. The location of these harmonic frequencies is loosely defined by Eqn. 1 for positive integer values of n.

$$F_h(n) = (60\text{Hz})(2n-1) \tag{1}$$

Using the values from a Fast Fourier Transform (FFT) of the channel activity, statistically favorable areas in the spectrum are found. To accomplish this, the fact that powerline harmonics are generally well regulated and stand far above the noise levels in the channel is utilized. The index values of these spikes are used as markers, and statistical data is computed related to the areas between harmonics. This data, weighted using application specific weighting factors, allows for quantification of the transmit channel decision making process, and channel ranking based on mean and variance. To avoid false positives, it is imperative to remove values near the peak. Once the index values of the spikes are found, it is relatively simple to calculate mean and variance of the “nulls” between spike indices.

IV. Implementation and Testing

The MSMA algorithm utilizes several statistics taken from spectral analysis of an input waveform. Specifically, the

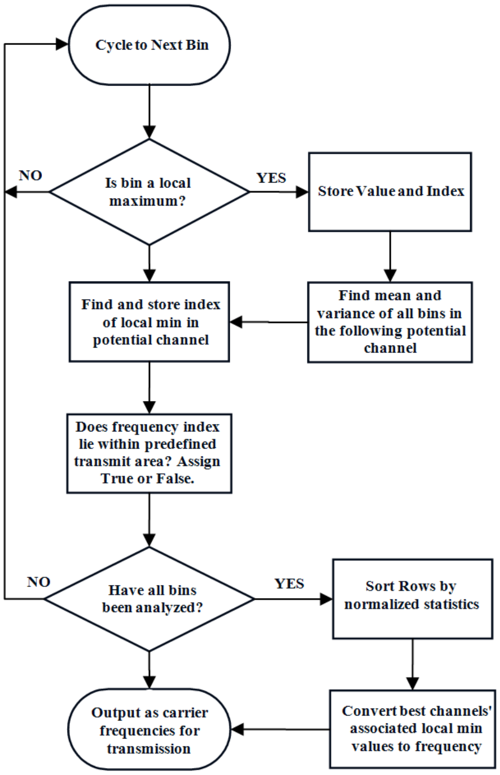

Figure 1. MSMA decision-making process.

mean and variance about mean of particular sections of the input waveform are utilized to create a detailed ranking of potential transmit channels. To calculate these statistics, an FFT of 2048 points is used to transform a time domain input, sampled at 8 kHz, into a frequency domain representation. In accordance with Eqn. 2, this means that each FFT bin represents 3.9063 Hz.

$$\frac{\text{Hz}}{\text{bin}} = \frac{\text{sampling frequency}}{\text{FFT length}} \tag{2}$$

Stepping through the input spectrum, maximum values and their corresponding indices are stored in an array. The number of maxima stored depends on user specifications. For this implementation, the 15 largest maxima were more than sufficient. Once a harmonic maximum is found, the usual sample mean (3), sample variance (4), minimum valued bin index, and allowable bitmask is stored in the array, alongside the peak bin index and maximum bin value. In this case, the allowable bitmask is a binary value indicating whether the candidate subcarrier lies inside the channel's admittance profile.

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x(i) \tag{3}$$

$$s_n^2 = \frac{1}{N-1}\sum_{i=1}^{N} (\bar{x} - x(i))^2 \tag{4}$$

Finding these maxima is not a trivial task. To find accurate maxima for this particular implementation of the MSMA algorithm, a bitmask is shifted to center about the index of the spectrum's current maximum bin. This bitmask is then multiplied by the input spectrum to annihilate the local maximum and neighboring elevated values. This action is repeated as many times as necessary to find the remove the requisite number of peaks and associated potential transmit channels. When sufficient maxima are found and associated statistics calculated, a weighted "ranking index" is computed which combines $\bar{x}$, s_n^2, and admissibility parameters, as shown in Eqn. 5.

$$R_i = k_m \frac{\bar{x}}{\text{AVG}(\bar{x})} + k_v \frac{s_n^2}{\text{AVG}(s_n^2)} \tag{5}$$

The set of "ranking indices" is used to prioritize subcarriers using a two-stage, masked sorting process. First, the admissible subcarriers are ranked above non-admissible subcarriers. Then these two groups are sorted in ascending order based on ranking index.

A variable width bit mask is used to center on the index of the maximum frequency. The input spectrum is then multiplied by the bit mask, eliminating the found maximum and surrounding high values. A new maximum value is then found and the elimination process repeated. This "find maximum, then annihilate" process is repeated until the requisite number of peaks is found. Once these peak indices is established, it is assumed that these values correspond with the regulated odd-harmonic peaks of the supplied power. The minimum valued bin index within the potential transmit channel is then located and stored in an array. This potential transmission frequency remains linked to the corresponding channel during the ranking process. By calculating the mean and variance of the following spectrum, the transmission potential of these transmit channels is quantified and used to rank the channels from best to worst.

This method is classified as O(n), where n corresponds to the spectrum array length to be analyzed. Once the number of potential transmit channels is specified, the speed of the algorithm itself will only vary based on input length. The only thing that may affect this categorization is the construction of the `max()` operation, which may scale differently depending on input array length. It is assumed here that the `max()` operation is O(n), and is the primary limiting factor in algorithm decision speed.

Obviously, this technique would need adjustment in order to accommodate multiple users, but the mean and variance based ranking concepts behind transmit channel choice should remain valid.

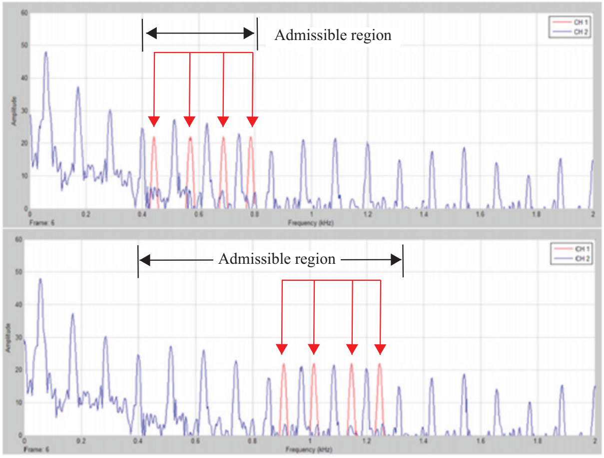

Figure 2. Frequency domain representations of MSMA transmitter output with admittance windows of 400 Hz to 800 Hz and 400 Hz to 1400 Hz, respectively. The admittance window restricts admissible subcarrier frequencies.

All of the following graphical samples were taken by applying a Hanning window to the input, followed by a 2048 length FFT. The channel denoted by CH1 in red in the graphic legend of each figure, represents the result of feeding the MSMA algorithm output into a low-rate BPSK transmitter. The channel denoted as CH2 in blue, shows the spectral content of the input data.

A. *Transmit Channel Ranking*

Figure 2 shows transmit peaks shifting upward in frequency, to the spectral regions with lower average power and activity. This is a natural tendency of the algorithm, as the transformer filtering reduces both noise and harmonic presence. For these same reasons, correct adjustment of the high-admittance window is vital in order to avoid losses in transmitted signals. The effect of the admittance window is evident in Figure 2 where subcarrier frequencies are restricted to particular spectral regions.

B. *Transmit Channel Noise Avoidance*

Figure 3 shows the micro-adjustment of transmit frequency, based on centering the transmission frequency at the minimum valued bin index. The top graph has no delay, while the middle graph has a 1 buffer sample delay (1600 input samples), and the bottom graph has a 2 buffer sample delay (3200 input samples). In the figure, vertical dotted lines denote the original positioning of subcarriers (top plot), and arrows indicate micro-adjusted subcarriers (subsequent plots). Micro adjustment of the carrier frequency is used to center transmission over low power areas of the transmit channel. By using the minimum valued index from the chosen channel, interference is minimized, producing a superior bit error rate.

C. *Reaction to Changes in Channel Conditions*

Figure 4 shows a clear example of channel adaptation based on changing input conditions. All channels are shifted downwards in response to increased noise in the upper region of the spectrum.

V. CONCLUSIONS AND FUTURE WORK

Future enhancement of the MSMA algorithm may include using different approaches to scan the incoming FFT data or may include alternative approaches to spectral estimation. For example a sliding discrete Fourier transform (DFT) or a sliding Goertzel algorithm [18] could work through the input spectrum in small blocks, find areas with the lowest power, and send data out to transmit at these points. The Goertzel algorithm is mentioned here because of its use in telecommunications networks for Dual Tone Multiple Frequency (DTMF) tone detection which could be extended for detecting signaling tones that would act as control indicators in PLC.

Additionally, advanced statistics such as curve fitting, elimination of outliers, and specialized metrics could be used to find a more exact center for transmission as well as more effective analysis of channel superiority.

Overall, the MSMA algorithm has potential application in "Smart Grid" communication systems to enable direct adaptation of channels or subcarriers. The key concept for this algorithm is dynamic adaptation. As in cognitive radio and mesh networking systems, the MSMA algorithm is adaptable, able to quickly and effectively make decisions about the location of optimal transmission regions in a given spectrum, as long as the spectral characteristics of the channel are well defined. This could be valuable for audio processing, statistical data-mining, and transmissions in other channels with well defined spectral tendencies.

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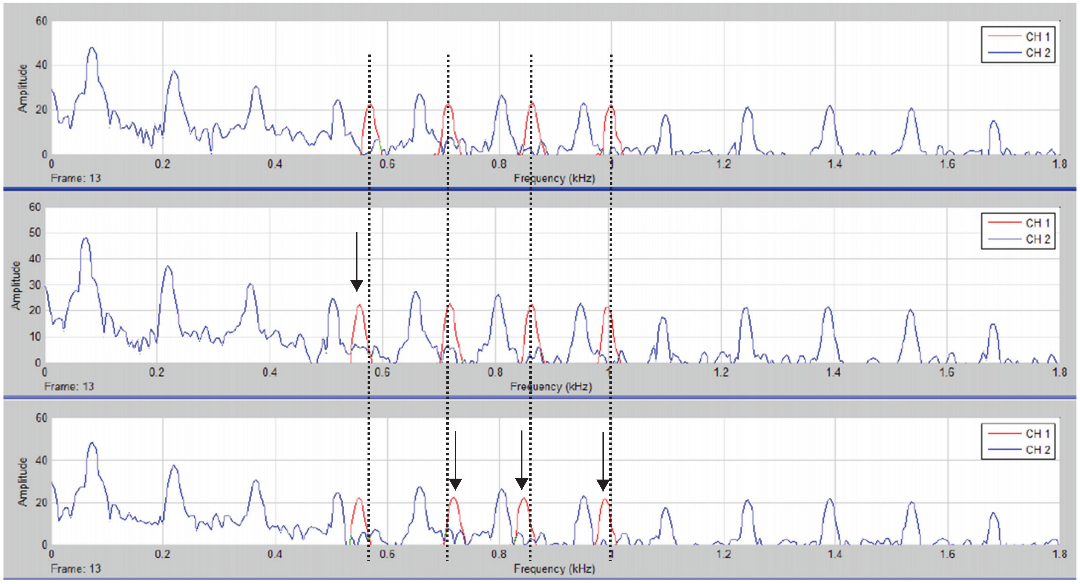

Figure 3. Micro-adjustment of transmit peaks to maximize SNR. The top plot shows initial positioning of subcarriers. Subsequent plots show subcarrier micro-adjustment relative to the initial positioning (vertical dotted lines).

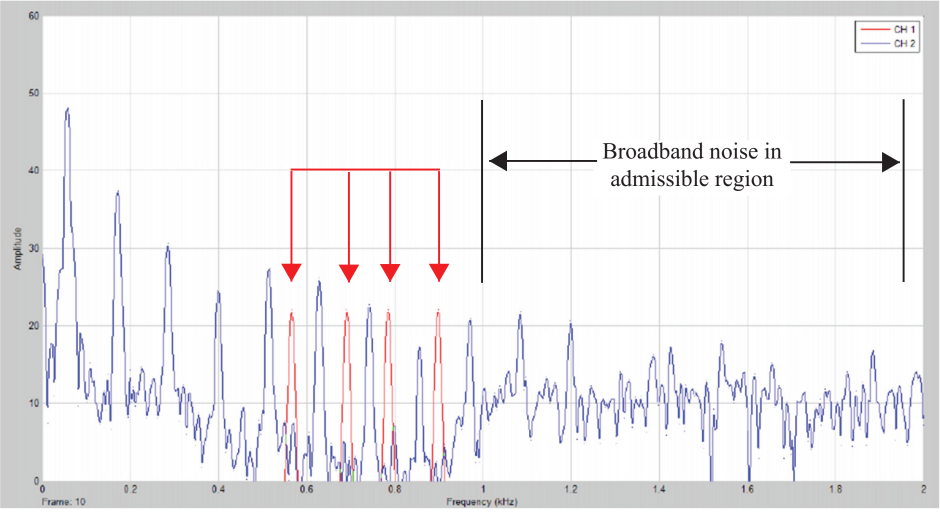

Figure 4. Example of transmit channels adapting in response to wideband noise interference above 1 kHz.

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