

Soft Decision Design of Spectrally Partitioned CI-SMSE Waveforms for Coexistent Applications

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Abstract—Applicability of Spectrally Modulated, Spectrally Encoded (SMSE) waveform design has been expanded for future Cognitive Radio (CR)-based Software Defined Radio (SDR) applications. As previously demonstrated, the SMSE waveform design process can exploit statistical knowledge of PU spectral and temporal behavior to maximize SMSE system throughput (bits/second) while adhering to SMSE and Primary User (PU) spectral constraints. The capacity of SMSE systems is extended here using spectral partitioning with carrier-interferometry (CI) coding to increase SMSE waveform agility in the presence of a spectrally diverse transmission channel. By adaptively varying the modulation order and optimally allocating power within each spectral partition, inherent SMSE flexibility is more fully exploited and substantially increases system throughput while meeting Power Spectral Density (PSD) constraints. A coexistent scenario is provided in which the analytic optimization of the SMSE waveform is demonstrated while meeting spectral mask requirements. Results show that spectrally partitioned CI-SMSE waveforms have a significantly greater ability to adapt to varying spectral requirements.

I. INTRODUCTION

Both Cognitive Radio (CR) and Software Defined Radio (SDR) technologies are widely recognized as having considerable potential to increase efficient spectrum usage in next generation communication systems [1], [2]. A broad range of design approaches exist for achieving spectral efficiency, ranging from simple spectral notching/avoidance [3] to more complex methods such as spectral water-filling [4], [5]. However, these conventional methods generally provide limited performance improvement or impose unrealistic design constraints. More practical techniques are designed around Orthogonal Frequency Division Multiplexing (OFDM) fundamentals and employ traditional modulation schemes on either an *inter-symbol* (symbol-to-symbol [6]) or *intra-symbol* (within a symbol [7]–[13]) basis.

Spectrally Modulated, Spectrally Encoded (SMSE) waveforms have been exploited to design spectrally and temporally adaptive OFDM-based waveforms via intra-symbol variation of subcarrier power and modulation order [14]–[18]. Using a coexistent environment containing multiple PU signals, SMSE system throughput (bits/second) was maximized while enforcing bit error rate (BER) constraints on both the SMSE and in-band PU systems. Results demonstrated that by exploiting knowledge of PU signal structure and transmission statistics, the SMSE waveform can be intelligently designed to maximize system throughput while limiting coexistent interference to desired levels.

However, it is frequently the case that CR systems must comply with constraints based on the Power Spectral Density (PSD) of their transmitted waveform rather than explicit PU BER limits. This may arise when the CR is unable to obtain knowledge of certain aspects of the PU signal structure (e.g., modulation type and order) or when requirements are set by regulatory agencies (see for example [19]). Depending on the spectral band of interest, the CR PSD can be required to adhere to a spectral mask requirement (maximum PSD constraint).

In this case, traditional OFDM-based systems may not be able to achieve suitable performance, given that desired performance would require non-compliant maximum PSD levels. However, by employing a MC-CDMA based system [20], the waveform design process is able to more effectively exploit available spectral regions to increase system performance. By intelligently designing the spreading code of interest, the SMSE PSD can be explicitly designed in a more flexible manner. While not directly intended for explicit PSD design, the work in [21] has demonstrated the ability to optimize subcarrier power allocation in MC-CDMA systems to improve performance. While only designed for BPSK modulated MC-CDMA, the process lends itself to SMSE waveform design using adaptive power and modulation order assignment on an inter-symbol basis.

Demonstration of SMSE adaptability is continued here using a maximum PSD constraint applied to the SMSE waveform design process. It is shown that by partitioning the subcarriers into groups, the SMSE can efficiently design a spectrally agile signal to maximize its throughput (bits/sec) while adhering to given PSD constraints. Furthermore, through independent selection of subcarrier power, the SMSE waveform is able to fully exploit desired spectral regions. As the size of the spectral partition increases, the performance of the SMSE system is shown to improve dramatically while continuing to meet PSD constraints. Additionally, by independently selecting the modulation order employed in each spectral partition, SMSE system performance increases further.

II. SMSE WAVEFORM DESIGN

A. SMSE Analytic Framework

The general SMSE framework specifies the transmitted waveform design for the k^{th} SMSE symbol using a specific collection of waveform design parameters, including: *coding*, $\mathbf{c} = [c_1, c_2, \dots, c_{N_f}]$, $c_m \in \mathbb{C}$, *data modulation*, $\mathbf{d} = [d_1, d_2, \dots, d_{N_f}]$, $d_m \in \mathbb{C}$, *windowing*,

$\mathbf{w} = [w_1, w_2, \dots, w_{N_f}]$, $w_m \in \mathbb{C}$, and a phase-only *orthogonality* term, $\mathbf{o} = [o_1, o_2, \dots, o_{N_f}]$, $o_m \in \mathbb{C}$, $|o_m| = 1 \forall m$ [22], [23]. Collectively, these terms functionally incorporate various waveform design features that are commonly employed in communications. The intra-symbol frequency components used to generate each SMSE symbol are controlled by the *assignment*, $\mathbf{a} = [a_1, a_2, \dots, a_{N_f}]$, $a_m \in \{0, 1\}$, and *use*, $\mathbf{u} = [u_1, u_2, \dots, u_{N_f}]$, $u_m \in \{0, 1\}$ parameters, where zeros indicate there is no transmission at that particular frequency. The spectral representation of the k^{th} SMSE symbol is given by [17], [22], [23]

$$\mathbf{s}_k = \mathbf{a}_k \odot \mathbf{u}_k \odot \mathbf{c} \odot \mathbf{d}_k \odot \mathbf{w} \odot \mathbf{o}_k. \quad (1)$$

The original SMSE framework in (1) has been extended to enable soft decision SMSE (SD-SMSE) waveform design [17], [24]–[26]. In SD-SMSE, the original hard-decision restriction on SMSE *assignment* (\mathbf{a}) and *use* (\mathbf{u}) parameters (on or off) is relaxed and a range of continuous non-negative real values are applied. For the form of SD-SMSE considered here, elements of the *assignment* sequence $\{\mathbf{a}\}$ and *use* sequence $\{\mathbf{u}\}$ include values of $a_m \in [0, 1]$ and $u_m \in [0, 1]$. In the context of the more general SD-SMSE framework, the desired soft decision effects include: 1) the *assignment* parameter indicating the total amount of power that the SD-SMSE system is allowed to allocate in specific spectral regions, with $a_m = 1$ indicating maximum possible (normalized) transmission power; and 2) the *use* parameter indicating the fraction of total available transmission power that is actually used across all possible spectral regions. Accounting for these two effects, the total (normalized) power transmitted on the m^{th} subcarrier is $P_m = (a_m u_m)^2 \times |c_m w_m|^2$.

B. Spectrally-Partitioned CI-SMSE

While the framework in (1) offers a unified means for describing OFDM-based waveforms using a compact parameter set, the selection of various parameters must be done intelligently. In general, the exploitation of SMSE waveform design flexibility may introduce a computationally infeasible search space. To simplify the waveform design process while still leveraging the design flexibility of the SMSE framework, a spectrally partitioned process is proposed.

For spectrally-partitioned CI-SMSE, the framework in (1) is modified to enable N_v data symbols (d_k^v) to be modulated onto the k^{th} SMSE symbol according to

$$\mathbf{s}_k[m] = \sum_{v=0}^{N_v-1} d_k^v a_m^v u_m^v c_m^v w_m e^{j\Theta_{m,k}^v}, \quad (2)$$

$$\Theta_{m,k}^v = \theta_{c_m^v} + \theta_{d_k^v} + \theta_{w_m} + \theta_{o_m^v},$$

where $m = 0, 1, \dots, N_f - 1$ is the subcarrier index number, N_f is the total subcarriers, and a_m^v , u_m^v , c_m^v , $\theta_{c_m^v}$, d_k^v , $\theta_{d_k^v}$, w_m , θ_{w_m} and $\theta_{o_m^v}$ are corresponding magnitudes and phases of the design parameters. The framework in (2) is well-suited for optimization given that independent selection of intra-symbol subcarrier power and modulation type/order is enabled through

the u_m^v and d_k^v design parameters, respectively.

Spectrally partitioned SMSE is based on dividing the total available spectrum ($a_m \neq 0$) into N_p partitions (unique collection of contiguous subcarriers), each of which contains N_{SC} subcarriers that are modulated by the $N_v \leq N_{SC}$ data symbols (d^v) ($N_p N_{SC} = N_f$).

While maximum *inter-partition* (across partition) and *intra-partition* (within partition) design flexibility exists, the initial proof-of-concept results presented here are only based on inter-partition design subject to: 1) independent parameter design within each partition, 2) power allocation within a partition is accounted for in the frequency *use* parameter, and 3) an identical modulation scheme is used for each *data* symbol (d^v) within a given partition. These last two conditions can be expressed as

$$u_m^v \equiv u_m, \quad \forall m \in \mathcal{P}_i \quad (3)$$

$$\text{Modulation Order } \{d_k^v\} \equiv M_i, \quad \forall v \in \mathcal{P}_i \quad (4)$$

where there are N_{SC} total available subcarriers within each partition and N_v^i data symbols are placed within partition \mathcal{P}_i , with $0 \leq N_v^i \leq N_{SC}$.

Hence, while all N_v^i data symbols (d^v) within partition \mathcal{P}_i will employ the same power distribution and modulation scheme, the SMSE system will still have the ability to explicitly design its spectrum by selecting u_m independently for all N_f frequency components. Power allocation is implemented based on the process developed in [21], which has been extended here to consider adaptive modulation selection and spectral mask constraints.

Additionally, the *orthogonality* (\mathbf{o}) terms employed within each partition are selected from the set of Carrier Interferometry (CI) codes adapted from [27]–[29]:

$$\theta_{o_m^v} = \frac{2\pi m v}{N_v^i}, \quad v \in \mathcal{P}_i.$$

Thus, the resultant waveform is considered a Soft Decision designed Spectrally Partitioned CI-SMSE Waveform.

C. Waveform Design Process

SMSE system performance is maximized subject to imposed design constraints, including:

- 1) Fixed total average SMSE power (summed across all subcarriers).
- 2) Fixed maximum SMSE PSD mask (spectrally varying).
- 3) Fixed maximum SMSE BER limit (constant across all data symbols (d_k^v)).

For initial proof-of-concept demonstration, the design is further constrained to operate with a predetermined set of N_f contiguous *assigned* frequencies, with *coding* (\mathbf{c}) and *windowing* (\mathbf{w}) terms in (1) set to unity. Thus, the final design process involves optimal selection of *data modulation* (\mathbf{d}) and frequency *use* (\mathbf{u}) parameters. Specifically, within the overall goal of maximizing its average data rate (bits/sec), the

SMSE system first selects which subcarrier partitions will be used and which will go unused. For each selected partition, the SMSE system then determines 1) the number (N_v^i) of data symbols (d_k^v), 2) the data modulation scheme, and 3) the allocated power in each subcarrier (u_m^v).

Thus, the spectral design constraints for the k^{th} SMSE symbol are expressed as:

$$Max_{M_i} \left\{ \mathbf{E} \left[\sum_{i=0}^{N_P-1} N_v^i \log_2(M_i) \right] \right\}, \quad (5)$$

such that

$$\sum_{i=0}^{N_P-1} N_v^i \sum_{m \in \mathcal{P}_i} (a_m u_m)^2 \leq \Lambda_P, \quad (6)$$

$$N_v^i (a_m u_m)^2 \leq \Lambda_{PSD}^m, \quad m \in \mathcal{P}_i, \quad (7)$$

$$\begin{aligned} BER_v^i &= BER_{Desired} \\ \forall v &\in [0, \dots, N_v^i - 1] \\ \forall i &\in [0, \dots, N_P - 1], \end{aligned} \quad (8)$$

where M_i is the modulation order in partition \mathcal{P}_i , Λ_P is the total average SMSE symbol power, Λ_{PSD}^m is the PSD mask limit at the m^{th} subcarrier location, BER_v^i is the resultant BER of the v^{th} data symbol in partition \mathcal{P}_i , and $\mathbf{E}[\bullet]$ denotes the expectation operator.

III. SIMULATION RESULTS

Design performance of spectrally partitioned CI-SMSE waveforms is demonstrated using a maximum of $N_f = 128$ possible subcarriers using a subcarrier spacing of 312.5 KHz. The resultant maximum SMSE bandwidth is 40 MHz centered at 5.0 GHz. The SMSE signal uses a 32 length cyclic prefix and propagates through multipath Rayleigh faded channel with an exponential power delay profile having rms and maximum delay spreads of 0.1 μ s and 0.8 μ s, respectively. The AWGN channel is modeled as having a noise power spectral density of $N_0 \approx 1.36 \times 10^{-5}$ Watts/Hz. For design purposes, the SMSE system is constrained to a maximum channel BER of $P_B = 10^{-2}$.

Results are presented for a varying number of subcarrier partitions N_P under both non-adaptive and adaptive modulation conditions. A contrived spectral mask constraint is used that does not vary with time. While the mask constraint was arbitrarily chosen to demonstrate design flexibility, its actual characteristics are consistent with what can actually be imposed in practice (see for example [19]).

Confidence interval analysis is used when making comparative qualitative assessment and indicating better, poorer or consistent (identical) performance. Confidence intervals provide one means for declaring statistically significant differences and/or similarities when comparing alternatives, e.g., performance observed by employing various subcarrier partition sizes. All comparative conclusions drawn in this section are

based on a 95% confidence interval given by [30]

$$\varepsilon \approx \pm 1.96 \sqrt{\frac{\sigma^2}{N_T}}, \quad (9)$$

where σ^2 (the sample variance of the value being assessed) is calculated over $N_T \approx 300$ independent channel realizations. Note that confidence intervals have been intentionally omitted from some plots given that 1) they are very small for some data points and tend to obscure/blur marker discrimination (visual clarity) and 2) the focus here is on general revelation and demonstration versus precise assessment for a particular set of conditions and/or parameters (reliable trend analysis is sufficient). All comparative conclusions drawn in this section are based on a 95% confidence interval given by (9).

A. Design Demonstration: Non-Adaptive Modulation

The time-frequency PSD responses of the spectral mask constraint Λ_{PSD}^m and the adapted SMSE signals are shown in Fig. 1. In this case the SMSE system: 1) employs 4-QAM for all data symbols, 2) operates in a multipath fading environment, and 3) adapts its waveform in response to the current subchannel response while limiting its transmitted PSD to be less than or equal to the spectral mask constraint Λ_{PSD}^m . Performance with no spectral partitioning ($N_P = N_f = 128$, $N_{SC} = 1$) is shown in Fig. 1b. These results are consistent with what is expected for traditional OFDM and similar performance has been demonstrated previously [14]–[18]. Results for $N_P = 16$ with $N_{SC} = 8$ subcarriers per partition are shown in Fig. 1c. Visual comparison of the responses in Fig. 1b and Fig. 1c qualitatively show how spectral partitioning has enabled the SMSE system to better approximate the spectral mask constraint.

The benefit of spectral partitioning is further illustrated in the two dimensional cross-time average results in Fig. 2. These results clearly show that partitioned SMSE performance is more efficient, i.e., the partitioned response better approximates the spectral mask and has a higher resultant total transmit power (proportional to area under the PSDs). Given the fixed BER constraint, the higher resultant transmit power for a given modulation translates into higher throughput. This improved efficiency is directly attributable to spectral partitioning given that both systems were designed under identical constraints (maximum average SMSE transmit power and a maximum spectral mask limit).

B. Design Demonstration: Adaptive Modulation

Adaptive modulation analysis was conducted using results from both non-partitioned (traditional OFDM) and partitioned SMSE systems. The modulation order was independently selected for each partition from the set of 1) only 4-QAM, 2) 4-QAM and 16-QAM, and 3) 4-QAM, 16-QAM, and 64-QAM. The results are presented using two dimensional cross-time average PSD responses and are based on more than $N_T \approx 300$ independent channel realizations.

Results in Fig. 3 are for the case where the SMSE employs traditional OFDM without spectral partitioning ($N_P =$

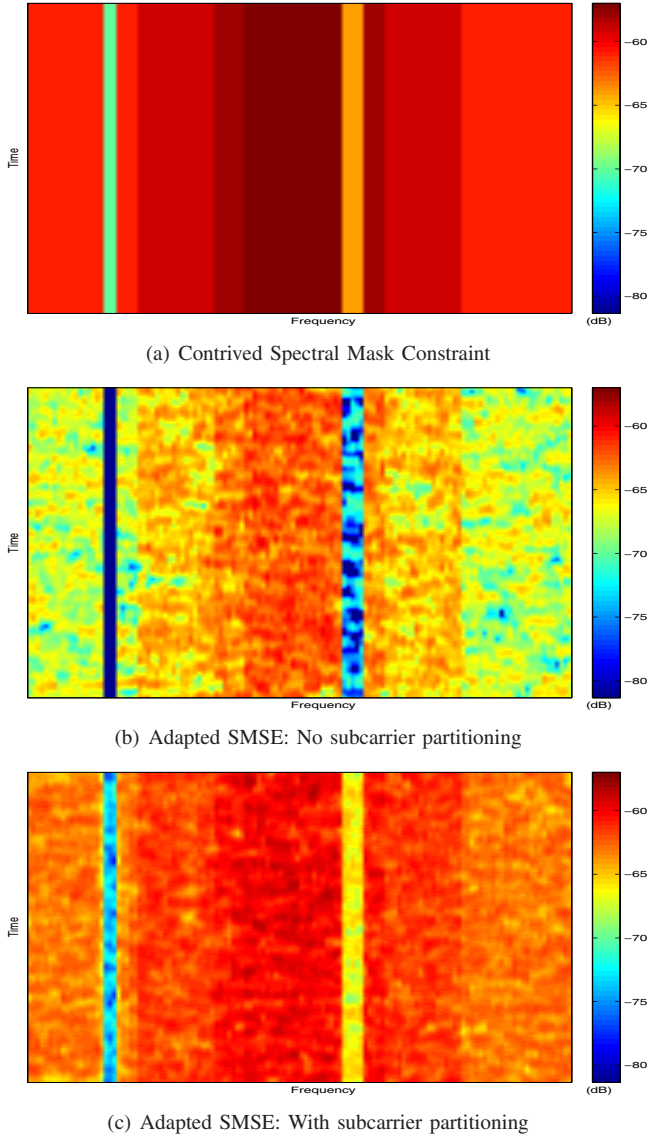


Fig. 1. Time-frequency PSDs for non-adaptive 4-QAM modulation: (a) Contrived spectral mask constraint; (b) Adapted SMSE response with *no subcarrier partitioning* ($N_P = N_f = 128$ and $N_{SC} = 1$); and (c) Adapted SMSE response with *subcarrier partitioning* ($N_P = 16$ and $N_{SC} = 8$). Results based on a maximum SMSE BER constraint of $P_B = 10^{-2}$ and maximum transmission power of $\Lambda_P = 35$ mW.

$N_f=128$ and $N_{SC} = 1$). Note that as the SMSE system is allowed to select from higher-order modulations, it is able to transmit more power and its response approaches the spectral mask limitation. Similar behavior is reflected in Fig. 4 which provides results for the case where the SMSE employs spectral partitioning with $N_P = 16$ partitions and $N_{SC} = 8$ subcarriers per partition. While results in Fig. 3 and Fig. 4 enable visual assessment of how modulation order selection impacts spectral PSD shaping for a given case (non-partitioned or partitioned), it is difficult to directly assess the impact of spectral partitioning. As presented next, this assessment is best made using resultant (actual) transmit power and average

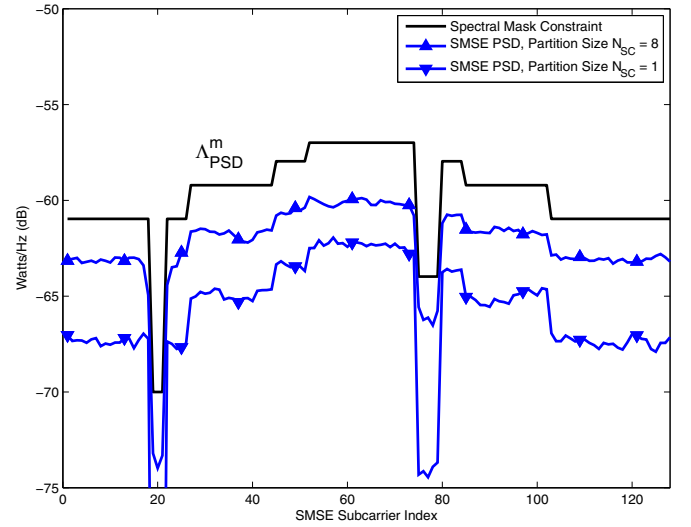


Fig. 2. Cross-time average responses for PSDs in Fig. 1 for adapted SMSE signal: Contrived spectral mask, $N_{SC} = 8$ subcarrier partitions and no subcarrier partitioning ($N_{SC} = 1$) as indicated.

SMSE system throughput (bits/symbol).

C. Design Demonstration: Throughput Assessment

Average SMSE throughput (bits/sec) is shown in Fig. 5 as a function of the SMSE transmission power limit for various various partition sizes (N_{SC}) with non-adaptive 4-QAM modulation. As the partition size increases, the SMSE system is better able to exploit more spectral regions to design its waveform, without violating the spectral mask constraint. As a result, the performance of the SMSE system is shown to increase substantially for larger partition sizes.

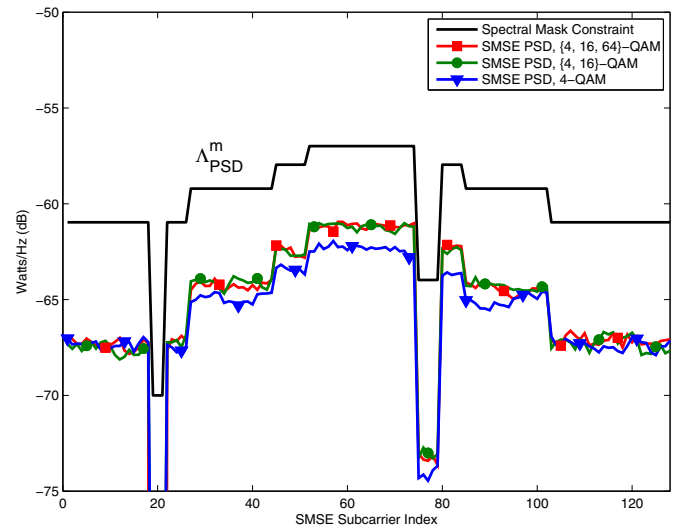


Fig. 3. Average resultant PSD responses for spectrally adapted SMSE signals using adaptive modulation selection with *no subcarrier partitioning* ($N_P = N_f = 128$ and $N_{SC} = 1$). Results based on a maximum SMSE BER constraint of $P_B = 10^{-2}$, maximum transmission power of $\Lambda_P = 35$ mW, and QAM modulation order selection of $M = \{4, 16, 64\}$.

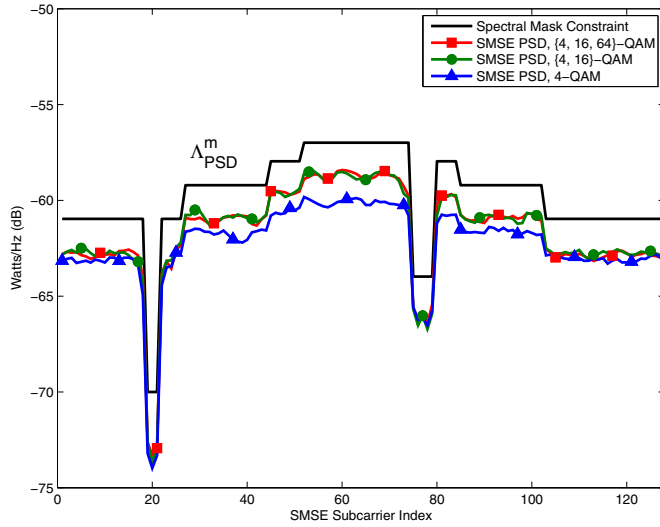


Fig. 4. Average resultant PSD responses for spectrally adapted SMSE signals using adaptive modulation selection with subcarrier partitioning ($N_P = 16$ and $N_{SC} = 8$). Results based on a maximum BER constraint of $P_B = 10^{-2}$, maximum transmission power of $\Lambda_P = 35$ mW, and QAM modulation order selection of $M = \{4, 16, 64\}$.

To better understand how larger partition sizes enable the SMSE system to increase its performance, the amount of SMSE transmit power *actually used* versus the total maximum power *limit* (Λ_P) is shown in Fig. 6. Here, it can be seen that the spectrally partitioned SMSE system is able to allocate more power to the channel, and hence is able to transmit data at a higher rate. Alternatively, the non-partitioned SMSE system transmits in each spectral region much less often since the BER constraint would require a transmitted PSD level greater than that allowed by the PSD constraint. As a result, a large portion of the available spectrum remains unused.

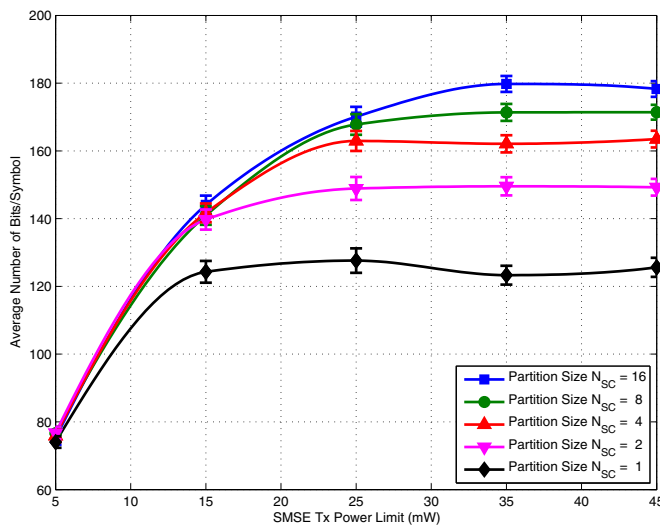


Fig. 5. Average SMSE throughput (Bits/Symbol) versus total maximum SMSE power at various partition sizes (N_{SC}). Results based on a maximum BER constraint of $P_B = 10^{-2}$ and 4-QAM modulation.

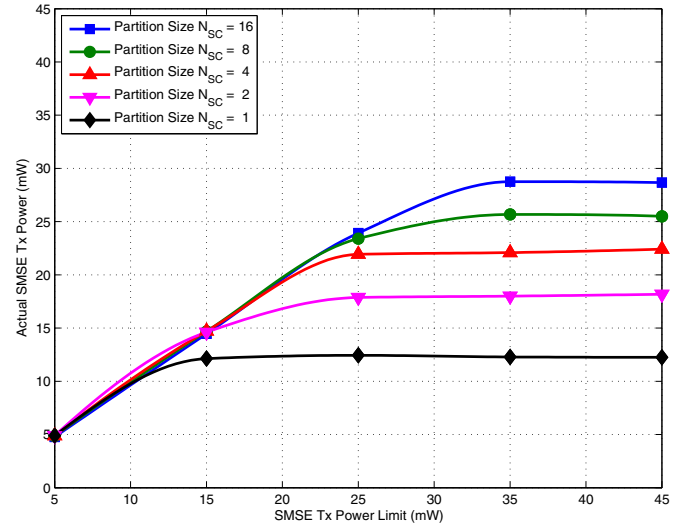


Fig. 6. Average SMSE power *actually used* versus total maximum power *limit* (Λ_P) at various partition sizes (N_{SC}). Results based on a maximum BER constraint of $P_B = 10^{-2}$ and 4-QAM modulation. Confidence intervals omitted for visual clarity.

Average SMSE throughput (bits/sec) is shown in Fig. 7 as a function of the SMSE transmission power limit for various various partition sizes (N_{SC}) with adaptive modulation. Results are provided for non-partitioned SMSE ($N_P = N_f = 128$ and $N_{SC} = 1$) or 2) and partitioned SMSE ($N_P = 16$ and $N_{SC} = 8$). For both cases, the ability to select between 4-QAM and 16-QAM provides a considerable increase in throughput relative to the non-adaptive 4-QAM only case. However, increasing the set of available modulation orders to include 64-QAM provides no statistically significant difference in throughput. In this case, the amount of power required to employ 64-QAM generally would require a transmitted PSD level greater than the PSD constraint.

The spectrally partitioned SMSE waveform is generally able to transmit at a higher data rate by increasing the number of data symbols (N_v^i), versus increasing the modulation order (M_i) within a partition. Also, for all parameters chosen (modulation order and partitioning size) SMSE system performance reaches a maximum at power limits of $\Lambda_P < 45$ mW. This makes sense since the total integrated power spectrum of the PSD mask is approximately 45 mW and the SMSE system is unable to transmit waveforms having a total average power level greater than this.

IV. SUMMARY AND CONCLUSIONS

Applicability of the Spectrally Modulated, Spectrally Encoded (SMSE) design process has been expanded for future CR-based SDR applications. Consistent with earlier work, the practical utility of the SMSE framework has been demonstrated using spectral partitioning with soft decision (SD) selection and dynamic assignment of SMSE design parameters.

Spectral partitioning was employed with carrier interferometry (CI) coding to exploit SMSE waveform adaptability

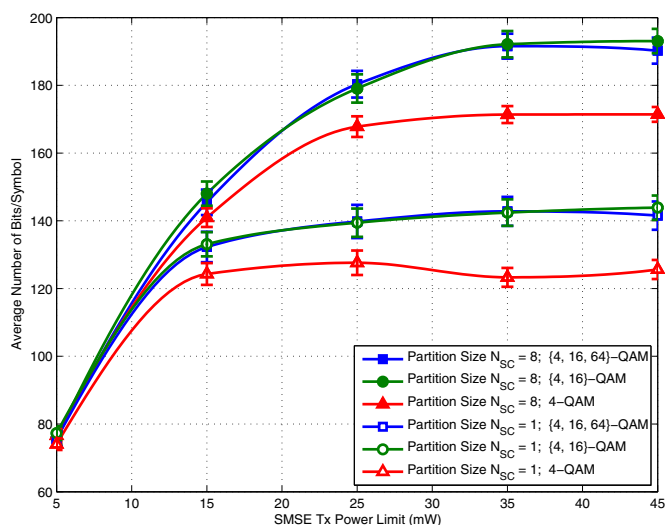


Fig. 7. Average SMSE throughput (Bits/Symbol) versus total maximum SMSE power at various partition sizes (N_{SC}) and possible modulation orders. Results based on a maximum BER constraint of $P_B = 10^{-2}$.

and improve average throughput. System design complexity remains within reasonable levels and adaptive modulation selection from among 4-QAM only, 4-QAM/16-QAM, and 4-QAM/16-QAM/64-QAM design options yielded higher transmit powers within spectral mask constraints—spectrally partitioned designs with CI coding emerged as superior and provided an appreciable increase in throughput (bits/sec) relative to non-partitioned designs.

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