ASYMMETRIC MODULATION FOR COGNITIVE RADIO AND INTELLIGENT ENVIRONMENTS

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ABSTRACT

In this paper, asymmetric modulation schemes are presented to establish the potential for fully adaptable signal design in cognitive radio and intelligent environments. Two categories of design are addressed, asymmetric phase-shift keying and asymmetric quadrature-amplitude modulation. The former is a phase-shift keying scheme that has been altered from symmetric form to generate a condition of phase invariance by virtue of unequal phase differences among symbols of the constellation. The later is a quadrature-amplitude modulation scheme that is based on the optimal (geometric) simplex lattice. These modulation schemes are defined by continuous and discrete parameters, which can be used to carry additional information or to adapt to unexpected changes in the environment. By tuning the parameters of these asymmetric constellations, dynamic control of bandwidth and error performance can be used to optimize channel efficiency.

1. INTRODUCTION

Modern communication systems commonly use symmetric modulation schemes to transmit information across wireless channels. Constant envelope, phase-shift keying (PSK) signals are used to keep signal recovery inexpensive and minimally complicated. Standard PSK constellations are constructed of symbols with equal energy that are evenly distribute about the origin of the normalized unit circle in the complex plane. Modulated envelope, quadrature-amplitude modulation (QAM) signals are used to improve power efficiency, with added device cost for highly linear amplifiers. With standard QAM, symbols are positioned to form a square lattice in the complex plane. The constellation structures of both of these signals lend themselves to ambiguity in phase and are limited in their ability to adapt in dynamic environments.

Coherent recovery of these signals requires accurate frequency and phase measurements, requiring some form of synchronization. Quick synchronization can be attained through data-aided methods or pilot tones, both of which have the disadvantage of reducing throughput efficiency since additional bandwidth is occupied for synchronization. Non-data aided methods of synchronization, like phase-locked loops or discrete-time signal processing algorithms, are throughput efficient, but they require more time for synchronization [1].

Alternatively, phase synchronization can be avoided by noncoherent modulation techniques that key off differences in the phase between consecutive signals. Two of these differentially coherent modulation schemes are differential phase-shift keying (DPSK) and differential quadrature-amplitude modulation (DQAM), each of which require higher signal-to-noise ratio (SNR) to realize the same bit error rates (BER) as their coherent counterparts, PSK and QAM.

In this study, we explore synchronization based on the phase invariance of asymmetric constellations and the extended capabilities of dynamic design. Previous study, in [2], has shown benefits of adding flexibility to coding schemes with asymmetric constellations. Also, it has been shown in [3] that asymmetric PSK can perform better than symmetric PSK in fading channels. Further, asymmetric QAM has been demonstrated to facilitate blind estimation in [4]. Extending these ideas to dynamic constellations, opportunities arise for increased throughput and signal integrity. Continuous and discrete parameters used in constellation design incorporate asymmetric reference parameters that can improve synchronization capability and convey additional information. Among the networks that can benefit from the added functionality of asymmetric modulation (AsM) are those that would support intelligent environments.

2. ASYMMETRIC MODULATION

We present AsM schemes for two general categories of modulation and analyze them over the additive white Gaussian noise (AWGN) channel. To support communication systems that require constant envelope signals and to directly compete against M-ary PSK and M-ary DPSK, two instances of M-ary asymmetric phase-shift keying (AsPSK) are defined by mapping functions that morph symbol phases from symmetric PSK constellations. To support systems that allow modulated envelope signals and to directly compete against M-ary QAM and M-ary DQAM, two constellation schemes based on a rigid lattice and malleable lattice are defined as instances of asymmetric quadrature-amplitude modulation (AsQAM). The designs of AsM are here presented in two dimensions; however exploitation of the characteristics can be fully explored in multi-dimensional signal space.

2.1. AsPSK

The nominal requirements for AsPSK are that the symbols must have equal energy and that the constellation must be phase invariant. We chose two AsPSK mapping functions defined to compare the potentials of linearly mapped and nonlinearly mapped constellations. The linearly map for AsPSK evenly distributes the reduction of phase among all but one adjacent neighbor pair; the nonlinearly map distributes the differences in phase unevenly. Coherent performance of the linear version is expected to be better than the coherent performance of the nonlinear when largest phase differences are equivalent, since the nearest neighboring symbols are farther apart; however, the nonlinearly mapped AsPSK is fully phase invariant and may lead to advantages that could be used for synchronization or for transfer of additional information.

The mapping equations for the phases of linear and nonlinear mapped AsPSK symbols from PSK constellations are

$$y = (1-\alpha_1)x + 2\pi\alpha_1 \tag{1}$$

and

$$y = (2\pi)^{\alpha_2} x^{(1-\alpha_2)} \tag{2}$$

where x is the phase of symmetric PSK and y is the phase of AsPSK. The continuous parameter, α, ranges from zero to one. A discrete parameter, β, can be incorporated in the nonlinearly mapped constellation to reference the rearrangement of phase differences among symbols to produce uniquely different constellations. And in reference to the use of various mapping functions, another discrete parameter can be made available, which we will refer to as γ. These parameters offer dynamic control to the transmitter that can act on feedback information from the receiver to compensate for changes in a dynamic environment or can be used to convey fuzzy information or additional low priority information, with little or no compromise to the otherwise standard throughput. Example constellations of AsPSK γ=1 and γ=2 are presented in Fig. 1, with equivalent maximum adjacent neighbor pairs for each constellation. Signal amplitudes in the figure are not to scale in order to overlay the plots for phase comparison.

For PSK signals, the probability of symbol errors affected by AWGN can be approximated by summing the likelihood of detecting adjacent neighbors in error for each symbol, then averaging the sums; the resulting equation is

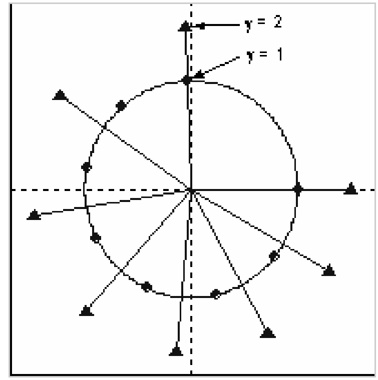

Fig. 1. AsPSK [γ=1, γ=2]

$$P_e \approx Q\left(\frac{d_{\min}}{\sqrt{2N_o}}\right) \tag{3}$$

where

$$Q(u) = \frac{1}{\sqrt{2\pi}}\int_u^\infty \exp\left(-z^2/2\right)dz \,, \tag{4}$$

$d_{\min}$ is the nearest neighbor distance, and $N_0/2$ is the power spectral density of noise. The minimum distance for symmetric PSK is

$$d_{\min\_PSK} = 2\cdot\sqrt{E_S}\cdot\sin\left(\frac{x}{2}\right) \tag{5}$$

and for AsPSK, as they are defined for γ=1 and γ=2 where y_{M-1} represents the phase of the symbol nearest $y_M=2\pi$,

$$d_{\min\_AsPSK} = 2\cdot\sqrt{E_S}\cdot\sin\left(\frac{2\pi - y_{M-1}}{2}\right) \,. \tag{6}$$

This leads to AsPSK γ=1 and γ=2 minimum nearest neighbor distances

$$d_{\min\_\gamma_1} = 2\cdot\sqrt{E_S}\cdot\sin\left\{\frac{\pi\cdot(M-1-\alpha)}{M}\right\} \tag{7}$$

and

$$d_{\min\_\gamma 2} = 2\cdot\sqrt{E_S}\cdot\sin\left\{\pi\left[\frac{M-1}{M}\right]^{(1-\alpha)}\right\} \tag{8}$$

when

$$x_{M-1} = 2\pi\left(\frac{M-1}{M}\right) .$$

Applying (7) and (8) to (3) and noting that

$$E_S = \lg(M)\cdot E_B \,,$$

the following BER estimates result:

$$P_{b1} \approx Q\left(\sqrt{2 \cdot \lg(M)} \cdot \sqrt{\frac{E_B}{N_0}} \cdot \sin\left\{\frac{\pi \cdot (M-1-\alpha)}{M}\right\}\right) \quad (9)$$

and

$$P_{b2} \approx Q\left(\sqrt{2 \cdot \lg(M)} \cdot \sqrt{\frac{E_B}{N_0}} \cdot \sin\left\{\pi\left[\frac{M-1}{M}\right]^{(1-\alpha)}\right\}\right) \quad (10)$$

To demonstrate the dynamic control of AsPSK design, an analysis of BER versus SNR in AWGN shows AsPSK γ=1 and γ=2 performing as well or better than DPSK for a predetermined SNR. In Fig. 2, each versions of AsPSK was defined by an α to result in a signal constellation that required lower SNR for BERs of 10^{-3}.

Several opportunities for synchronization present themselves. Clock synchronizers can be designed to remove phase ambiguities that are present in PLL's that are based on standard symmetric constellations. Over a block of data, rotation in phase can be corrected based on phase differences among most probable transmitted asymmetric symbol locations. A graphical view of these opportunities can be seen in the signal space vector diagram; the two dimensional eye diagram for AsPSK γ=2, α=0.25 and excess bandwidth of 60% is shown in Fig. 3. The single widened eye opening implies improved timing opportunity for AsPSK over PSK. Unfortunately, the nearest neighbor distance between the symbols is reduced, causing an increase to the probability of error during signal detection. By evaluating the advantages and disadvantages of flexible asymmetric signal design, communication systems can be optimized to capitalize on the diverse characteristics enabled by the ability to seamlessly tune in and out of the synchronization mode and the signal recovery mode of operation.

Alternatively, noncoherent detection can be achieved by acting on the history of signals, using hard and soft decisions. By making a soft decision on the history of received signals, a detector can predict the most likely incoming symbol based on the relative phase to the best synchronizing fit of the signal buffer. Once the signal is predicted the decision buffer can be evaluated for a hard decision update on cells that were previously determined with lower levels of certainty. A noncoherent receiver that was designed on these ideas was simulated for Gray coded AsPSK using Matlab; the results are in Fig. 4 and Fig. 5. Comparison of the performances for buffer sizes of 2, 10 and 50 demonstrate the tradeoffs between the linear and nonlinear versions of AsPSK. The nonlinear AsPSK recovered better with a small buffer, and the linear AsPSK recovered better with a larger buffer. It should be noted that there was a significant increase in the level of computational complexity for increased buffer sizes, so the case could be made for nonlinear AsPSK over linear AsPSK under certain conditions. The receiver resulted in poorer power efficient

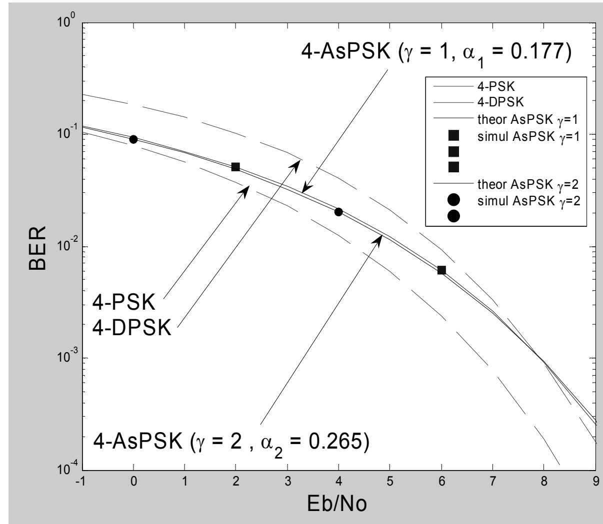

Fig. 2. Precise Design Control for AsPSK

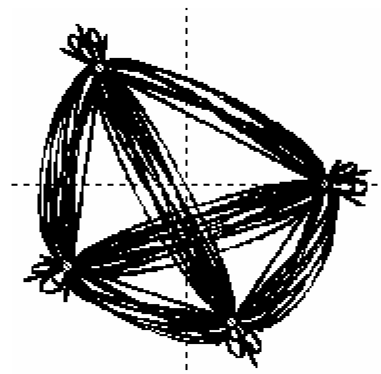

Fig. 3. AsPSK Signal Space Vector Diagram
AsPSK, α=0.25, β=1,γ=2, BWeff = 60%

than DPSK; however, the results successfully demonstrated the potential of asymmetric coherence, offering promise for further development of the algorithm.

An application that could benefit from the synchronizing capability of AsPSK is Orthogonal Frequency Division Multiplexing (OFDM). IEEE has based the 802.11a wireless network standard on OFDM, specifying 52 sub-channels to form OFDM symbols, 48 of which carry data and 4 that carry pilot signals for synchronization. A similar network could be designed using AsPSK, which would allow even distribution of synchronization across all frequencies. This would also allow sub-networks to optimize throughput by allowing dynamic fluctuation between optimal synchronization and optimal throughput modes, based on the dynamics of a given channel. As well, additional information could be transmitted based on the continuous and/or discrete fluctuation of constellations for the support of intelligent environments that transmit information that are similar in nature.

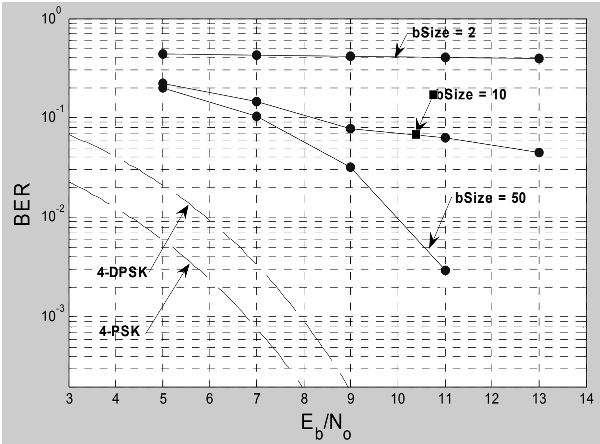

Fig. 4. Noncoherent AsPSK (γ=1) Simulation

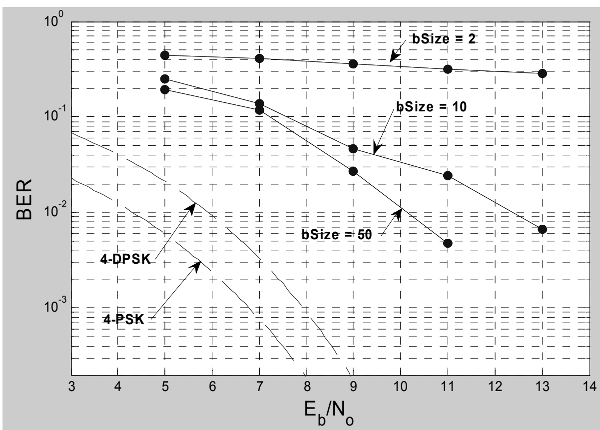

Fig. 5. Noncoherent AsPSK (γ=2) Simulation

2.2. AsQAM

Our design for AsQAM is based on the simplex lattice, which is a lattice that is composed of a simplex base structure. Briefly defined, the geometric simplex is an N-dimensional structure with equal length sides and maximum area (eg. point, line, equilateral triangle, regular tetrahedron). The simplex lattice allows the greatest distance between nearest neighbor symbols within the signal space of a constellation, since it is the densest normalized structure available. Although other arrangements of lattice points could be chosen, the measurements represented in Fig. 6 demonstrate the advantage of the equilateral triangular (two-dimensional simplex) lattice of AsQAM, over the square lattice used for standard QAM. The upper left corner of the figure represents the normalized nearest neighbor distance of square lattice constellations for signal sizes of 1 to 19 symbols per constellation; the upper right corner represents the corresponding results for the equilateral triangle lattice. In the lower half of the figure, the vertical axis represents the nearest neighbor distance improvement

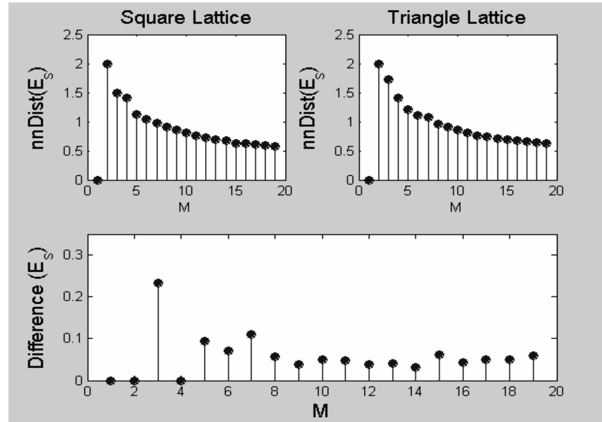

Fig. 6. Nearest Neighbor Distance Improvement of Equilateral Triangle Lattice over Square Lattice

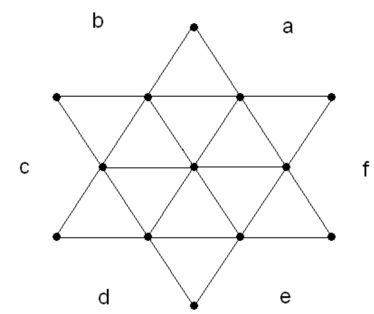

Fig. 7. AsQAM Constellation Design

of the equilateral triangle lattice over the square lattice for constellations normalized to the average symbol energy.

The static lattice version of AsQAM, which we label γ=1, is developed from a center symbol, with additional symbols added to the next energy level of points available on the lattice, and so on until the necessary symbols are placed on the lattice. To construct 16-AsQAM γ=1, three symbols are in the forth energy level, where six possible locations are available. Four distinct, phase-invariant arrangements are possible, and therefore four similar discrete 16-AsQAM γ=1 constellations, β=[1..4]. The four similar 16-AsQAM (α=0, β=[1..4], γ=1) designs are represented in Fig. 7, with a selection of three possible symbols of the outer energy level as follows:

β=1 [a b c],
β =2 [a b d],
β =3 [a b e],
β =4 [a c e].

The constellation designs are completed by positioning the centroid of energy at the origin, and quasi-Gray mapping the structure.

Relaxing the static nature of the lattice design, 16-AsQAM γ=2 is defined. Each lattice is bent to increase nearest neighbor distances to form new constellations, which are still distinct from each other. To support the continuous parameter, α, constellations of AsQAM γ=2 can be morphed from the modulated envelope signal to a chosen constant envelope signal. Energy centroid centering and quasi-Gray mapping are applied as in 16-AsQAM γ=1.

AsQAM (α=0, β=1, γ=1) with excess bandwidth of 95% in Fig. 8 serves to demonstrate the widened eye opening for AsQAM that implies increased opportunity for clock synchronization over standard QAM. Optimized algorithms may key off high energy symbols to reduce the computational complexity and open a sub-eye of AsQAM to better realize the synchronization capacity.

A noncoherent algorithm similar to that described for AsPSK could be applied. Another option for avoiding phase synchronization, also increasingly complex for high order signals, is the Viterbi decoder that would exploit the phase invariance of the modulation scheme.

Probably the most direct benefit of AsQAM over QAM is its tolerance to noise. The nearest neighbor distance has been shown to be greater with the simplex lattice than with the square lattice of symmetric QAM, which leads to better performance for AsQAM in AWGN. The following equations mathematically compare the nearest neighbor distances of 16-AsQAM (α=0, β=1, γ=1) to standard 16-QAM. Average power for standard QAM using the square lattice is

$$E_{S\_QAM} = \frac{5}{2} d_{\min}^2$$

and AsQAM γ=1 before shifting the centroid to the origin,

$$E_{S\_AsQAM-\gamma_1} = \frac{9}{4} d_{\min}^2.$$

Approximation for the probability of error, by averaging the sum of overlapping error regions for symbols of the constellations results in

$$P_{b\_QAM} \approx \frac{3}{4} Q\left(\frac{2}{\sqrt{5}} \sqrt{\frac{E_B}{N_0}} \right) \quad (11)$$

for standard QAM, and

$$P_{b\_AsQAM} \approx Q\left(\frac{2\sqrt{2}}{3} \sqrt{\frac{E_B}{N_0}} \right) \quad (12)$$

for AsQAM (α=0, β=1, γ=1), before centroid shift optimization. Given that Gray coding is not realizable for AsQAM, the probability of bit error may be higher. On the other hand, positioning the centroid at the origin will increase the normalized distance between symbols, resulting in reduced probability of error. The following nearest neighbor distances result from QAM and centroid centered AsQAM:

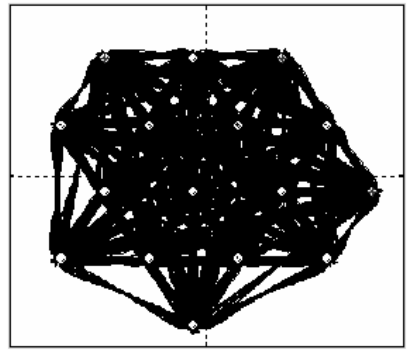

Fig. 8. AsQAM γ=1 Signal Space Vector Diagram

$$d_{QAM} = 0.6325,$$

$$d_{AsQAM\_\gamma 1} = 0.6761$$

The resulting BER approximations are

$$P_{b\_QAM} \approx \frac{3}{4} Q\left(0.89 \sqrt{\frac{E_B}{N_0}} \right) \quad (13)$$

and

$$P_{b\_AsQAM} \approx Q\left(0.96 \sqrt{\frac{E_B}{N_0}} \right) \quad (14)$$

A theoretical comparison using the union bound on the probability of error [1] is presented in Fig, 9, which shows a 1/2 dB SNR loss for 16-AsQAM over 16QAM, with equivalent BER and low SNR. Extended to multiple dimensions, the power efficiency is further improved, mitigating the concern of the increasing cost of computational complexity.

Recent research has considered the use of DQAM for noncoherent QAM [5]. As previously stated, AsQAM offers a coherent QAM design that performs better than standard coherent QAM. Additionally, the geometry of AsQAM constellations can be used to facilitate a synchronizing circuit or to facilitate an asymmetrically coherent design with additional error correction capabilities. The potential is a noncoherent AsQAM that outperforms noncoherent DQAM and, more significantly, coherent QAM.

An application that could benefit from the power efficiency of the multidimensional simplex lattice of AsQAM is Code Division Multiple Access (CDMA). IEEE 802.11g orthogonalizes several sub-channels with CDMA; the simplex lattice would exploit these orthogonal sub-channels optimally for coherent and noncoherent functionality. As with AsPSK, fluctuation between

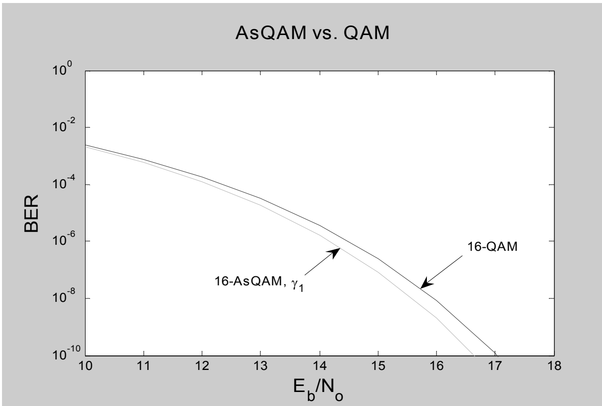

Fig. 9. Coherent AsQAM vs. Coherent QAM

synchronization mode and data transfer mode would optimize channel throughput and increase system performance.

3. COGNITIVE ENVIRONMENTS

These flexible constellations give cognitive power to environments that would benefit from sending dynamic, fuzzy information in forms with similar characteristics. Small changes in information that is not immediately critical could take the form of subtle signals that do not interrupt or noticeably hinder higher priority information.

A software defined radio in an indoor environment might receive input from several transmitters. Those transmitters could send continuously altered information to update likes or dislikes to songs, decisions that might not be so clear cut. An estimate of user volume could be transmitted continuously in time by the asymmetry of the constellation that is transmitting the otherwise standard information. Similarly, room temperature or lighting characteristics could be altered according to the dynamics of group desires. Further, outside influence may have an effect on the needs of the user or users, which can be tipped off by the reception of asymmetry that is noticed to have passed a defined threshold. Over longer periods of time subtle changes in the constellation would be recognized; the importance of the transmitted information could be sent appropriately.

Discrete constellation changes could be used to update environmental states based on the discrete number of users in an environment or the significance of a particular group of users or single user within that group. On the entry of a new user to the environment, the transmitted constellation could switch, queuing the receiver to shift to the next constellation of an algorithm and charge the processor to briefly enter a welcome mode.

Further, using an algorithm similar to the sliding window protocol of TCP/IP networks, signal quality can be altered to compensate for bursts of bit errors or uncertainties. In fact, AsQAM can result in the most noise resistant constellation available.

4. CONCLUSION

This paper has focused on three significant benefits of AsM: improved tolerance to noise, added opportunity for synchronization, and dynamic constellation design. Asymmetric modulation that is based on the simplex lattice has been shown to have increased distance between nearest neighbor symbols of constellations, and to perform better than symmetric QAM in AWGN. Phase invariance has been shown to offer opportunity for the design of asymmetrically coherent receivers, and an argument has been put forward for an improved synchronization circuit that takes advantage of phase invariance. And most significantly, freedom from symmetry and static structure has been shown to allow multiple opportunities for discrete and continuous information to be transferred by virtue of dynamic constellations.

Intelligent environments can exploit these capabilities by transferring continuous and discrete information at minimal cost; in fact, an opportunity for increased throughput is apparent. Subtle changes to room temperature or music preference for a dynamic set of multiple users could be updated with subtle alterations to constellation design, to result in improved overall system performance. Largely overlooked, asymmetric modulation has several strong benefits that could be exploited to improve wireless communication systems.

4. REFERENCES

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