A New Approach to Spread-spectrum OFDM

Mohammad Kaisb Layous Alhasnawi[1], Ronald G. Addie[2] and Shahab Abdulla[3]

[1]*Faculty of Administration and Economics, Sumer University, Thi-Qar, Iraq*

[2]*School of Agricultural, Computational and Environmental Science, University of Southern Queensland, Toowoomba, Australia*

[3]*Open Access College, University of Southern Queensland, Toowoomba, Australia*

Keywords: OFDM, Spread-spectrum OFDM, Spectrum Sharing, Ideal Channel, Galois Field, Nearly Orthogonal.

Abstract: Orthogonal frequency division multiplexing (OFDM) systems are reviewed and the Shannon bound is discussed as a criterion of efficient spectrum use and a design criterion. The problem of efficient sharing of spectrum by wireless communication systems is discussed and combined use of direct-sequence spread-spectrum (DSSS) coding and OFDM is proposed as an approach which can achieve efficient spectrum sharing. A system which enables DSSS, with codes from the Galois field of order f where f is a prime larger than 2, to be used efficiently in conjunction with OFDM is then defined, analysed, and implemented. Experiments with this system are described.

1 INTRODUCTION

Spectrum sharing is a problem of considerable interest and importance (Pandit and Singh, 2017). The number of wireless devices has been growing significantly in the last decade, including IPTV receivers, tablets, smartphones, remote controls, GPS devices, wireless sensors (Xin and Song, 2015). This growth of wireless devices leads to increased demand on the available and more need for efficient spectrum sharing. This study investigates improvement in the efficiency of spectrum use by using *spread spectrum orthogonal frequency division multiplexing (SS-OFDM)* (Akare et al., 2009; Xia et al., 2003; Jaisal, 2011; Meel, 1999; Tu et al., 2006).

Spread-spectrum systems which are nearly colocated systems will perceive each other as noise, and when doing so will not suffer any loss in overall efficiency of spectrum use, therefore the use of spread-spectrum *with* OFDM has the potential to enable efficient spectrum sharing. However, evaluation of OFDM-SS from the point of view of spectrum efficiency has not received close attention in much of its literature up to this point.

In this paper the direct-sequence spread-spectrum (DSSS) system uses symbols from the Galois field $GF(f)$, where $f > 2$ is a prime number. For efficiency it is likely that f will usually be larger than 10. Most DSSS systems use symbols from $GF(2^m)$ for some $m > 0$. This choice is more straightforward to implement and seems more natural, given that most digital hardware uses binary arithmetic and binary representation for numbers, but the nearly-orthogonality property of codes based on this field does not directly lead to the necessary orthogonality conditions when used with OFDM, as we show in Subsection 5.8. Use of a field $GF(f^m)$ with $m > 1$ is also possible, but has not been investigated in this paper.

According to (Zhang et al., 2015) the significant challenge facing researchers in wireless communication is efficient spectrum sharing. There is an imbalance between the rapidly growing demand and the limited resources of wireless spectrum. The authors (Ji and Liu, 2007) show that in order to acheive efficient and full utilization of available common spectrum, the protocols and/or technologies used in wireless communication need to be changed so that efficient spectrum sharing is one of the key design objectives. The aim of this paper is to investigate a strategy for using OFDM which allows efficient sharing of spectrum to occur without excessive additional effort.

OFDM systems are considered to be effective techniques and are used for several of the latest standards for wireless, telecommunications standards and digital video broadcasting (Sung et al., 2010; Armstrong, 2009; Coleri et al., 2002). However, it can be difficult to share available spectrum efficiently while

Alhasnawi, M., Addie, R. and Abdulla, S.
A New Approach to Spread-spectrum OFDM.
DOI: 10.5220/0006828602810288
In *Proceedings of the 15th International Joint Conference on e-Business and Telecommunications (ICETE 2018) - Volume 1: DCNET, ICE-B, OPTICS, SIGMAP and WINSYS*, pages 281-288
ISBN: 978-989-758-319-3
Copyright © 2018 by SCITEPRESS – Science and Technology Publications, Lda. All rights reserved

using OFDM.

In this paper, a new method for combining DSSS with OFDM has been defined and implemented in matlab and an algorithm for predicting wifi throughput of a full implementation of such an SS-OFDM system has been developed. We shall show, first of all, that optimal sharing can be consistent with nearby wifi domains appearing as noise to each other (which is the characteristic property of spread-spectrum).

The SS-OFDM system has been implemented in matlab and used to demonstrate simultaneous communication of a large number of co-located users (up to 1000), using spread-spectrum to share access to the medium, with minimal impact on spectral efficiency. It has also been estimated that when users are not co-located, total system throughput achievable is significantly greater than systems in which the available spectrum is used exclusively by each pair of communicating devices one at a time.

The paper is organized as follows with the arrangement; Section 2 explains the mathematical model by using Shannon Bound theory to a model wireless system. In Section 3 provides the literature review and background on SS-OFDM. The design of an idealised SS -OFDM will clarify at Section 4. In Section 5 displays the execution of the SS-OFDM system. Section 6 demonstrates the proof of the proposed system. The conclusion is set out in Section 7.

2 SHANNON BOUND THEORY

When OFDM is used, with highly efficient error-correcting codes, system capacity can be relatively close to the Shannon-Hartley bound. As a consequence, it can be used as a design principle. Any innovation or method (coding, modulation, filtering, ...), can be evaluated according to the degree to which it brings us closer, or further, from the Shannon-Hartley bound.

Consider a situatuation where several wifi networks operate in the same geographical region, and share the same spectrum, as depicted in Figure 1.
The concept of *nearly orthogonal* codes was introduced as part of the CDMA mobile communication system, which is sometimes referred to as 2.5G mobile communication.

The concept of *nearly orthogonal* systems can be applied not just to codes, but also to, for example, OFDM systems.

Currently, wifi tends to be managed so that those concurrently operating wifi domains use either the same channel, or channels which do not overlap. A typical example (from the USQ campus) is shown in

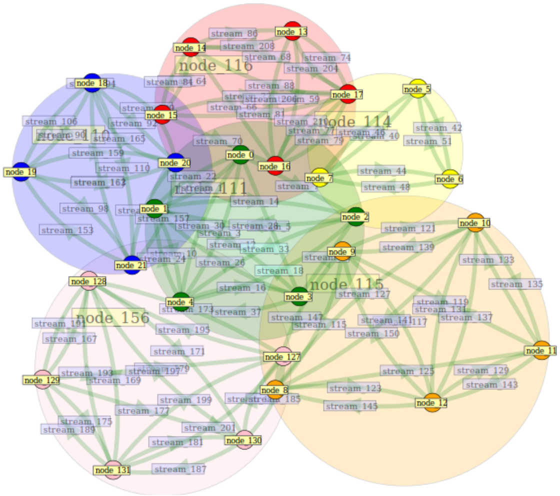

Figure 1: Six wireless networks sharing spectrum.

Figure 2.

This approach to designing wifi networks reduces capacity for two different reasons. Firstly, part of the spectrum is not used at all. Secondly, the type of sharing used between wifi systems using *the same* wifi channel, will be of the inefficient type. Each system will share with the others by CSMA/CA, therefore the total throughput will be the same as one system operating in isolation.

However, it is not clear how to enable nearby OFDM systems to share spectrum while treating each other as noise. This can be done by each system using codes. How effectively these nearby systems are able to communicate, at the same time, may depend on the choice of OFDM parameters made in each system. In this paper, the concept of *nearly* orthogonal systems for OFDM is introduced. This means that each subchannel in one system experiences the signals of the other OFDM systems as white noise at *lower* power than the actual OFDM signal power. The power of the signals from other users is further reduced by propagation loss. The reduced power of neighbouring systems in this situation leads to the complete system acheiving greater spectral efficiency than time-division or frequency-division multiplexing.

3 EXISTING MODELS OF SS-OFDM

The approach using SS-OFDM systems has emerged from the assembly of DSSS with OFDM (Akare et al., 2009). Using these techniques together overcomes radio channel weakness, and improves reliable communication with frequency selective channels. The SS-

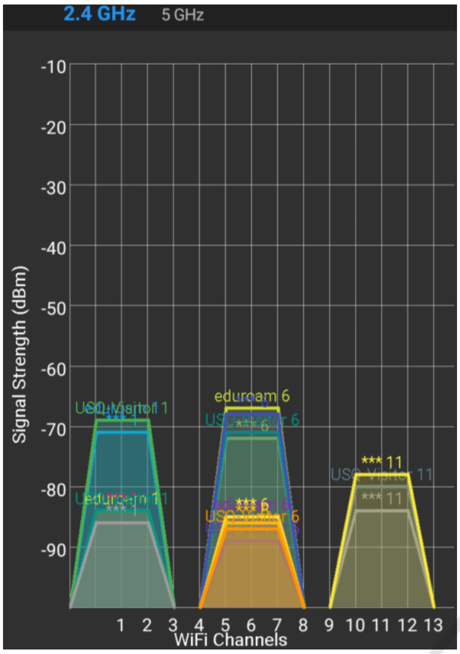

Figure 2: Sample of wifi sharing on a campus.

OFDM systems adopt a technique whereby various copies of each symbol are transmitted on all available N sub-carriers (Xia et al., 2003). On this study (Jaisal, 2011) referred to spread spectrum OFDM systems having many features such as DSSS technique. The main difference between the two models is that the SS-OFDM model utilises a spreading waveform consisting of samples with non-discrete values of amplitude. On the other hand, the DSSS model utilises a binary of spreading code which consisting of a sequence 1's and -1's.

Previous papers on SS-OFDM (Tu et al., 2006; Akare et al., 2009; Xia et al., 2003; Jaisal, 2011; Meel, 1999) all use, primarily, DSSS in combination with OFDM in the form set out in Figure 3. The best choice for the OFDM system when a DSSS module is used with it, is a key topic explored in these papers. In this paper, by contrast, the OFDM module will be *assumed* to be *ideal* (in a sense explained below), and the focus will be instead on the best choice of DSSS module.

In DSSS, a stream of data at the transmission point is combined with a pseudo-random bit sequence to become a higher data-rate signal. This technique of spreading the data helps the signal resist interference and also enables the original data to be recovered if data bits are destroyed during transmission from the origin point to the destination. In addition, when this technique is used by two or more communicating systems at once, they are able to perceive each other as noise, and therefore share the same spectrum without destructive interference. This last feature of spread-spectrum is often more important than the spreading idea itself.

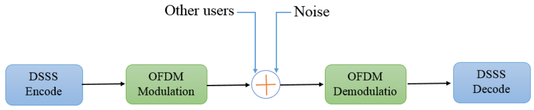

Figure 3: SS-OFDM systems.

3.1 Performance of SS-OFDM

The high rate of data is a key component of modern communications systems for wireless access networks of mobile users. OFDM techniques have been used for many decades. This modulation is widely utilised in modern telecommunications systems such as digital radio and TV, wireless networking, and transmission of data through the phone line. OFDM is a suitable system, especially for high speed communication because of its resistance to inter symbol interference (ISI), avoiding multipaths in wave transmission. Also, DSSS is a spread spectrum technique by which the original data signal is increased with a pseudo-random noise for spreading code (Meel, 1999). This spreading code uses a higher rate of the chip which leads to a wideband time continuously scrambled signal. A DSSS system enhances protection against interfering signals, especially narrowband. It also supplies transmission security, if the code is not known to the public.

The study (Akare et al., 2009) proposes to use the combination of OFDM system with DSSS for the multi-user system. The combination is named the SS-OFDM model. This model can be used to control the received signal bandwidth through the design of matching filters. The bandwidth of transmission can be selected flexibly to suit different modern telecommunication systems under various circumstances. SS-OFDM techniques supply reliable communications with a frequency-selective channel. The fading of multi-path impacts on the performance of wireless broadband link (Jaisal, 2011).

The essential results of this study mean that we can use the SS-OFDM model for wireless broadband. Also, it has been established that this model can efficiently deliver communication over short or long distances by using M-ary Quadrature Amplitude Modulation (M-QAM) with effectively reduced interference and improved Bit Error Rate (BER). In addition, the authors (Tu et al., 2006) referred to the results of simulation showing that the theoretical curves and the simulation curves matched well. This indicates that SS-OFDM can achieve the desired level of performance.

4 DESIGN OF AN IDEALISED SS-OFDM SYSTEM

A study undertaken by (Tu et al., 2006) used the Shannon-Hartley formula to justify a theory of the aggregate capacity achievable by spread-spectrum communication systems. When spread-spectrum systems interract, one system perceives the other as noise with power reduced in accordance with the mechanism of interraction of the two systems.

In this paper, rather than exploring the changes which are needed in the OFDM module, a specific hypothesis for the form this module should take is posited. The hypothesis is that the OFDM module transforms the original channel into an ideal (i.e. flat frequency-response) channel with additive Gaussian white noise. This OFDM module will exhibit a fixed non-zero *latency*. Minimising overall system latency may be a concern, and it is well-known that any system which achieves an ideal (or close to ideal) transfer function must introduce a large delay; however this issue will be put to one side initially.

This hypothesis needs to be tested first. It can then be used as a starting point for the *other* question which needs to be investigated in SS-OFDM, namely what form of DSSS should be used in a system of the form shown in Figure 3? The hypothesis enables us to investigate this question in a much simpler form, as shown in Figure 4.

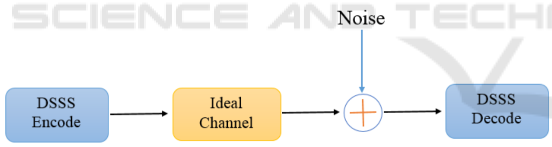

Figure 4: Ideal channel.

5 AN IMPLEMENTATION OF DSSS-OFDM

Assuming an ideal OFDM system, a design which exhibits effective working with a DSSS module to provide a combined DSSS-OFDM system is described in this section. The details of how the DSSS module and the OFDM module work together must be clearly specified and we need to check that the desirable properties of both DSSS and OFDM are achieved in the combined system. A key requirement for this to be achieved is that the DSSS system uses higher-order symbols (not binary digits), so that when these symbols *interfere* with other users of similar DSSS-OFDM systems, the nearly orthogonal property of the DSSS sequences is preserved algebraically even when the different signals are combined together as electromagnetic radiation before being decoded, as depicted in Figure 5.

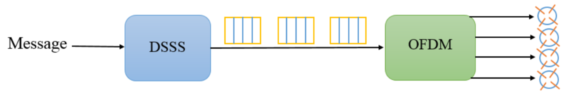

Figure 5: SS-OFDM with DSSS uses higher order symbols.

5.1 An Example System

As with all DSSS systems, there are many parameters of the system which affect the design. In this subsection we arbitrarily choose these parameters, and we adopt choices with a view to simplicity rather than capacity or performance. However, it should be clear how the parameters can be changed to suit other objectives.

The system we consider is based on the Galois field with prime $p = 5$, and power $m = 1$.

5.2 Orthogonality Property

For any DSSS system to work efficiently, it must have an orthogonality or *nearly orthogonal* property which is, firstly, a mathematical property of the codes and, secondly, is preserved by the way signals are modulated, aggregated, and demodulated by the system. If the DSSS system has a (nearly) orthogonality property, but the implementation does not actually operate in the way required by this principle, it will not serve our purposes.

5.3 The Galois Field Theory of DSSS Codes in the Complex Domain

The theory of DSSS codes formed from binary sequences is well understood and widely used. However, in the present context, where the DSSS codes must be transmitted through an OFDM system, the DSSS codes needed must be represented as sequences of complex numbers. Let us therefore review the theory of Galois fields and apply it to identify the necessary codes.

Suppose f is a prime number. Then, $GF(f)$ denotes the Galois field of numbers $\{0, 1, \ldots, f-1\}$, with addition operation defined as addition modulo f and multiplication operation defined as multiplication modulo f. This field is known to possess a *primitive*, p, which is an element of the field, with the property that $1,\ p,\ p^2,\ \ldots, p^{f-1}$ is an enumeration of all the non-zero elements.

Let $z_k = e^{2\pi ki/f}$, $k = 0,\ \ldots,\ f-1$. When symbols in this field are used for transmission, these complex numbers are a better representation of the physical form taken by the signal. The magnitude of the complex number represents the power, and the complex argument represents the phase, of the transmitted signal.

5.4 Near-orthogonality

Suppose $x = (x_1, \ldots, x_4)'$ and $w = (w_1, \ldots, w_4)'$. are complex vectors. The appropriate inner-product between these vectors is $(x, w) = \sum_{k=1}^{4} x_k \overline{w_k}$.

Observe that $z_k = \overline{z_{-k}}$ and $z_k \times z_j = z_{k+j}$. Define $\chi_j = (z_{p^{j-1}}, z_{p^j}, \ldots, z_{p^{(j-2) \bmod f}})$, $j = 1, \ldots, f-1$. These will form the codes of our DSSS-OFDM system.

Proposition 1.

$$(\chi_k, \chi_j) = \begin{cases} f, & k = j, \\ -1 & k \neq j. \end{cases} \tag{1}$$

Proof. Observe that in all cases the components of χ_j form an enumeration of all the complex numbers corresponding to elements of the field except 1 (which corresponds to the field element 0). The sum of *all* the complex numbers of this form (including 1) is zero, hence the sum of the components of χ_k is equal to -1, for any $j \in \{1, \ldots, f-1\}$. Let us now show that $(\chi_k, \chi_j) = -1$, also, $j, k = 1, \ldots, f-1$.

Suppose $j \neq k$. Then

$$(\chi_j, \chi_k) \quad = \quad z_{p^j}\overline{z_{p^k}} + z_{p^{j+1}}\overline{z_{p^{k+1}}} + \cdots + z_{p^{j-1}}\overline{z_{p^{k-1}}}$$

$$(\chi_j, \chi_k) \quad = \quad z_{p^j} z_{-p^k} + z_{p^{j+1}} z_{-p^{k+1}} + \cdots + z_{p^{j-1}} z_{-p^{k-1}}$$

which, using the property $z_s \times z_t = z_{s+t}$,

$$= \quad z_{p^j - p^k} + z_{p^{j+1} - p^{k+1}} + \cdots + z_{p^{j-1} - p^{k-1}}.$$

Now $p \times (p^j - p^k) = p^{j+1} - p^{k+1}$ so the sequence $z_{p^j - p^k}, \ldots, z_{p^{j-1} - p^{k-1}}$ is one of the codes χ_k and hence has sum -1. □

Example: $f = 5$

The field GF(5) has primitive element 2. This means that all non-zero elements are enumerated by 2^k, $k = 1, \ldots, 4$. The codes corresponding to this primitive element are:

$$\chi_1 = (1, 2, 4, 3),\ \chi_2 = (2, 4, 3, 1),$$

$$\chi_3 = (3, 1, 2, 4),\ \chi_4 = (4, 3, 1, 2).$$

5.5 Encoding

Suppose the messages to be transmitted are stored in an array:

$$m = \begin{pmatrix} m_{11} & \ldots & m_{1,n} \\ \vdots & \ddots & \vdots \\ m_{L,1} & \ldots & m_{L,n} \end{pmatrix} \tag{2}$$

and the code used for user u is $\chi_u = (\chi_{1,u}, \ldots, \chi_{\kappa,u})$, with the defining property $\chi_{k+1,u} = \chi_{k,u} \times p \mod f$, in conjunction with the obvious necessity that each user has a distinct value for $\chi_{1,u}$, in which κ denotes the chip-length. Thus, each code *rotates* (by multiplication of each element by the primitive of the field) during use and the different users are distinguished by their different *starting codes*.

For notational convenience we define $\chi_{k,u} = \chi_{(k-1) \bmod \kappa + 1, u}$ for all k. E.g. $\chi_{0,u} \doteq \chi_{\kappa,u}$.

The array of messages expressed as *symbols* (complex numbers with magnitude less than 1)

$$S = \begin{pmatrix} s_{11} & \ldots & s_{1,n} \\ \vdots & \ddots & \vdots \\ s_{M,1} & \ldots & s_{M,n} \end{pmatrix} \tag{3}$$

in the usual way, based on an arbitrary constellation (e.g. as in Figure 6). The value of M depends on L and also on the constellation.

The codes also have a complex representation:

$$X = \begin{pmatrix} \xi_{11} & \ldots & \xi_{1,\kappa} \\ \vdots & \ddots & \vdots \\ \xi_{\kappa,1} & \ldots & \xi_{\kappa,\kappa}, \end{pmatrix} \tag{4}$$

where

$$\xi_{kj} = e^{2\pi i \xi_{kj}/f}, \tag{5}$$

$k = 1, \ldots, \kappa$, $j = 1, \ldots, \kappa$. The symbols of the message are *encoded* into an array

$$C = \begin{pmatrix} C_{11} & \ldots & C_{1,n} \\ \vdots & \ddots & \vdots \\ C_{\kappa M,1} & \ldots & C_{\kappa M,n}, \end{pmatrix} \tag{6}$$

by the formula:

$$C_{kj} \quad = \quad S_{k \div \kappa, j}\, \xi_{k \bmod \kappa, j},$$

$k = 1, \ldots M\kappa$, $j = 1, \ldots, n$. The values of $\chi_{1,j}$ may be arbitrarily chosen, so long as they are different for each j. An obvious choice, which has been used in the implementation, is $\chi_{1,j} = j$, $j = 1, \ldots, f-1$.

The signals of all users are transmitted simultaneously into the medium which we model as numerical addition:

$$Z_j = \sum_{k=1}^{n} Z_{kj}, \tag{7}$$

$j = 1, \ldots, L$.

SCITEPRESS SCIENCE AND TECHNOLOGY PUBLICATIONS

5.6 Decoding

Consider the user with index j and let us ignore the signal due to the other users. For simplicity, assume $M = 1$, or putting it another way, we show the decoding for the first symbol only.

The chip $(Z_{1j}, \ldots, Z_{\kappa j})'$ is converted to a symbol by first using the formula:

$$\begin{aligned} W_j &= \sum_{k=1}^{\kappa} Z_{kj}\bar{\xi}_{kj} \\ &= \sum_{k=1}^{\kappa} S_{1j}\xi_{kj}\bar{\xi}_{kj} \\ &= \kappa S_{1j} \end{aligned} \tag{8}$$

$j = 1, \ldots, L$. The signal is therefore recovered with a gain in amplitude of the factor κ.

Next, these estimates of the signal are translated to symbols by finding the closest element of the constellation, and then to bits by using the inverse of the algorithm originally used to create the symbols from the message.

5.7 User Sharing Noise

The desired outcome is that when the message of User 1 is demodulated, the messages of all other users appear as noise of low power. The demodulation algorithm, when applied to a message using a nearly orthogonal code, should produce a result with power much lower than white noise of the actual power of the interfering signal.

Consider now how the decoding algorithm applies to a signal from a user with a different code. An appropriate way to quantify their impact is to determine the power of the signal appearing in the form W_j, at (8), which is caused by the targeted user, and compare this to the power of the signal appearing in W_j caused by the other users.

We Assume, without loss of generality, that the radius of the constellation is 1. Without loss of generality, let us assume the targeted user is using code 1 (i.e. the code which starts with symbol 1), and the interfering user uses code $j \neq 1$. In this case, (8) becomes

$$W_j = \sum_{k=1}^{\kappa} Z_{kj}\bar{\xi}_{kj},$$

which, assuming worst case zero loss for the interfering signal

$$\begin{aligned} &= \sum_{k=1}^{\kappa} S_{1j}\bar{\xi}_{kj}\xi_{k1} \\ &= S_{1j}\sum_{k=1}^{\kappa} \bar{\xi}_{kj}\xi_{k1} \\ &= S_{1j} \times (-1) \end{aligned}$$

by the near orthogonality property. Thus, the noise power due to one other user is 1. If there are n users, the power of their combined signal will therefore be n. As for the *signal*, each symbol of the chip independently communicates the original message symbol, so the strength of the signal, when we calculate the effective signal to noise ratio in this system, should be the square of $\kappa\times$ half the distance between different symbols in the constellation.

The spreading gain due to use of chips of length κ is κ, i.e. the power of the received signal is increased by the factor κ^2. On the other hand, because n users are sharing the same medium, each user must use less than the full power available, by the factor κ. Due to the arrangement of symbols in the constellation, assuming the *size* (number of symbols) of the constellation is ϕ, signal strength is not 1, but instead, $\approx \frac{1}{2}\sqrt{\pi/\phi}$. Thus, the signal power due to the whole chip is $\approx \kappa\pi/(4\phi)$. For example, if 28 symbols are used, as in the constellation shown in Figure 6, the distance to half-way between two symbols will be approximately 0.17. It follows that the SNR of a system with background noise power η and n users will be $\approx \kappa\pi/(4\phi(\kappa\eta^2 + n/\kappa))$.

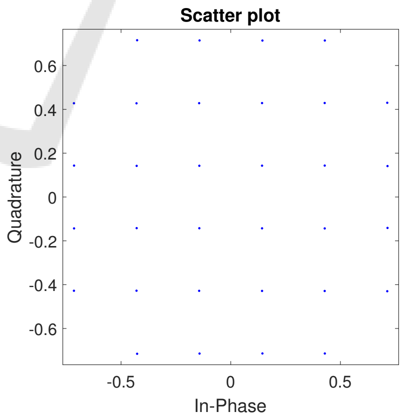

Figure 6: A QPSK constellation for SS-OFDM.

Hence the system capacity according to the Shannon-Hartley formula is

$$C \approx \frac{Bn\log_2(\phi)\log_2\left(1 + \kappa\pi/(4\phi(\kappa\eta^2 + n/\kappa))\right)}{\kappa}.$$

The total throughput achievable in this system is shown as the curve labelled `Sharing by DSSS-OFDM` in Figure 7 as a function of the number of users.

SCITEPRESS SCIENCE AND TECHNOLOGY PUBLICATIONS

In Figure 8, physical separation of domains is modelled. The the measured power due to other nearby wifi domains, is reduced by propagation loss. Hence, the power transmitted by each user can be increased, while still respecting the regulated power constraint. The ratio between the maximum power which may be transmitted when all κ users are present at the same location, and when they are so distant from each other that their power is insignificant is κ, so a "typical" situation can be modelled, simplistically, by assuming that a user can transmit at κ^α times the minimum allowed power, for $0 \le \alpha \le 1$. With this assumption, system capacity is

$$\frac{Bn\log_2(\phi)\log_2\left(1+\kappa^{1+\alpha}\pi/(4\phi(\kappa\eta^2+n\kappa^{\alpha-1}))\right)}{\kappa}.$$

The choice $\alpha = 0.5$ is plotted in Figure 8, again assuming $n = \kappa$.

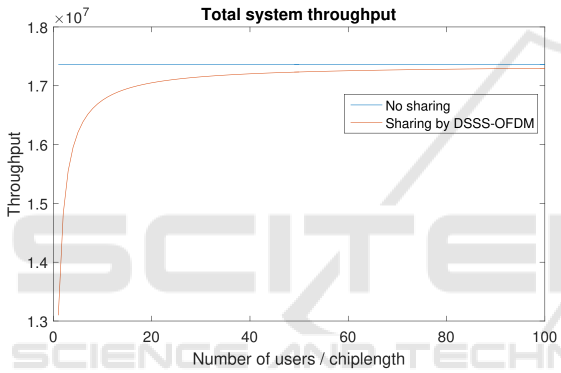

Figure 7: Throughput when users are co-located.

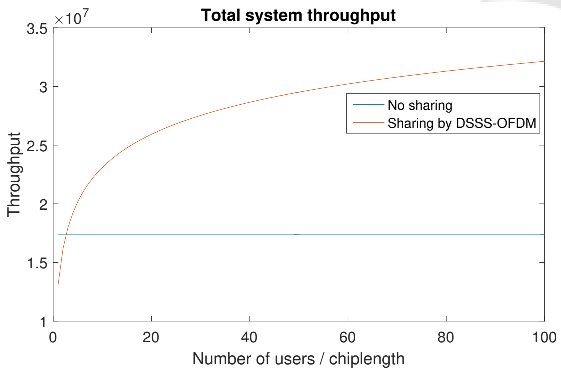

Figure 8: Throughput when users are separated ($\alpha = 0.5$).

5.8 Why $f > 2$

Let us now return to the issue of how to choose f. Traditionally, DSSS systems use code from GF(2^m). If we use a DSSS system with codes from GF(2^m) in conjunction with OFDM, the nearly orthogonal property, Proposition 1, fails, because the proof of this proposition relies on the mapping $k \mapsto z_k$, from GF(2^m) to the unit circle ($\{z : |z| = 1\}$), being a morphism, i.e. $z_k \times z_j = z_{k+j}$.

The choice $f = 2$ is only consistent with this requirement when the constellation is limited to the choices ± 1, which is not sufficient for efficient operation of OFDM.

6 AN EXPERIMENT WITH DSSS-OFDM

The DSSS-OFDM wireless communication system has been implemented in Matlab (Alhasnawi and Addie, 2018) and a number of experiments have been carried out, for different choices of f, η and constellation. Here we describe an experiment in which $f = 1023$. This experiment is sufficient to convey the key features of the system.

In this system it was found that if the number of users is less than or equal to 1000, and the constellation size was < 32, all users were able to communicate simultaneously without error; when the constellation size was increased to 60, some errors were experienced. The system implemented did not include error-correction. The main outcome of these simulations was to confirm that the system described in theory, in Section 5, can be implemented.

The background noise of this system has a standard deviation of 0.05, so the Shannon capacity is approximately 8.65 bits/s. The implemented system was transmitting at ≈ 5 bps wihout error, At higher rates (with a larger constellation), errors began to occur.

6.1 Measured User Noise

A key design objective of any spread-spectrum system is to achieve low interference between users. We can quantify this interference by the power (or standard-deviation) of the interfering signal due to the presence of other users. Confirming that user noise is at the level predicted by theory is the most critical validation to apply to an experiment of this type. Once this is confirmed, we can be confident that the theory *and* its implementation are sound.

In the experiment, the constellation size was $\phi = 60$, so signal strength is $\approx \frac{1}{2}\sqrt{\pi/(\phi\kappa)} = 0.003578853$. Note: the reduction in signal strength by $1/\sqrt{\kappa}$ is to ensure that total signal power is within the original regulated limit, as discussed in Section 5.

Given that the estimates from each symbol in the chip are *averaged*, at the detector, signal strength is still 0.003578853. The standard deviation (σ_t) of total noise in the experiment, where the chip length is 1022 and the number of users is 1000, was measured at the detector and found to be 0.0017. Background noise standard deviation was 0.05, at the point where it enters the system, so after averaging over chip symbols, this becomes $0.05/\sqrt{1022} = 0.00156$ at the detector. Taking account that the standard deviation of the symbols, in the constellation used in this system is 0.6873, the standard deviation of user noise, at the detector, predicted by theory, in this system, is $0.6873\sqrt{1000/1022}/\kappa = 0.000665$. Thus, standard deviation of total noise is expected to be $\sqrt{(0.00156^2 + 0.000665^2)} = 0.001695$ which is almost exactly the same as measured in the experiment.

These experiments confirmed that the system described in theory, in Section 5, can be readily implemented, and performs as predicted by the theory.

7 CONCLUSIONS

A communication system which combines spread-spectrum codes and OFDM with the potential to operate at optimal efficiency has been defined, implemented and tested. The system implemented uses a simple constellation of phases and amplitudes which demonstrates the operation of the proposed SS-OFDM system but without making full use of the available combinations of phase and amplitude. For this reason this system does not approach optimal efficiency. The efficiency of a similar system which *does* use a full range of phases and amplitudes has been analysed theoretically and the efficiency of this system has been estimated.

ACKNOWLEDGEMENTS

The authors are sincerely thankful to the University Southern Queensland (USQ) for providing a platform for doing this research work.Indeed, we would like to thank all the reviewers for their feedback and appreciated notices about the paper and we are happy to consider them all as they are very useful and they can refine the paper to make it very consistent and successful. The first author's is grateful also to the Ministry of Higher Education and Scientific Research of Iraq for supporting his Ph.D. study.

REFERENCES

Akare, U. P., Lande, S. B., Balpande, S., and Thakre, L. P. 2009. Performance of simulink based ss-ofdm model for broadband wireless access network. In *Emerging Trends in Engineering and Technology (ICETET), 2009 2nd International Conference on*, pages 1132–1137. IEEE.

Alhasnawi, M. K. L. and Addie, R. G. 2018. Matlab code for implementing SS-OFDM. Technical report, University of Southern Queensland.

Armstrong, J. 2009. Ofdm for optical communications. *Journal of lightwave technology*, 27(3):189–204.

Coleri, S., Ergen, M., Puri, A., and Bahai, A. 2002. Channel estimation techniques based on pilot arrangement in ofdm systems. *Broadcasting, IEEE Transactions on*, 48(3):223–229.

Jaisal, P. K. 2011. Performance of a spread spectrum ofdm system in a dispersive ifading channel with interference. *IJCST*, 2(4).

Ji, Z. and Liu, K. R. 2007. Cognitive radios for dynamic spectrum access-dynamic spectrum sharing: A game theoretical overview. *IEEE Communications Magazine*, 45(5):88–94.

Meel, J. 1999. Spread spectrum (ss). *De Nayer Instituut, Hogeschool Voor Wetenschap & Kunst*.

Pandit, S. and Singh, G. 2017. An overview of spectrum sharing techniques in cognitive radio communication system. *Wireless Networks*, 23(2):497–518.

Sung, T.-Y., Hsin, H.-C., and Cheng, Y.-P. 2010. Low-power and high-speed cordic-based split-radix fft processor for ofdm systems. *Digital Signal Processing*, 20(2):511–527.

Tu, P., Huang, X., and Dutkiewicz, E. 2006. A novel approach of spreading spectrum in ofdm systems. In *Communications and Information Technologies, 2006. ISCIT'06. International Symposium on*, pages 487–491. IEEE.

Xia, P., Zhou, S., and Giannakis, G. B. 2003. Bandwidth-and power-efficient multicarrier multiple access. *IEEE Transactions on Communications*, 51(11):1828–1837.

Xin, C. and Song, M. 2015. *Spectrum Sharing for Wireless Communications*. Springer.

Zhang, H., Chu, X., Guo, W., and Wang, S. 2015. Coexistence of wi-fi and heterogeneous small cell networks sharing unlicensed spectrum. *IEEE Communications Magazine*, 53(3):158–164.