“Advanced Wireless Connectivity"

SigNexT

Joint Constellation Multiple Access (JCMA)

This paper prepared by:

Gill R Tsouri
Assistant Professor
Rochester Institute of Technology
Department of Electrical Engineering
Senior R&D scientist at SigNexT

Dov Wulich
Professor
Ben-Gurion University of the Negev
Department of Electrical and Computer Engineering
Chief Scientist of SigNexT

www.signext.com
SigNexT Wireless Ltd., P.O. Box 94, Yavne 81101 Israel Tel: +972-8-932-7907

Table of Content

1 Proposed approach 5
1.1 Model and optimization 8
1.2 Illustrative nested QAM scenario 10
2 Decoding gain for power limited transmitters 12
3 Generating joint constellations 13
3.1 Sub-optimal BB sets 14
3.2 Nested QAM 15
4 Maximum likelihood detection 20
5 Synchronization, power control, unit failure and mobility 21
5.1 Synchronization and power control errors 22
5.2 Unit failure 26
5.3 Mobility and channel de-correlation 26
5.4 Discussion 30
6 Transmission security properties 31
6.1 Securing entire transmission bursts 31
7 Illustrative scenario – three transmitters 35
8 Summary 40
9 Refferences 41

Table of Figures

Figure 1 – The multiple access scenario 5
Figure 2 – Baseband model of JCMA 8
Figure 3 – Illustrative scenario of JCMA vs. TDMA 11
Figure 4 – Performance gain building random symbol search 15
Figure 5 – Joint constellation using random search for N=2 16
Figure 6 – Joint constellation using arbitrary symbol sets for N=2 16
Figure 7 – Joint constellation using random search for N=4 17
Figure 8 – Joint constellation using arbitrary symbol sets for N=4 17
Figure 9 – Gain in for nesting QAM joint constellation 20
Figure 10 – Single transmitter in TDMA 22
Figure 11 – Single transmitter in JCMA 23
Figure 12 – JCMA as a Shannon secrecy model 32
Figure 13 – B_d vs. B_s for various encoder efficiencies, Rayleigh fading JCMA 33
Figure 14 – Joint constellation for the three transmitters scenario 36
Figure 15 – Time diagram for JCMA vs. TDMA for the three transmitters scenario 37
Figure 16 – 8QAM constellation of TDMA reference system 38
Figure 17 – Performance curves for the three transmitters scenario 39
Figure 18 – Consecutive joint constellations of eavesdropper 40

Table of Tables

Table 1 – Nesting QAM for variable bit loading 18
Table 2 – pilot transmission for Rayleigh channel with 30
Table 3 – pilot transmission frequency for Rayleigh channel with 30
Table 4 – Reduction in required velocity for securing mobile WiMax with JCMA 34
Table 5 – LUT for ML detection of the three transmitters scenario 38

Acronyms and abbreviations

AWGN – Additive White Gaussian Noise
BB – Base-Band
BER – Bit Error Rate
BPSK – Binary Phase Shift Keying
BS – Base Station
CCDF – Complementary Cumulative Distribution Function
CDF – Cumulative Distribution Function
CDMA – Code Division Multiple Access
CRB – Cramer Rao Bound
CRC – Cyclic Redundancy Check
CSI – Channel State Information
DES - Data Encryption Standard
DF – Decode and Forward
DS – Direct Sequence
FDMA – Frequency Division Multiple Access
FEC – Forward Error correction
FH – Frequency Hopping
GPS – Global Positioning System
JCMA – Joint Constellation Multiple Access
LO – Local Oscillator
LUT – Look Up Table
M-PSK – M-ary Phase Shift Keying
MAP – Maximum A Posteriori
MF – Matched Filter
ML – Maximum Likelihood
NLoS – Non Line of Sight
OFDM – Orthogonal Frequency Division Multiplexing
OFDMA – Orthogonal Frequency Division Multiplexing Access
PDF – Probability Density Function
PLL – Phase Locked Loop
QAM – Quadrature Amplitude Modulation
QPSK – Quadrature Phase Shift Keying
QoS – Quality of Service
RSA – Rivest Shamir Adleman
RV – Random Variable
RX – central receiver unit
SM-SD – Superposition Modulation with Successive Decoding
SNR – Signal to Noise Ratio
TDMA – Time Division Multiple Access
TranSec – Transmission Security
TX – remote transmitting unit
WIPO – World Intellectual Property Organization
WSN – Wireless Sensor Networks

1 Proposed approach

A method for over-loading sub-carriers in a wireless OFDM system using superposition modulation and joint decoding is proposed. The multiple access scenario is depicted in Fig. 1.

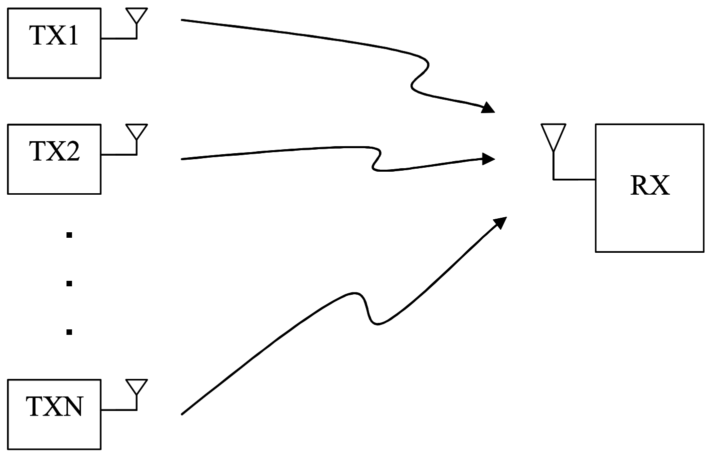


Figure 1 – The multiple access scenario

In the proposed method a sub-carrier frequency and phase of multiple transmitters are matched and synchronized with those of the receiver. All transmitters transmit together and their start of transmission is coordinated by the receiver to have their signals reach the receiver simultaneously. All transmitters use the same carrier frequency or equivalently, the same signature waveform when spectral spreading is used. The receiver is equipped with a single MF matched to this carrier frequency or signature waveform. Each transmitter is assigned a set of arbitrary BB symbols to represent its information bits and uses any type of linear modulation. Since the transmit-channel-receive path is linear, the receiver's MF output is a sum of the BB symbols of all the transmitters, and represents the transmitted bits of all the transmitters at once. The BB symbol sets are computed offline to have all their possible summations create a signal constellation which has a high resistance to noise. The receiver decodes the information bits of all the transmitters at once from a single received symbol. Since the received constellation is jointly formed by all the transmitters BB symbols, the proposed method is hereon termed JCMA.

To implement JCMA a reverse piloting protocol is defined and given below:

1. The receiver assigns *index* & *delay* parameter to each transmitter.
2. Each transmitter uses its *index* to access a predefined table for retrieving a constellation set.
3. RX sends pilot signal and starts sensing channel.
4. Each transmitter estimates channel phase and amplitude.

5. Each transmitter awaits its *delay* and sends a burst of information symbols compensated for channel phase and amplitude.
6. The receiver receives a burst of joint information symbols, which belong to its predefined joint signal set.
7. The receiver decodes all transmitters at once.
8. The receiver uses decision feedback to compensate for slow channel de-correlation in time.
9. Steps 3-8 are repeated after the channel de-correlation period has passed.

Note that in the above protocol only the receiver transmits pilots, as opposed to SM-SD where all transmitters send pilots [3].

In JCMA the overall energy collected by the receiver MF grows with the number of transmitters. It follows that the received constellation structure could grow as well and become more robust to noise. It makes sense that with the right BB symbol sets the transmitters could actually "help" each other increase their reception quality at the receiver. This intrinsic quality to JCMA is in contrast to TDMA and FDMA where the transmitters are competing over channel resources, or CDMA where the transmitters are interfering with each other.

For multiple access systems with peak power limitation on the transmitters, JCMA can be used to over-load the channel with multiple transmitters over the same OFDM sub-carriers, resulting in an increase of the ratio of energy per received joint symbol to receiver noise and an increase in spectral efficiency. Equivalently, the receiver's SNR gain can be traded for a decrease in power emissions of the transmitters.

It would be shown in following sections that the increased energy invested in the joint constellation may be translated to coding gain. It would also be shown that the decoding complexity of JCMA can be made equivalent to that of a single transmitter when using an equal rate QAM constellation. These properties make JCMA an attractive channel over-loading method for enhancing performance of OFDM based multiple access systems. It would also be shown that JCMA has intrinsic transmission security properties which allow for securing all participating transmitters from eavesdropping with no overheads on throughput, energy and computation power. These overheads are required when implementing traditional encryption methods such as RSA, DES and Diffie-Hellman key distribution algorithms.

JCMA may also be coupled with TDMA, CDMA or FDMA systems. For example, in CDMA networks signature waveforms may be shared by multiple users in a JCMA setting. The same applies to time slots in TDMA networks and carriers in FDMA.

JCMA may be viewed as superposition modulation with joint decoding. It should be distinguished from the well known SM-SD [3]. In SM-SD the transmitters transmit at the same time and frequency and a joint signal is formed at the receiver. Each transmitter's symbol is treated as noise to the other transmitters. The receiver decodes the information of each transmitter individually in a successive manner. First the transmitter with the highest received signal energy is decoded. Then the decoded bits are used as feedback to remove the transmitter signal from the received joint signal. Then the next transmitter with the highest received signal SNR is decoded, and so on. SM-SD suffers from error propagation due to the feedback of erroneous bits, and although it was proven to achieve the highest capacity [1-3] it is avoided in practical systems [3]. In addition, in SM-SD the transmitters use pilot signals to facilitate channel estimation at the receiver which compromises security.

JCMA should also be distinguished from multi-user detection [4] and rather recent advances in cooperative transmit diversity [5]. In multi-user detection the structure of the interfering signals from multiple transmitters is used to reduce its effect. The achievable gains are considerable, but it requires the use of multiple MFs and its computational complexity grows exponentially with the number of transmitters. In cooperative transmit diversity the transmitter sends its own information while relaying the information of another transmitter to the receiver. The method offers some performance gains, but the limited power of the relaying transmitter has to be distributed between the data streams of the participating nodes.

In addition to SM-SD and multi-user detection, the literature presents other approaches to channel over-loading of transmitters over the same frequency band. For example, the work in [6-8] uses symbol-synchronous superposition modulation to create a joint rectangular lattice at the receiver to support multiple transmitters using trellis codes. There are also numerous works dealing with the adder-channel for performing joint coding from multiple transmitters through super-imposed signals. In general, codebooks of individual transmitters are optimized under some criterion over the joint signal at the receiver – usually the focus is on coding gain. More relevant to the focus of this work is the work in [9,10], where the joint minimal Euclidean distance was used as the optimizing criterion of a symbol-synchronous superimposed signal. A comprehensive review of other channel over-loading techniques may be found in [11].

In contradistinction to previous work in the literature, the focus of the analysis of this work is on facilitating channel over-loading of multiple transmitters over sub-carriers in an OFDM system. The purpose of JCMA is to increase decoding gain and security strength of transmitters in an OFDM system with limited emission power, memory space and on-line computation power. Previous works found in the literature focus on capacity, coding and SNR gains, and none on security strength.

1.1 Model and optimization

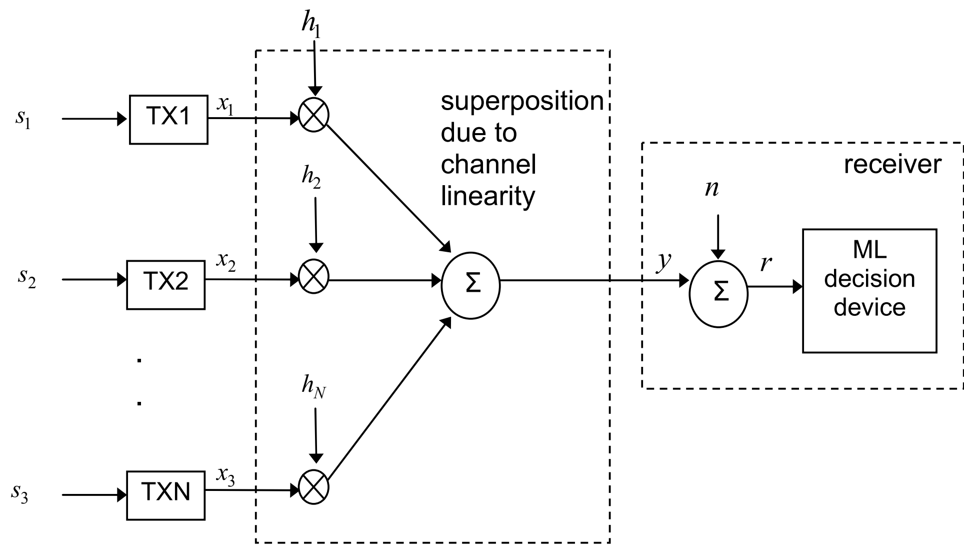


Figure 2 – Baseband model of JCMA

The BB model of the multiple access scheme is depicted in Fig. 2. $x_i; i = 1, 2, ..., N$ represent the transmitted complex BB symbols. In OFDM the channels over any single sub-carrier are flat and defined by the complex channel coefficients h_i. The transmitted symbols are summed via channel superposition and the MF result without noise is given in y. n is the BB additive white complex Gaussian noise. The received signal r is fed to a ML decision device, which evaluates all the transmitted symbols at once, as if originating from a single transmitter (the so called "super-user" in [3]).

Let us define:

$$h_i = \alpha_i \exp(j\beta_i); x_i = \frac{\exp(-j\beta_i)}{\alpha_i} s_i. \tag{1}$$

s_i is an information carrying symbol with unit energy which belongs to a predefined set S_i. It is assumed that $1/a_i$ is small enough to allow the transmitter to adjust its power within its power constraint. If this is not the case communication would be severed, as would also happen for a standard point to point scenario.

For now, it is assumed that β_i, α_i are known without error at transmitter i alone (perfect CSI), and that h_i remains constant during transmission/reception (no mobility of transmitters) – so that full synchronization is achieved between transmitters. In later sections derivations to the model are defined to analyze the effects of imperfect CSI and mobility on system performance.

It follows from (1) and Fig. 2 that

$$r = y + n = \sum_{i=1}^{N} s_i + n \tag{2}$$

The signal constellation at the receiver is made up of all the permutations in $s_i, i = 1,2,...,N$ which generate y.

$S_i; i = 1,...,N$ are sets of complex numbers, where $S_i = \left\{ s_1^i, s_2^i, ..., s_{2^M}^i \right\}$. M is the number of bits per symbol per transmitter. y is a set of complex numbers made of all possible summations of N numbers, where each number belongs to a different set S_i. $y = \left\{ y_1, y_2, ..., y_{2^{MN}} \right\}$, $y_i = \sum_{j=1}^{N} l_i^j$; $l_i^j \in S_j$ where $\left\{ l_i^1, l_i^2, ..., l_i^N \right\} \neq \left\{ l_k^1, l_k^2, ..., l_k^N \right\}$ for all $i \neq k$.

1.1.1 Finding the best BB symbol sets:

The symbol sets are determined offline and for Gaussian noise should yield the largest minimum Euclidian distance between the nearest neighbors in the joint constellation at y, under the constraint that the average energy per transmitter symbol be always less than *P* – this is the peak power constraint on transmitted power.

Finding the best BB symbol sets is formulated as follows. Given the definition:

$$d_{\min} \overset{def}{=} \min_{i \neq j} \left\{ \left\| y_i - y_j \right\|_2 \right\} \tag{3}$$

find $S_i; i = 1,...,N$ which yield $\max\left\{ d_{\min} \right\}$, under the constraint:

$$\frac{1}{2^M} \sum_{j=1}^{2^M} \left\| S_j^i \right\|_2 \leq P; P \in I, \forall i \tag{4}$$

Eq. (3), (4) are difficult to solve and no general analytical solution is available. The problem may be approached by heuristics or a random/parametric search approach. A solution derived in this manner would be sub-optimal. However, since the solution is derived off-line we may assume near infinite computation time, which would most probably result in solutions close to optimal.

1.1.2 Derive a maximum likelihood detector:

For the AWGN case ML detection translates to finding the constellation symbol g in y which has the smallest Euclidean distance from the received symbol q, so

$$g = \arg\left\{ \min_{y_i} \left(\left\| q - y_i \right\|_2 \right) \right\} \tag{5}$$

1.2 Illustrative nested QAM scenario

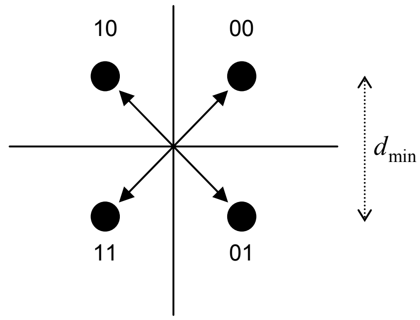
In this scenario 2 transmitters are sending data to the receiver by modulating the same carrier frequency or by using the same signature waveform. A reference case is defined where TDMA is used to access the channel where each transmitter uses a QPSK constellation. In TDMA the receiver decodes the information bits of the first transmitter from the received QPSK constellation during the first time slot and the information bits of the second transmitter from the received QPSK constellation during the second time slot. $P=1$ is assumed. The received constellation at y has $d_{\min}=\sqrt{2}$ which determines a certain performance level.

This TDMA scenario is compared to a JCMA scenario, where each transmitter is assigned an arbitrary set of 2 symbols to represent 1 information bit per symbol. Recall that in JCMA the transmitters transmit simultaneously. $S_i; i=1,2$ are arbitrarily defined to be:

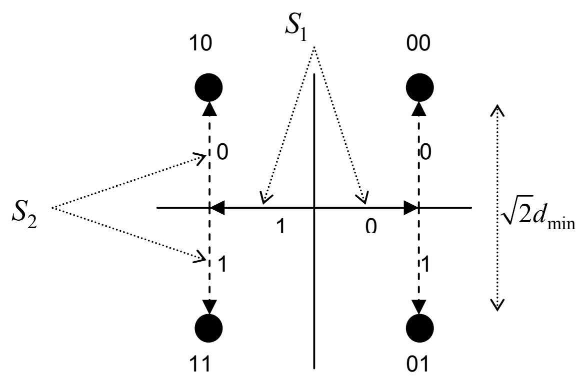
$$S_1=\{1;-1\}$$
$$S_2=\{j;-j)\} \quad (6)$$

The received constellation at y is also QPSK and the overall bit rate is the same as before. Since the individual constellations of the transmitters and the joint constellation are all BPSK and QPSK respectively, this scenario is termed nested QAM. The receiver decodes the information of both transmitters from a single constellation point. This is possible because each constellation point can be formed only by a single combination of symbols from both transmitters. The decoding complexity is the same as for the TDMA system but $d_{\min}=2$, which means performance in the presence of noise would be better. Gray coding is possible for the JCMA scenario as well.

Note that (6) meets the power constraint in (4), while the overall energy used in the JCMA system is twice that of the TDMA system. This allows for an increase in $d_{\min}$ while agreeing with the transmitters peak power constraint. See Fig. 3 for a graphic description. The JCMA symbol sets are marked with arrows and the bit assignment is cited near each symbol and constellation point.



a. TDMA constellation at y



b. JCMA constellation at y

Figure 3 – Illustrative scenario of JCMA vs. TDMA

This approach to two user QPSK constellation may be extended to any 2^M-QAM for even M. Any such constellation may be generated at the receiver by two transmitters in a JCMA setting by allocating them the following symbol sets:

$$S_1 = \{-L; -L+d; -L+2d; \ldots; L\}$$
$$S_2 = \left\{-L\exp(j\frac{\pi}{2}); (-L+d)\exp(j\frac{\pi}{2}); (-L+2d)\exp(j\frac{\pi}{2}); \ldots; L\exp(j\frac{\pi}{2})\right\} \qquad (7)$$
$$L = \sqrt{\frac{2^{(M/2-1)}(2^{M/2}-1)^2}{\sum_{i=1}^{2^{(M/2-1)}}(2i-1)^2}}; d = \frac{2L}{2^{M/2}-1}$$

The derivation of (7) is simple but tedious and is omitted for brevity. The received 2^M-QAM joint constellation would have a $d_{\min}$ larger by a factor of $\sqrt{2}$ than that of an equal rate single transmitter. Although the power constraint of each transmitter is met the overall energy spent by each transmitter is doubled compared to the TDMA system, since the transmitters transmit all the time. This is responsible for the gain in received SNR. For the chosen symbol sets the SNR gain is the same as the energy increase of each transmitter. It may be concluded that the JCMA system increased the received SNR by allowing the transmitters to use more energy without violating their power constraint. For a number of transmitters greater than 2, the symbols sets must be found using some optimization procedure. Such procedures are given in later sections.

2 Decoding gain for power limited transmitters

The overall signal energy collected by the receiver's MF in JCMA grows with the number of transmitters. However, this does not necessarily mean that performance would be enhanced. The decoding performance of ML detection in Gaussian noise is governed by the Euclidean distance between points in the constellation [12]. A key requirement for enhancing performance with JCMA is that the increased energy per joint symbol be translated to an increase in the minimal Euclidean distance. In what follows a probabilistic approach is taken to prove that this is indeed possible.

From (2)

$$y_N = \sum_{n=1}^{N} s_n \,, \tag{8}$$

where the index N is introduced to denote that y was created by N transmitters.

Assuming equal probability for each transmitted symbol per transmitter

$$\Pr\left(s_n = s_l^n\right) = 2^{-M}, \quad l = 1,2,\ldots,2^M \,. \tag{9}$$

Let μ_n and σ_n^2 denote the mean value and the variance of the random variable s_n respectively. It is assumed that the transmitters transmit independent data and therefore $\{s_n\}_{n=1}^{N}$ are mutually independent. For N sufficiently large, y_N is a complex normal random variable with mean $\mu_N = \sum_{n=1}^{N} \mu_n$ and variance

$$\sigma_N^2 = \sum_{n=1}^{N} \sigma_n^2 \,. \tag{10}$$

The following random variable is defined

$$\Delta_N \overset{def}{=} y_N^{(1)} - y_N^{(2)} \,, \tag{11}$$

where $y_N^{(1)}$ and $y_N^{(2)}$ are two received constellation points. $y_N^{(1)}$ and $y_N^{(2)}$ are independent random variables, each one having a complex normal distribution with mean μ_N and variance σ_N^2. Another random variable is defined:

$$\Delta_N^2 \overset{def}{=} \left|\Delta_N\right|^2 . \tag{12}$$

Δ_N^2 has a chi-squared distribution with two degrees of freedom and its PDF is given by [13]:

$$f_{\Delta_N^2}(x) = \frac{\exp\left(-\frac{x}{2\sigma_N^2}\right)}{2\sigma_N^2}. \quad (13)$$

Δ_N^2 is the squared Euclidean distance between two randomly chosen points from the joint constellation. It follows that for Gaussian noise Δ_N^2 governs system performance as it is directly related to BER.

In order to proceed, let us define a d_N^2 such that:

$$\Pr\left(\Delta_N^2 > d_N^2\right) = 1 - \delta, \quad (14)$$

where δ is a small positive number. Eq. (14) means the probability that the Euclidian distance between two arbitrarily chosen points from the joint constellation would be greater than d_N is very close to 1.

Let us find d_N^2 that satisfies (14). From (13)

$$\Pr\left(\Delta_N^2 > d_N^2\right) = \int_{d_N^2}^{\infty} f_{\Delta_N^2}(x)\,dx = \exp\left(-\frac{d_N^2}{2\sigma_N^2}\right). \quad (15)$$

Introducing (14) into (15) yields

$$d_N^2 = -2\sigma_N^2 \ln(1-\delta) = \sigma_N^2 \ln[(1-\delta)^{-2}]. \quad (16)$$

From (10) it follows that $\sigma_{N+1}^2 > \sigma_N^2$ therefore, from (16)

$$d_{N+1}^2 > d_N^2. \quad (17)$$

In conclusion, the minimum distance increases (in a probability sense) as N increases. Equivalently, it may be stated that the increased energy reaching the receiver can be translated to increased distance between hypotheses at the receiver. It follows that it is possible to increase overall system performance by increasing the number of power limited transmitters using the channel.

Now consider a TDMA system with power limited transmitters and the same data rate as a JCMA system. To maintain the same data rate as that of the JCMA system, the constellation of each transmitter would have to become more crowded as N increases. Because the overall constellation power remains constant, the minimal distance of the received constellation would decrease and performance would deteriorate.

3 Generating joint constellations

To find the optimal joint constellation one must solve (3), (4) analytically. The purpose is to find BB symbol sets which maximize the minimal Euclidean distance in the resulting joint symbol constellation, as was explicitly defined before. This is an optimization problem with quadratic constraint. While a closed form solution may be found with limiting assumption, this approach is avoided and sub-optimal search methods are used instead. This alternative approach is justified in this case because the optimization is done only once for a set of transmitters and is performed off-line, so there is no need for a fast real-time solution. For presentation simplicity it is assumed from now on that each transmitter has two symbols in its symbol set, which means that each transmitter has a single information bit represented in the joint constellation. To make sure no transmission power is wasted, each BB symbol set is made to be a rotated and scaled version of BPSK. This insures that the mean value of each BB symbol set and the mean value of the joint constellation are zero. The derivations that follow are easily applicable to other JCMA configurations as well.

3.1 Sub-optimal BB sets

A random search approach may be used, for which symbol sets are found using a Monte Carlo simulation. A random set of BB symbols for each transmitter is randomly generated and is normalized to meet the power constraint in (4). The resulting joint constellation is derived and its minimal Euclidean distance as defined in (3) is evaluated. This process is repeated in numerous trials and the BB sets which result in the best joint constellation is chosen. It is possible to add constraints on the BB symbol sets sizes to comply with QoS demands. In addition, the peak power constraints may vary across transmitters to address unequal channel fading attenuations which could represent near-far scenarios prevalent in multiple access scenarios. The solutions found with the random symbol search are asymptotically optimal as the number of search trials approaches infinity.

A parametric symbol search approach may be taken as well, where the phase and amplitude of each BB constellation point is quantized with some resolution. The resulting joint constellation is tested for each sample of phase and amplitude. The granularity of the parametric search increases with the quantization resolution, and the result is asymptotically optimal for infinitely small granularity.

Results

To explore the proposed approach for multiple transmitters the joint constellation for N transmitters was optimized, where each transmitter is assigned two symbols (1 information bit). The symbol sets were found using a random symbol search. For comparison a TDMA system using a 2^N-QAM constellation is used, which results in the same overall bit rate. Fig. 4 displays the gain in d_{min} for the received constellations. It is clearly seen that JCMA results in better constellations for all tested N. This result shows that the performance gain buildup proven before is achievable using the random symbol search approach.

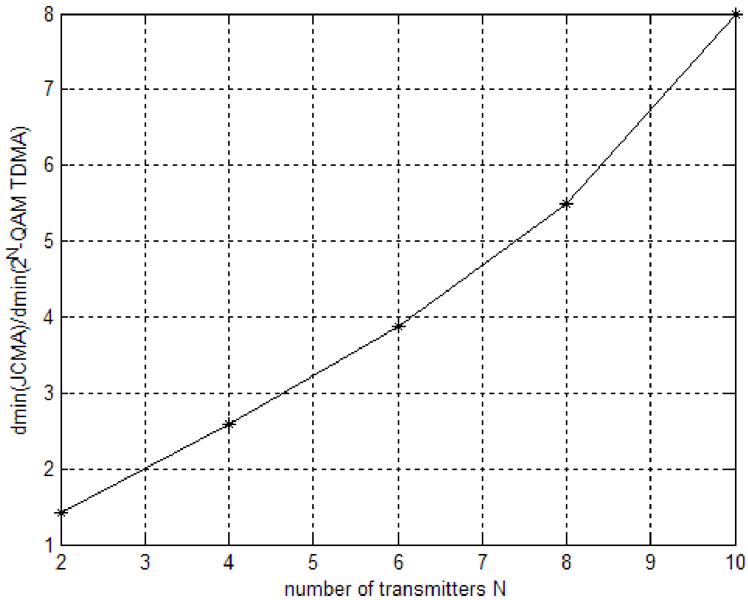


Figure 4 – Performance gain building random symbol search

Examples of joint constellations obtained via random symbol search are given in later sections.

3.2 Nested QAM

The BB symbol sets search discussed before is asymptotically optimal when system performance is considered. However, it may pose restrictions on higher layers of a JCMA system. For example, for each N the BB symbol sets are different. In accordance with the reverse piloting protocol depicted before this means that when a transmitter wishes to leave or join the JCMA system new indexes have to be passed from the receiver to the transmitters. In addition, the joint constellation has an altogether different structure for each N, forcing a different efficient ML decoding algorithm at the receiver for each N. For highly dynamic systems, where transmitters join and leave the system frequently, such restrictions may exert a high price in terms of operating and throughout overhead. In what follows, an empirical analysis of joint signal constellation is performed in order to find BB symbol sets which have the following features:

- A transmitter may leave/join the system without reassigning BB symbol sets to existing transmitters in the system.
- The joint constellation general structure remains the same for any N.

An explicit expression for generating symbol sets by nesting standard QAM constellations is derived based on the results of empirical analysis. The resulting joint constellation is 2^N-QAM, regardless of N. The performance of these joint constellations is analyzed by evaluating $d_{\min}(N)$ as was done for the random symbol search approach.

3.2.1 Empirical analysis

It is assumed that each BB symbol set is a rotated and scaled BPSK with average symbol power of less than 1. A short random symbol search is performed and the resulting joint constellation is displayed. Arbitrary symbol sets are suggested in order to resemble the random search constellation as much as possible. After numerous trials a heuristic formula for nesting QAM constellations from multiple transmitters is proposed.

For $N=2$:

A random symbol sets search yields the joint constellation in Fig. 5.

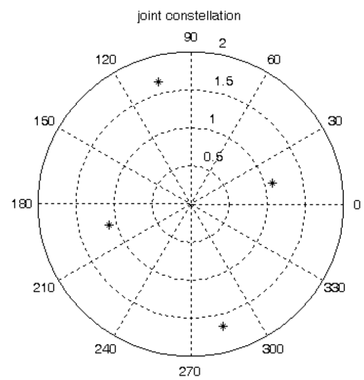


Figure 5 – Joint constellation using random search for N=2

The joint constellation exhibits a square minimal Euclidean distance of: $d^2 = 2$

Using the arbitrary BB symbol sets defined in (6) yields the joint constellation depicted in Fig. 6.

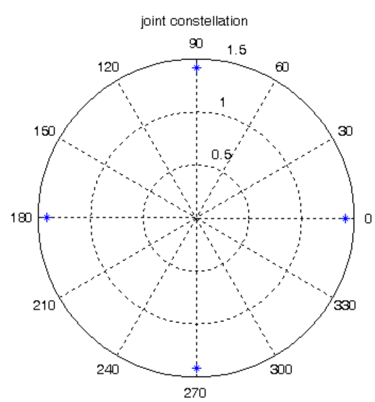


Figure 6 – Joint constellation using arbitrary symbol sets for N=2

The joint constellation exhibits: $d^2 = 2$

For N=4:

A random symbol sets search yields the joint constellation in Fig. 7.

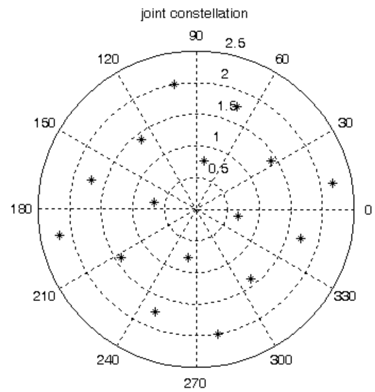


Figure 7 – Joint constellation using random search for N=4

The joint constellation exhibits: $d^2 = 1.4160$

Using the following arbitrary BB symbol sets yields the joint constellation depicted in Fig. 8.

$$\begin{aligned} S_1 &= \left\{\exp(j\,{}^1\!/_3\,\pi);\exp(j\,{}^4\!/_3\,\pi)\right\} \\ S_2 &= \left\{\exp(j\,{}^2\!/_3\,\pi);\exp(j\,{}^5\!/_3\,\pi)\right\} \\ S_3 &= \left\{\exp(j\,{}^1\!/_3\,\pi);\exp(j\,{}^4\!/_3\,\pi)\right\} \\ S_4 &= \left\{2\exp(j\,{}^2\!/_3\,\pi);2\exp(j\,{}^5\!/_3\,\pi)\right\} \end{aligned} \tag{17}$$

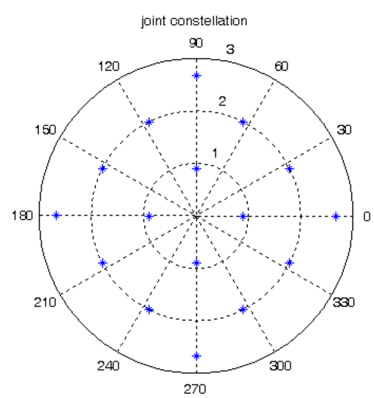


Figure 8 – Joint constellation using arbitrary symbol sets for N=4

The joint constellation exhibits: $d^2 = 1.2649$.

From these results, a heuristic symbol sets formula may be deduced:

$$S_n = [1,-1]\sqrt{\frac{d_n}{2}}\,exp(\,j\vartheta_n\,)$$
$$d_n = 2^{\left\lceil \frac{n}{2} \right\rceil -1} d\,;\,\vartheta_n = \frac{\pi}{4}\left[1-(-1)^{n+1}\right] \tag{18}$$

The symbol sets of (18) are scalable in the sense that the JCMA group size can change without reassigning new symbol sets. Also, the joint constellation is always QAM, which has low complexity ML decoding.

The nesting can accommodate variable bit loading across transmitters. The sets $S_n; n = 1,...,N$ can be allocated to L transmitters in subsets. Each subset would have L_i sets of $S_n; n = 1,...,L$ and would be allocated to a single transmitter. This means that each transmitter would have L_i bits per joint symbol. In order to achieve 2^N-QAM at the receiver, the allocation has to comply with the condition:

$$\sum_{i=1}^{L} L_i = N; L \leq N \tag{19}$$

Some examples of such allocations for $N = 6$ are demonstrated in Tab. 1.

Table 1– Nesting QAM for variable bit loading

	S_1	S_2	S_3	S_4	S_5	S_6
$L = 6, L_i = 1; \forall i$	L_1	L_2	L_3	L_4	L_5	L_6
$L = 3, L_i = 2; \forall i$	L_1		L_2		L_3	
$L = 4, L_1 = L_2 = 1, L_3 = L_4 = 1$	L_1	L_2	L_3		L_4	
$L = 2, L_1 = 2, L_2 = 4$	L_1		L_2			

3.2.2 Minimum distance buildup

To evaluate the performance of the sub-optimal nesting QAM joint constellation, its minimal Euclidean distance is compared to that of 2^N-QAM of a single transmitter. An allocation of single bit per transmitter is evaluated. The derivation is done for even and odd N separately.

Even N:

Geometrical analysis of the 2^N-QAM of a single transmitter shows that to achieve a constellation with $d_{min} = d$ the single transmitter must use the following average power:

$$P_S = \frac{1}{(N/2)}\sum_{i=1}^{N/2}\left(\frac{d}{2}+(i-1)d\right)2 = ... = \frac{d}{2}N \tag{20}$$

To achieve the same d_{min} in a JCMA nesting QAM with $L_i = 1; \forall i = 1,...,N$ the following average power across transmitters has to be used:

$$P_J = \frac{1}{(N/2)} \sum_{i=1}^{N/2} \left(\frac{d}{2} + 2^{i-1} \right) = \ldots = \frac{d}{N} \left(2^{N/2} - 1 \right) \tag{21}$$

The power gain can be defined as:

$$G_E = \frac{P_S}{P_J} = \ldots = \frac{N^2}{2\left(2^{N/2} - 1\right)} \tag{22}$$

Odd N:

Geometrical analysis obtains:

$$P_S = \frac{1}{(N/2)} \sum_{i=1}^{N/2} \left(\frac{d}{2} + (i-1)d \right) 2 = \ldots = \frac{d}{2} N \tag{23}$$

$$P_J = \frac{1}{(N/2)} \sum_{i=1}^{N/2} \left(\frac{d}{2} + 2^{i-1} \right) = \ldots = \frac{d}{N} \left(2^{N/2} - 1 \right) \tag{24}$$

The power gain can be defined as:

$$G_O = \frac{P_S}{P_J} = \ldots = \frac{N(N+1)}{3 \cdot 2^{(N+1)/2} - 4} \tag{25}$$

In both cases JCMA invests N times more energy. Energy loss is given by:

$$L_S = \frac{1}{N} \tag{26}$$

It may be stated that using nesting QAM with the chosen allocation achieves the power gain for the price of the energy loss. The power gain is depicted in Fig. 9. It is clearly seen that the exponential gain in performance achieved by the random symbol search approach are unattainable for large N. Rather, the gain increases up to $N = 4$ and then decreases until performance is actually worse than that of a single transmitter for $N > 9; N > 13$ for odd and even N respectively. Note that the gain is substantially larger for even N. It may be stated that for $N > 4$ the invested energy doesn't translate to better performance.

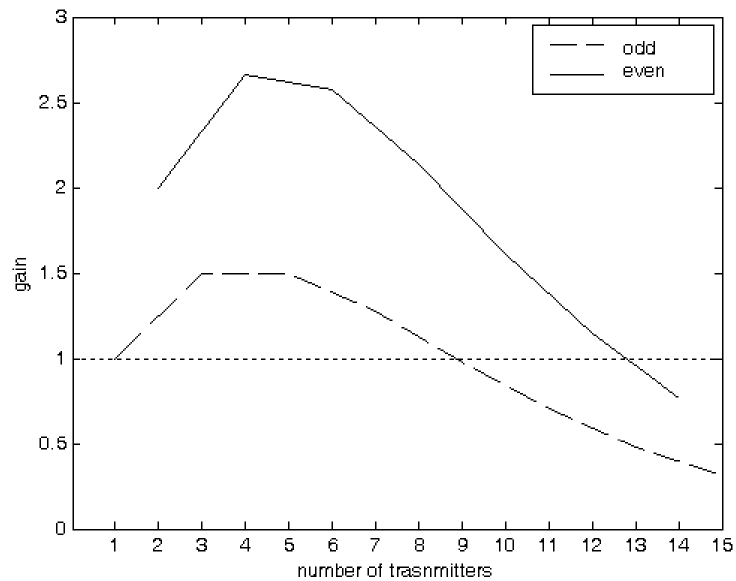


Figure 9 – Gain in for nesting QAM joint constellation

4 Maximum likelihood detection

The received joint signal sample at the MF output has to be decoded based on the expected joint constellation using ML detection. ML detection in the presence of Gaussian noise boils down to finding the constellation point which is closest to the received sample (in the Euclidean distance sense). Performing ML detection using exhaustive search over all possible constellation points has algorithmic complexity of $O(2^N)$. This complexity grows exponentially with the number of transmitters to a point where it might be impractical to implement on-line. This complexity problem exists for any single transmitter user constellation with 2^N constellation points. Traditionally, for single transmitters, the decoding complexity is reduced by using sub-optimal constellations such as 2^M -QAM. These constellations exhibit structural symmetries which are used for efficient decoding of the received samples [14].

The JCMA constellation exhibits structural symmetries as well. The received joint symbol may be written as

$$y_N = s_i + \sum_{\substack{n=1 \\ n \neq i}}^{N-1} s_n ; \forall i . \qquad (27)$$

Symmetry lines may be drawn between the BB symbols of s_i shifted to $\sum_{\substack{n=1 \\ n \neq i}}^{N-1} s_n$. If the symmetry lines are drawn for all $i = 1,\dots,N$ symbol sets the receiver's observation space is divided to decision

regions with a constellation point at the center of each region. The ML decoding problem reduces to finding the decision region in which the received sample is located.
Assuming the angles of the symmetry lines with the *real* axis value in the complex place are given by $\varphi_i ; i = 1,...,N$, the following guidelines for finding a computationally efficient ML decoding algorithm are defined:

1. Rotate the received joint symbol sample r by an angle of φ_1: $q = r\exp(-j\varphi_1)$.
2. If $q_R = real(q)$ is to the right of the symmetry line intersection with the *real* axis set $L_i = 1$, else set $L_i = 0$.
3. Repeat steps 1,2 for all *i*.
4. Use $L_i ; i = 1,...,N$ to access a predefined LUT containing the bit loading of the constellation point in the decision region of the received sample.

The algorithmic complexity of the suggested efficient ML decoding is $O(N)$. This is also the complexity of traditional 2^N-QAM ML decoding of a single transmitter with equal rate to a JCMA system with N transmitters and 1 bit per symbol per transmitter.

5 Synchronization, power control, unit failure and mobility

JCMA requires synchronization between the transmitters at the symbol level. This is a higher synchronization demand than that of TDMA for example. Systems with equivalent synchronization demands as those of JCMA are symbol-synchronous CDMA [4, 15] and SM-SD [3]. In addition, JCMA demands a higher accuracy in power control. In this chapter the effects of synchronization errors, power control errors and mobility are analyzed for the JCMA system.
Lack of perfect synchronization may be represented by errors in the channel phase estimates, and inaccurate power control may be represented by errors in the channel amplitude estimate. It follows that both may be modeled by an additive complex RV representing an error in the channel estimate (CSI errors). The effects of CSI errors (phase and amplitude) on system performance are analyzed in a comparative manner to TDMA. Specifically, the required energy of the JCMA receiver sent pilot signal is found with respect to that of a TDMA system, so that the JCMA system performance loss would be the same as the TDMA system performance loss. This analysis results in a quantitative estimate of the effects of synchronization and power control errors, and the required system resources needed to support the synchronization demands of the JCMA system (pilot energy). In addition, the probability of transmitter failure to compensate for the fading channel receives attention as well.
A key issue in channel estimation is its validity over time. The fading channel changes constantly (de-correlates over time), but is considered to be constant for short periods of time – the channel coherence time. The coherence time depends on the Doppler spread of the channel, which is a function of the changing environment and the mobility of the transmitters relative to the BS. The

channel must be estimated at a rate of the order of the reciprocal of the channel coherence time. The exact rate is set according to the tolerated channel de-correlation for reliable communications and depends on system requirements. In what follows the rate of pilot transmission for a JCMA system is calculated to achieve the same channel de-correlation as for a TDMA system. This analysis results in a quantitative estimate of the effects of mobility of transmitters, and the required system resources to support such mobility (throughput loss due to pilot signal transmission).

If both synchronization/power control errors and channel de-correlation of JCMA can be reduced to have the same system performance loss as for the TDMA system by adjusting only the pilot signaling, then performance gain of JCMA for payload transmission would be unhindered.

5.1 Synchronization and power control errors

TDMA case

The TDMA BB model for a single transmitter (indexed *i*) with CSI errors and power control is depicted in Fig. 10:

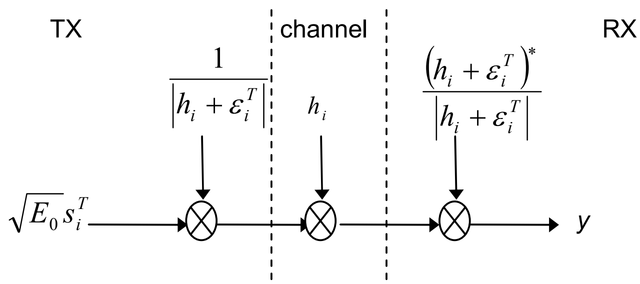


Figure 10 – Single transmitter in TDMA

where E_0 is the energy per symbol needed at the receiver to achieve a certain performance level, h_i is the, complex valued, channel fading coefficient, s_i^T is the TDMA symbol and ε_i^T is the channel estimation error. ε_i^T is usually modeled as a complex normal random variable with zero mean and arbitrary variance [16-21]. It is common practice to choose $\mathrm{var}(\varepsilon_i^T)=\delta\,\mathrm{var}(h_i)$ with $\delta=0.1, 0.01, 0.001$. ε_i^T is uncorrelated with h_i.

At RX the channel is estimated and compensated for phase by an erroneous estimate of the channel $\frac{(h_i+\varepsilon_i^T)^*}{|h_i+\varepsilon_i^T|}$. The channel estimated at RX is fed back to the transmitter for allowing the transmitter to compensate for channel fading before performing power control. It is assumed this is done without error. $\frac{1}{|h_i+\varepsilon_i^T|}$ represents the TX compensation for fading.

Power control is achieved by setting $\sqrt{E_0}$ and compensating for the fading $|h_i|$. It follows that:

$$y = \sqrt{E_0} s_i^T \frac{h_i}{\left(h_i + \varepsilon_i^T\right)} \quad (28)$$

Since channel estimation has to be fairly accurate, the pilot energy is such that high SNR is achieved for channel estimation. It follows that ε_i^T is expected to be much smaller in magnitude than h_i and it may be assumed that $\Pr\left(|h_i| << |\varepsilon_i|\right) \approx 1$. Using this assumption (28) reduces to:

$$y = \sqrt{E_0} s_i^T h_i \left(\frac{1}{h_i \left(1 + \frac{\varepsilon_i^T}{h_i}\right)} \right) \approx \sqrt{E_0} s_i^T h_i \frac{1}{h_i} \left(1 - \frac{\varepsilon_i^T}{h_i}\right) = \sqrt{E_0} s_i^T - \sqrt{E_0} s_i^T \frac{\varepsilon_i^T}{h_i} \quad (29)$$

The term $z^T \overset{def}{=} \sqrt{E_0} s_i^T \frac{\varepsilon_i^T}{h_i}$ represents the synchronization error and its variance is with relation to δ.

JCMA case

The JCMA BB model for a single transmitter with CSI errors and power control is depicted in Fig. 11:

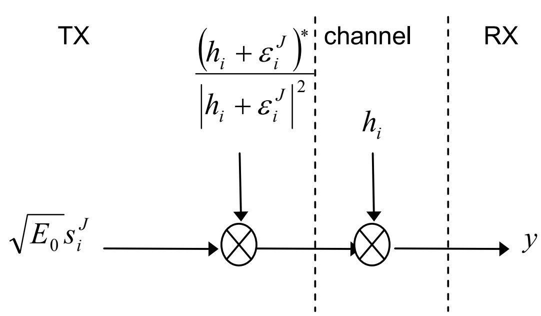


Figure 11 – Single transmitter in JCMA

where s_i^J and ε_i^J are the JCMA transmitted symbol and channel estimation error of transmitter i respectfully.

Here the channel is estimated at TX alone and is compensated prior to transmission. In the same manner as in (29) it follows that for single transmitter:

$$y = \sqrt{E_0} s_i^J \frac{\left(h_i + \varepsilon_i^J\right)^* h_i}{\left|h_i + \varepsilon_i^J\right|^2} = \sqrt{E_0} s_i^J \frac{h_i}{\left(h_i + \varepsilon_i^J\right)} \approx \ldots \approx \sqrt{E_0} s_i^J + \sqrt{E_0} s_i^J \frac{\varepsilon_i^J}{h_i} \quad (30)$$

The synchronization error of a single transmitter in JCMA $z^J \overset{def}{=} \sqrt{E_0} s_i^J \frac{\varepsilon_i^J}{h_i}$ has the same statistics as that of TDMA.

Now consider the entire JCMA system:

$$y = \sum_{i=1}^{N} \left(\sqrt{E_0} s_i^J + \sqrt{E_0} s_i^J \frac{\varepsilon_i^J}{h_i} \right) = \sum_{i=1}^{N} \left(\sqrt{E_0} s_i^J \right) + \sum_{i=1}^{N} \left(\sqrt{E_0} s_i^J \frac{\varepsilon_i^J}{h_i} \right) \quad (31)$$

The JCMA synchronization error is $Z^J \overset{def}{=} \sum_{i=1}^{N} \left(\sqrt{E_0} s_i^J \frac{\varepsilon_i^J}{h_i} \right)$.

The estimation errors $\varepsilon_i^J ; i = 1,2,...,N$ are uncorrelated and identically distributed. The same is true for the channels h_i and information symbols s_i^J. It follows that:

$$\mathrm{var}\left(Z^J\right) = N \,\mathrm{var}\left(z^J\right) \quad (32)$$

The channel is estimated at TX using a pilot signal from RX. Channel estimation using pilot signaling is well established in theory and practice [16-21], and it may be assumed that an "efficient estimate", as defined in [22], is used. This means that the CRB for the channel estimation error is achievable. In what follows the CRB is used as the error variance for ML estimation.

For now it is assumed that all transmitters are able to compensate for the channel fading $|h_i|$ with their limited peak power. This means that $|h_i|$ is higher than some threshold value. If $|h_i|$ falls beneath this threshold the transmitter fails to compensate for it and the connection between this transmitter and the receiver cannot be maintained. This phenomenon occurs in all multiple access methods in fading channels and is usually solved at a high level protocol. In cellular telephony, for example, a failing transmitter roams to a different BS for service. In JCMA the failing of a single transmitter affects all other transmitters. This issue is addressed later on.

5.1.1 Rayleigh fading with MAP estimation

The CRB for efficient MAP (and ML) estimation of a parameter with Gaussian distribution is given by [22, p. 273]:

$$var(\varepsilon) = var(h)\left(1 + \frac{2\,var(h)E_p}{N_0}\right)^{-1} \quad (33)$$

where E_p is the energy of the pilot symbol, and N_0 is the AWGN noise variance. The Gaussian case fits channel estimation in a Rayleigh fading channel (in-phase and quadrature estimates separately).

It is now possible to calculate the needed increase in pilot energy for JCMA in order to achieve the same synchronization/power control error as that of TDMA. For this the error variances must be equated:

$$\mathrm{var}\left(Z^J\right) = \mathrm{var}\left(z^T\right) \tag{34a}$$

$$N\,\mathrm{var}\left(z^J\right) = \mathrm{var}\left(z^T\right) \tag{34b}$$

Equivalently, in accordance with (29), (30):

$$N\,\mathrm{var}\left(\sqrt{E_0}\,s_i^J\,\frac{\varepsilon_i^J}{h_i}\right) = \mathrm{var}\left(\sqrt{E_0}\,s_i^T\,\frac{\varepsilon_i^T}{h_i}\right). \tag{34c}$$

$s_i^J, \varepsilon_i^J, s_i^T, \varepsilon_i^T, h_i; i = 1,\dots,N$ are all uncorrelated and have zero mean, so (34c) may be written as

$$NE_0E\left(\left|s_i^J\right|^2\right)E\left(\left|\varepsilon_i^J\right|^2\right)E\left(\left|\frac{1}{h_i}\right|^2\right) = E_0E\left(\left|s_i^T\right|^2\right)E\left(\left|\varepsilon_i^T\right|^2\right)E\left(\left|\frac{1}{h_i}\right|^2\right). \tag{34d}$$

Note that $E\left(\left|\frac{1}{h_i}\right|^2\right)$ exists and is finite because it is assumed that the transmitter can compensate for it, so $\left|h_i\right|^2$ is higher than some threshold. According to the peak power constraint: $E\left(\left|s_i^J\right|^2\right) = E\left(\left|s_i^T\right|^2\right)$ and (34d) reduces to:

$$NE\left(\left|\varepsilon_i^J\right|^2\right) = E\left(\left|\varepsilon_i^T\right|^2\right) \tag{34e}$$

Now using (33):

$$N\,var(h)\left(1+\frac{2*var(h)E_p^J}{N_0}\right)^{-1} = var(h)\left(1+\frac{2*var(h)E_p^T}{N_0}\right)^{-1} \tag{35}$$

It is expected that the pilot energy would be such that channel estimation would take place in high channel SNR (high pilot energy), so the following assumption is valid:

$$\frac{var(h)E_p^J}{N_0} >> 1;\quad \frac{var(h)E_p^T}{N_0} >> 1 \tag{36}$$

Using (36) in (35) reduces to the compact expression:

$$E_p^J = NE_p^T \tag{37}$$

Relating back to the reverse piloting protocol (37) gives the required energy of the JCMA pilot signal sent by the receiver to achieve the same overall system performance degradation, as for an equivalent TDMA system.

5.1.2 ML estimation for any flat fading channel

In the same manner as before, using the CRB for efficient ML estimation of any flat fading channel with additive Gaussian noise results with:

$$var(\varepsilon) = var(h)\left(\frac{2 * var(h) E_p}{N_0}\right)^{-1}, \quad (38)$$

Which is the same as MAP CRB given in (33) for high pilot signal SNR at the receiver. So the result in (37) holds for ML estimation of any type of flat fading channel.

5.2 Unit failure

A key feature in JCMA is that the joint constellation is formed by all the transmitters at once. This means that if a single transmitter fails the whole constellation breaks down. This comes in contrast to TDMA, for example, where transmitter failure wouldn't affect the other transmitters. SM-SD, however, would break down as well if a single unit fails. Unit failure can take two forms: (i) a transmitter can fail due to technical reasons, (ii) alternatively, it may experience a channel with strong fading, which cannot be compensated for by its limited peak power.

It is reasonable to assume that the JCMA receiver would become aware of a constellation breakdown very fast, since all decoded transmitters streams would exhibit consecutive errors. Knowledge of decoding errors may be acquired from higher level protocols, for example through the popular CRC.

Assume the probability for unit failure of any type for a TDMA system is p_f^T. The probability of no unit failure would be $p_{nf}^T = 1 - p_f^T$. This is also the probability of unit failure for a single JCMA transmitter ($N = 1$).

In JCMA all N transmitter must not fail together. It follows that the non-failure probability for a JCMA transmitter for any N is given by:

$$p_f^J = 1 - \left(p_{nf}^T\right)^N \quad (39)$$

Using a Taylor expansion series around $p_{nf}^T = 1$ results in [23]:

$$p_f^J = N\left(1 - p_{nf}^T\right) - \underbrace{0.5N(N-1)\left(p_{nf}^T\right)^{N-2}\left(p_f^T\right)^2}_{remainder} \quad (40)$$

The second term in (40) may be neglected for $p_f^T << 1$ and moderate N, resulting in:

$$p_f^J \approx N p_f^T \quad (41)$$

Eq. (41) means that the probability for unit failure experiences linear increase with N. For very small p_f^T, this probability rises one order for $N > 10$.

5.3 Mobility and channel de-correlation

Channel de-correlation manifests itself in a shift of the transmitted constellation points from their original position. The probability for a more significant shift increases as time passes from the last channel estimation time (pilot transmission time). It follows that channel de-correlation may be evaluated by deriving the expected shift of a constellation point over time.

A closely related approach is used when evaluating transmitter performance in the presence of linear and non-linear distortions using EVM [24-26]. EVM is defined as the normalized variance of a random additive error to the constellation points. EVM is a well founded parameter used to characterize the quality of communication links and is closely related to BER [24-26].

An EVM like approach is used here for JCMA. Disregarding the additive noise and errors in the channel estimate at the receiver, the received constellation points of any communication system are supposed to remain constant over time. However, as the channel de-correlates the points shift randomly, due to a discrepancy between the last channel estimate and the true value of the time-varying channel. Variances of the constellation points shifts over time for TDMA and JCMA are derived, compared and discussed.

The shift of a specific constellation point over time is a stochastic process defined as:

$$\Delta y_0(t) = y_0(t) - y_0(t_0) \tag{42}$$

where $t_0 \le t$ is the last time the channel was estimated (a pilot signal was sent) and $y_0(t_0) \in y$, where y denotes the constellation set. For ease of notation the ^{J} index is dropped from the following derivation. There is a one to one mapping between $\underline{x} \equiv [x_1, x_2, \ldots x_N]; x_i \equiv s_i h_i(t_0)$ and $y_0(t)$ given by:

$$y_0(t) = \sum_{i=1}^{N} [x_i h_i(t)]. \tag{43}$$

It follows that:

$$\Delta y_0(t) = \sum_{i=1}^{N} [x_i h_i(t)] - \sum_{i=1}^{N} [x_i h_i(t_0)] = \sum_{i=1}^{N} [x_i (h_i(t) - h_i(t_0))] \tag{44}$$

In a classical EVM approach the variance of $\frac{\Delta y_0(t)}{\max\limits_{y_0(t_0)}\left(|y_0(t_0)|^2\right)}$ should be averaged over all points in the constellation. Because the focus of analysis is performance degradation of a communication link due to channel de-correlation, it would be biased in favor of JCMA to normalize $\Delta y_0(t)$, since higher overall energy is invested in the JCMA constellation. In the following analysis the conditional variance of $\Delta y_0(t)$ is evaluated without normalization and then averaged over all points in the constellation.

$$E(\Delta y_0(t)|\underline{x}) = \sum_{i=1}^{N} [x_i (E(h_i(t)) - E(h_i(t_0)))] = 0 \tag{45a}$$

$$\begin{aligned} var(\Delta y_0(t)|\underline{x}) &= E\left(\left|(\Delta y_0(t)|\underline{x}\right|^2\right) = E\left(\{[y_0(t) - y_0(t_0)][y_0(t) - y_0(t_0)]^*\}|\underline{x}\right) \\ &= E\left(\left|(y_0(t)|\underline{x}\right|^2\right) + E\left(\left|(y_0(t_0)|\underline{x}\right|^2\right) - E\left(\{y_0(t) y_0^*(t_0)\}|\underline{x}\right) - E\left(\{y_0(t_0) y_0^*(t)\}|\underline{x}\right) \end{aligned} \tag{45b}$$

$$E\left(\left|y_0(t)\right|\underline{x}\right|^2\right)=E\left(\sum_{i=1}^{N}\left[x_i h_i(t)\right]\sum_{j=1}^{N}\left[x_j^* h_j^*(t)\right]\right)=\sum_{i=1}^{N}\left[\sum_{j=1}^{N}\left[x_i x_j^* E\left(h_i(t)h_j^*(t)\right)\right]\right] \qquad (46)$$

The channels are i.i.d, therefore:

$$E\left(\left|y_0(t)\right|\underline{x}\right|^2\right)=\sum_{i=1}^{N}\left(\sum_{j=1}^{N}\left(x_i x_j^* \delta_{i,j} var(h)\right)\right)=var(h)\sum_{i=1}^{N}\left(\left|x_i\right|^2\right), \qquad (47)$$

where $var(h) \equiv E\left(\left|h_i(t)\right|^2\right)$ for all (i,t).

$$\begin{aligned}E\left(\left\{y_0(t)y_0^*(t_0)\right\}\middle|\underline{x}\right)&=E\left(\sum_{i=1}^{N}\left[x_i h_i(t)\right]\sum_{j=1}^{N}\left[x_j^* h_j^*(t_0)\right]\right)=\sum_{i=1}^{N}\left(\sum_{j=1}^{N}\left(x_i x_j^* E\left(h_i(t)h_j^*(t_0)\right)\right)\right)\\&=\sum_{i=1}^{N}\left(\left|x_i\right|^2 E\left(h_i(t)h_i^*(t_0)\right)\right)=\sum_{i=1}^{N}\left(\left|x_i\right|^2 R(t)\right)\end{aligned} \qquad (48a)$$

where $R(t) \overset{def}{=} E\left(h_i(t)h_i^*(t_0)\right)$ is the channel autocorrelation function and depends on the channel fading statistics. Notice that since the in-phase and quadrature components of all channels are uncorrelated $R(t)$ is a real function and therefore $R(t)=E\left(h_i(t)h_i^*(t_0)\right)=E\left(h_i(t_0)h_i^*(t)\right)$. It follows that:

$$E\left(\left\{y_0(t_0)y_0^*(t)\right\}\middle|\underline{x}\right)=\sum_{i=1}^{N}\left(\left|x_i\right|^2 R(t)\right). \qquad (48b)$$

Using (47) ,(48a) ,(48b) in (45b) yields:

$$\operatorname{var}\left(\Delta y_0^J(t)\middle|\underline{x}^J\right)=2\sum_{i=1}^{N}\left(\left|x_i^J\right|^2\right)\left(\operatorname{var}(h)-R(t)\right)\overset{def}{=}\operatorname{var}\left(\Delta y_0^J(t)\right) \qquad (49)$$

where the ^{J} index was reintroduced.

For TDMA this variance is given by:

$$\operatorname{var}\left(\Delta y_0^T(t)\middle|x_i^T\right)=\operatorname{var}\left(\Delta y_0^J(t)\middle|\underline{x}^J\right)_{N=1}=2\left|x_i^T\right|^2\left(\operatorname{var}(h)-R(t)\right), \qquad (50)$$

where $x_i^T \equiv s_i^T h_i(t_0)$. Obviously, $\operatorname{var}\left(\Delta y_0^T(t)\right)<\operatorname{var}\left(\Delta y_0^J(t)\right)$ and $\operatorname{var}\left(\Delta y_0^J(t)\right)$ increases with N. It is easy to show that if normalization of $\frac{\Delta y_0(t)}{\left|y_0(t_0)\right|^2}$ was initially introduced to (45b), the result would have been the same for TDMA and JCMA.

It may be stated that JCMA performance is more sensitive to channel de-correlation. Or equivalently, in JCMA the channel coherence time becomes effectively smaller as N increases.

To achieve the same performance loss as that of a TDMA system, (49) and (50) should be equated. This can be achieved if the JCMA pilots are transmitted more frequently than those of TDMA. Assuming t_p^J and t_p^T are the time passed between consecutive pilots in JCMA and TDMA respectfully:

$$\operatorname{var}\left(\Delta y_0^T\left(t_p^T\right)\middle|x_i^T\right)=\operatorname{var}\left(\Delta y_0^J\left(t_p^J\right)\middle|\underline{x}^J\right) \qquad (51)$$

Now, using (49) and (50) in (51):

$$2\left|x_i^T\right|^2\left(\mathrm{var}(h)-R\left(t_p^T\right)\right)=2\sum_{i=1}^{N}\left|x_i^J\right|^2\left(\mathrm{var}(h)-R\left(t_p^J\right)\right) \qquad (52)$$

The solution to (52) depends on the channel fading instance and the symbols being transmitted. Averaging over all channel instances and symbol types on both sides of (52) gives:

$$2E\left(\left|x_i^T\right|^2\right)\left(\mathrm{var}(h)-R\left(t_p^T\right)\right)=2\sum_{i=1}^{N}E\left(\left|x_i^J\right|^2\right)\left(\mathrm{var}(h)-R\left(t_p^J\right)\right) \qquad (53a)$$

$$E\left(\left|s_i^T\right|^2\right)E\left(\left|h_i\right|^2\right)\left(\mathrm{var}(h)-R\left(t_p^T\right)\right)=\sum_{i=1}^{N}\left[E\left(\left|s_i^J\right|^2\right)E\left(\left|h_i\right|^2\right)\right]\left(\mathrm{var}(h)-R\left(t_p^J\right)\right) \qquad (53b)$$

$E\left(\left|s_i^T\right|^2\right)=E\left(\left|s_i^J\right|^2\right), E\left(\left|h_i\right|^2\right)=\mathrm{var}(h)$ for all i, so (53b) reduces to:

$$R\left(t_p^J\right)=\frac{R\left(t_p^T\right)+\mathrm{var}(h)(N-1)}{N} \qquad (53c)$$

For practical t_p^J and t_p^T, $R\left(t_p^J\right)$ and $R\left(t_p^T\right)$ are monotonic decreasing functions until full decorrelation is reached, so if the inverse of (53c) is taken and noting that $R(t=0)=var(h)$:

$$t_p^J=R^{-1}(\eta)$$
$$\eta=\frac{R\left(t_p^T\right)+R(0)(N-1)}{N} \qquad (54)$$

Now for a given $R(t)$, t_p^J may be explicitly derived based on a TDMA reference system with given t_p^T. Using t_p^J guarantees that the performance degradation due to channel de-correlation and mobility of the JCMA system would be the same as that of the TDMA reference system. $t_p^J < t_p^T$ means more overhead for pilot retransmission. It is shown in a later chapter that this shortening of effective channel coherence time proves to be beneficial when security is considered.

5.3.1 Rayleigh fading channel

For the Rayleigh fading channel [27]:

$$R(t)=var(h)J_0\left(2\pi f_d t\right), \qquad (55)$$

where $J_0(\cdot)$ is the zero order Bessel function of the first kind, and f_d is the maximum Doppler shift.

Example 1:

For $f_d=10Hz$ - equivalent to transmitters mobility of up to 5km/h relative to the receiver [28], $var(h)=1$ and assuming $R\left(t_p^T\right)=0.99$ is tolerated, $t_p^T=3.2\mathrm{msec}$ is obtained. It follows that $\eta=\frac{0.99+(N-1)}{N}$. See Tab. 2 for results of t_p^J for various N.

Table 2 – pilot transmission for Rayleigh channel with

N	1	2	3	4	5
$t_p^J\,[m\,sec]$	2	2.25	1.82	1.57	1.42
$\frac{t_p^T}{t_p^J}$ (transmission rates ratio)	1	1.42	1.76	2.04	2.25

Notice that even for $N=5$ the JCMA system has to transmit only about two times more pilots.

Example 2:

For $f_d = 100\text{Hz}$ - equivalent to transmitters mobility of up to 50km/h relative to the receiver, $var(h)=1$ and assuming $R\left(t_p^T\right)=0.99$ is tolerated, $t_p^T = 316\mu\text{sec}$ is obtained. See Tab. 3 for results of t_p^J for various N.

Table 3 – pilot transmission frequency for Rayleigh channel with

N	1	2	3	4	5
$t_p^J\,[\mu\text{sec}]$	316	220	178	150	135
$\frac{t_p^T}{t_p^J}$ (transmission rates ratio)	1	1.44	1.78	2.11	2.34

Notice that even for $N=5$ the JCMA system has to transmit only about two times more pilots.

5.4 Discussion

Equation (37) means that in order to achieve the same synchronization/power control error in a JCMA system with N transmitters as that of a TDMA system, the pilot energy used for channel estimation must have N times more energy. This increase in energy can be achieved by using longer pilots resulting with decreased throughput or by increasing pilot signal power.

In JCMA the receiver is a central unit and as such it is expected too have more transmission power than that of the transmitters (consider for example a cellular telephony cell with distributed units and a base station). It follows that the receiver could be able to increase pilot energy by also increasing pilot power rather than just pilot duration, resulting in less overhead on system throughput.

Most multiple access systems circumvent the need for synchronizing transmitters by having the transmitters transmit a packet made of a pilot signal and data. In cases where the transmitters have to make use of channel CSI (power control in TDMA for example), the channel estimates have to be fed back to them by the receiver without error. The JCMA system is relieved of such constraints. The channels are estimated at the transmitters and there is no need for feedback. The use of pilots by the transmitters makes the system vulnerable to eavesdropping.

The JCMA system was shown to effectively shorten the channel coherence time. This results in a need for more frequent pilot transmission. The Rayleigh fading examples show that for up to 5 transmitters about twice as much pilots are needed in JCMA compared to TDMA. As far as security is concerned the shortening of channel coherence time could be a benefit. This is because faster variation in the channel allows for a higher cryptographic key generating rate.

6 Transmission security properties

In JCMA the joint constellation at the receiver's MF output is the result of a coherent sum of the transmitters BB symbols and is unique to the position of the receiver in space. This is achieved due to the compensation of delay, phase and attenuation of each transmitter to receiver channel. Since an eavesdropper would have to occupy a different position in space, the transmitters BB symbols would create an incoherent sum at its MF output. This is practically always true even when the eavesdropper is close to the receiver, because the wireless channel de-correlates fast in space after a few carrier wavelengths which is a distance on the order of centimeters for frequencies of the order of GHz [29].

In accordance with the reverse piloting protocol, the transmitters use no pilot signals when forming the joint constellation. It follows that the eavesdropper would be blind to the structure of the joint constellation formed at its point in space. Its joint constellation would have sub-optimal structure and would change at a rate of the order of the channel de-correlation time (due to different compensation performed at the transmitters). In addition, the signals from the transmitters wouldn't reach the eavesdropper simultaneously. To summarize, the eavesdropper would have to decode the information based on a deteriorated joint signal constellation and its decoding complexity would be much higher than that of the receiver. It may be stated that JCMA uses the randomness of the wireless channel to jointly encrypt the transmitters' data symbols. Since N random channels take part in the process, security strength is expected to increase with the number of transmitters. Note that there is no need for a random key generator, no need to sacrifice bandwidth or data rate for key distribution, and no need to devote online computation power for encrypting and decrypting.

In this section the security strength increase due to JCMA is quantified for securing transmission bursts in a point to point scenario. In addition, other security factors unique to JCMA are described and analyzed. It is shown that JCMA encryption capabilities grow with N.

6.1 Securing entire transmission bursts

The JCMA BB model may also be viewed as a Shannon secrecy model. Fig. 12 depicts the secrecy model for an eavesdropper.

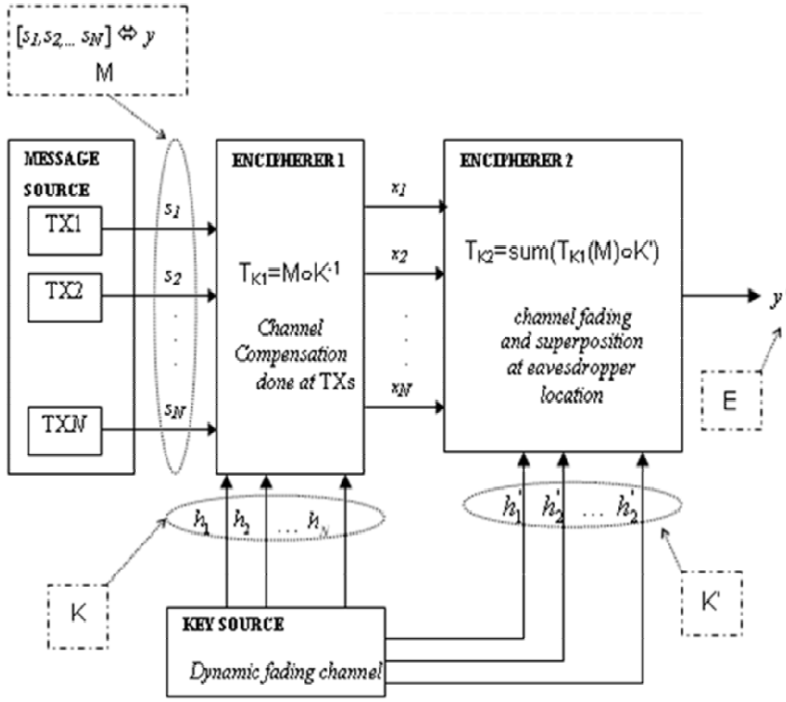


Figure 12 – JCMA as a Shannon secrecy model

The pilot from the receiver invokes key generation and distribution from the wireless medium to the transmitters. This key is the channel estimation at the transmitters. It is unique and is known exclusively at each transmitter. The message M is the vector of transmitted symbols across the transmitters. This joint message is encrypted by the transmitters – each transmitter transforms its symbol by scaling and rotating it with the key – the key being its channel estimation from receiver to transmitter. For the receiver's location in space, the channel itself performs a deciphering operation by rotating and scaling the encrypted message back to the original y. For the eavesdropper location in space the channel performs another enciphering operation with another key K', being the channels from the transmitters to the eavesdropper location. The eavesdropper constellation point y' is the cryptogram E. The eavesdropper has to decipher M from E using all possible prior knowledge, such as the offline determined transmitters BB symbol sets, the channel PDF and the prior probabilities of the messages M.

In the point to point scenario only the channel phase took part in the encryption operation. In a typical wireless channel the channel phase is assumed to be uniformly distributed and the channel amplitude may vary considerably. It follows that it is safe to assume that for $N > 1$ encryption is close to a random cipher [30]. The unicity distance of a random cipher is given by [30]:

$$U_d \approx \frac{H(\mathrm{K})}{1-\eta}. \tag{56}$$

where $H(\cdot)$ is the entropy. Assuming the transmitters are reasonably apart (more than a few wavelengths), the channels from them to the receiver are uncorrelated. It follows that $H(\mathrm{K}) = NH(h)$ and (56) may be written as

$$U_d \approx \frac{NH(h)}{1-\eta}. \tag{57}$$

It is evident that in JCMA with N transmitters, the unicity distance is increased N times compares to the point to point scenario ($N=1$). This means that a transmission burst N times longer may be secured.

6.1.1 Performance of Rayleigh fading channel

For a Rayleigh fading channel h is a complex normal RV. It is easy to show that $H(h) = \ln\sqrt{2\pi e\sigma^2}$, where σ is the channel variance. By properly normalizing σ (57) may be written as

$$U_d \approx \frac{N}{1-\eta}, \tag{58}$$

The normalization assists in evaluating the impact of JCMA on security strength. In Fig. 13 an expansion of the results presented in Fig. 2.5 is depicted for the case where the pilot is a single symbols.

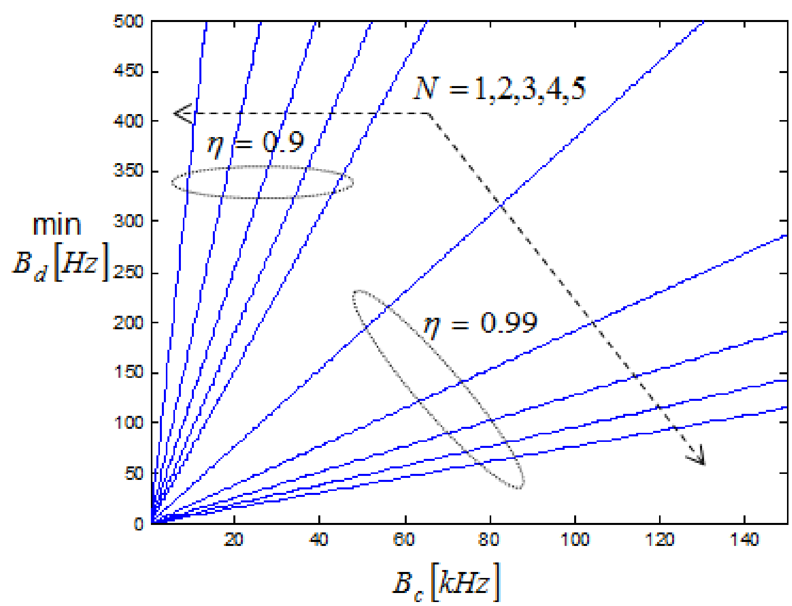


Figure 13 – B_d vs. B_s for various encoder efficiencies, Rayleigh fading JCMA

It is evident from Fig. 13 how JCMA reduces the required source encoder efficiency for any channel condition. Returning to the mobile WiMax example from chapter 2 and using Fig. 13, the required

Doppler spread (in Hz) and corresponding velocity for securing the entire data burst decreases when N increases – see Tab. 4 for results.

Table 4 – Reduction in required velocity for securing mobile WiMax with JCMA

η \ N	1	2	3	4	5
0.9	rather high				
0.99	380	190	125	95	75
$v[kph]$	59	30	19	15	12

6.1.2 Increased key generation rate

An important feature of any encryption method is the rate of key generation. Keys have to be changed frequently to keep the system safe. In JCMA the rate of key generation depends on the channel de-correlation over time. As was shown in a previous section, the de-correlation time shortens as N increases. This requires more frequent transmission of pilots which results in higher overheads on data throughput. For security purposes however, shortening of the de-correlation time is beneficial because it increases the key generation rate which increases security strength. For example, it was shown that in Rayleigh fading, pilots have to be transmitted twice as much for up to 5 transmitters. This means that the key generation rate doubled compared to the single transmitter case.

6.1.3 Additional security factors

Until now complete secrecy for the entire data transmission burst was required which is a very demanding requirement. Deciphering amounts to discovering the bit mapping from the transmitters to each joint symbol. Knowledge of the mapping is obtained by the eavesdropper after the unicity distance has passed only if the eavesdropper uses the best possible algorithm to decipher the data. After deciphering is accomplished the eavesdropper still has to decode the data. Usually security boils down to making decoding much more difficult for the eavesdropper, as compared to the intended receiver. As explained before, the TranSec of JCMA is based on the forming of a deteriorated signal at the eavesdropper's location in space. Four security factors of JCMA make deciphering by the eavesdropper much more difficult than deciphering by the receiver:

1. The eavesdropper would have difficulty knowing the expected joint symbol constellation at its MF output and the bit mapping from the transmitters to each joint symbol, since it has no knowledge of the channel compensation done at each transmitter and no immediate knowledge of the CSI from the nodes to itself.

2. The signals from the group nodes would not reach the eavesdropper simultaneously, resulting with an overlap of past and present symbols.
3. The decoding complexity of the eavesdropper would be much higher than that of the receiver. This is because for each channel instance the eavesdropper joint constellation would change, making it impossible to design a constant and computational efficient decoding algorithm. At the same time the receiver decoding algorithm would be constant because each channel instance is compensated for. This means that decoding by the eavesdropper is much more complex than at the receiver.
4. The joint constellation formed at the eavesdropper MF output is not optimal, since it was made to be optimal at a different and unique point in space – that of the receiver.

To be prudent it is assumed that by some means (blind channel estimation perhaps), the eavesdropper could have complete knowledge of the joint constellation it has to expect at its MF output – factor 1 could be compromised. In the context of the secrecy model used before this could happen only after the unicity distance has passed. Also, the eavesdropper might be close enough to the receiver to have the nodes signals reach him simultaneously – factor 2 could be compromised. It is further prudent to assume that the eavesdropper might have unlimited computational power, which would allow it to perform ML detection using exhaustive search – factor 3 could be compromised. Factors 1 to 3 make deciphering by the eavesdropper difficult but not impossible. Factor 4 remains a fundamental property of the wireless channel which cannot be undone. Due to factor 4 the eavesdropper has to decode the nodes information from a suboptimal joint symbol constellation and is expected to suffer a considerable loss in decoding performance.

7 Illustrative scenario – three transmitters

In this scenario a single sub-carrier is overloaded by 3 transmitters in a JCMA setting. $S_n,\ n=1,2,3$ were found using a random symbol search with $\max\{d_{\min}\}$ (3) being the optimizing criterion and (4) being the optimization constraint. The following symbol sets were found offline and assigned arbitrarily to the transmitters:

$$\begin{aligned} S_1 &= \{0.7124\exp(-j2.5558);\ 0.7124\exp(j0.5858)\} \\ S_2 &= \{0.9965\exp(j1.3720);\ 0.9965\exp(-j1.7696)\} \\ S_3 &= \{0.9890\exp(-j0.2016);\ 0.9890\exp(j2.9400)\} \end{aligned} \quad (59)$$

The received joint constellation along with the corresponding bit mapping is depicted in Fig. 14. Each set of 3 bits represents the bits of TX1, TX2 and TX3 from left to right respectively. Notice that the average energy of the received constellation is larger than 1. Interestingly, this joint constellation has the exact structure of a type of 8QAM constellation used in some industry standards for single transmitter signals [31, page 53].

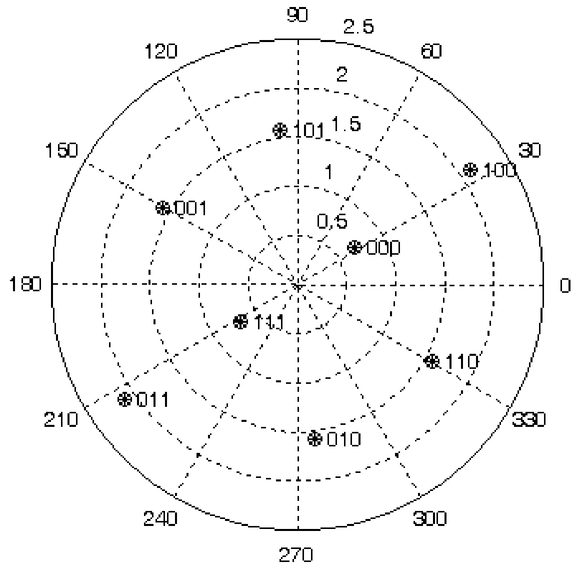


Figure 14 – Joint constellation for the three transmitters scenario

In Fig. 15 a comparative time diagram between JCMA and TDMA with equal data rates is given. T_{slot} denotes the time span of the TDMA time slot, and $1\mathrm{BPS}_n$ denotes 1 bit per symbol transmission of transmitter n in JCMA. In TDMA, each transmitter transmits 8-QAM during its allocated time slot and is idle during other slots. The receiver sees the 8-QAM constellation of each user at a time. In JCMA all transmitters transmit during all time slots by using their allocated symbol set with 1 bit per symbol. The receiver sees the joint constellation given in Fig. 14 during all time slots.

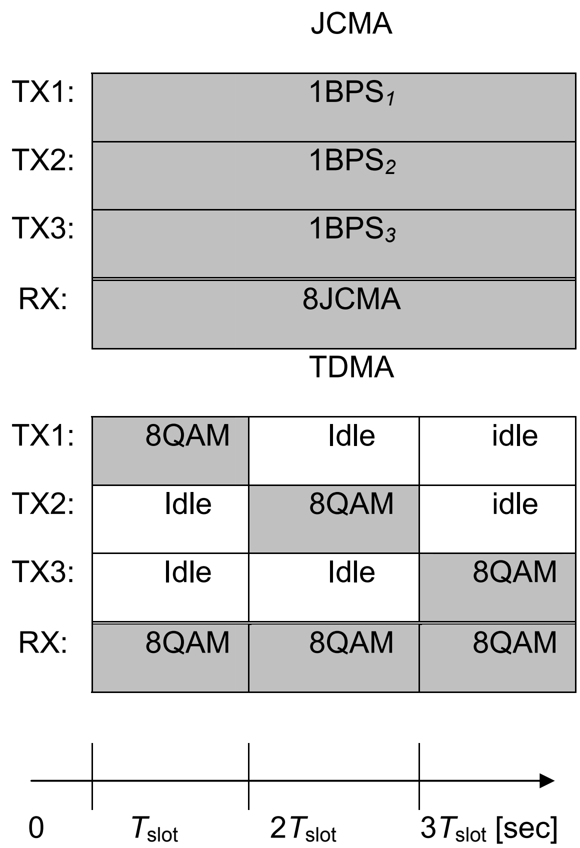


Figure 15 – Time diagram for JCMA vs. TDMA for the three transmitters scenario

Next an efficient ML decoding algorithm is designed, based on constellation symmetries. The algorithm comprises three steps for decoding a received joint sample r :

1. Rotate the received sample: $q = r\exp(-j0.1865\pi)$.
2. Calculate:

$$q_R = real(q)$$
$$q_I = imag(q)$$
$$u_R = real(q * \exp(-j\pi/4)$$
$$u_I = imag(q * \exp(-j\pi/4))$$

Use Tab. 5 for decoding.

For hard decoding, each table entry denotes the decoded bits of TX1, TX2 and TX3 from left to right respectively. For soft decoding the distance from the closest joint constellation point has to be evaluated.

Table 5 – LUT for ML detection of the three transmitters scenario

	$q_I < -0.775$	$-0.775 \le q_I < 0.775$	$0.775 \le q_I$
$q_R < -1.545$	if($u_I < 0.555$) 010 else 011	011	if($u_R < -0.555$) 011 else 001
$-1.545 \le q_R < 0$	010	111	001
$0 \le q_R < 1.545$	110	000	101
$1.545 \le q_R$	if($u_R < 0.555$) 110 else 100	100	if($u_I < -0.555$) 100 else 101

This efficient decoding algorithm consists of three easy steps and its complexity is much lower than that of the exhaustive ML decoding algorithm.

A Rayleigh fading channel is assumed. It is also assumed that all channels to receiver and eavesdropper are independent and have equal variance. As mentioned, this assumption is valid if the eavesdropped is located at least a few wave-lengths away from the receiver, which is surely the case, because the transmission is likely to be at high frequencies. The JCMA system is compared to a TDMA with the same power constraint on the transmitters which is using the 8QAM constellation depicted in Fig. 16.

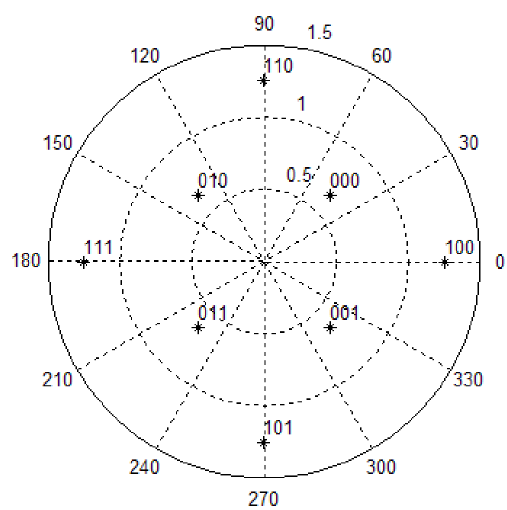


Figure 16 – 8QAM constellation of TDMA reference system

In Fig. 17 hard decoding BER vs. SNR (defined here as the ratio between the average energy per transmitter symbol and the noise variance at the receiver) is depicted for the JCMA system and compared to the reference TDMA system. Results were obtained using computer simulation. Note that a gain of 4 dB is achieved with JCMA while adhering to the overall transmitters power constraints. This means that the increased overall energy invested in JCMA (3 times more, equivalent to 4.7 dB) was successfully translated to performance gain. Note that the efficient ML decoding algorithm performs as well as the exhaustive search algorithm.

In order to analyze the impact of security factor 4 of sub-section 6.2, BER of the receiver is also compared to that of an eavesdropper. It is clear that for the eavesdropper ML decoding is unsatisfactory for decoding of data. For example, if the receiver operates at Eb/N0 of 14dB it would have an average error rate of 10^{-3}, and the eavesdropper would have an error rate of 10^{-1}. It follows that for the given scenario the eavesdropper cannot effectively decode the messages from the nodes, even when security factors 1-3 are compromised.

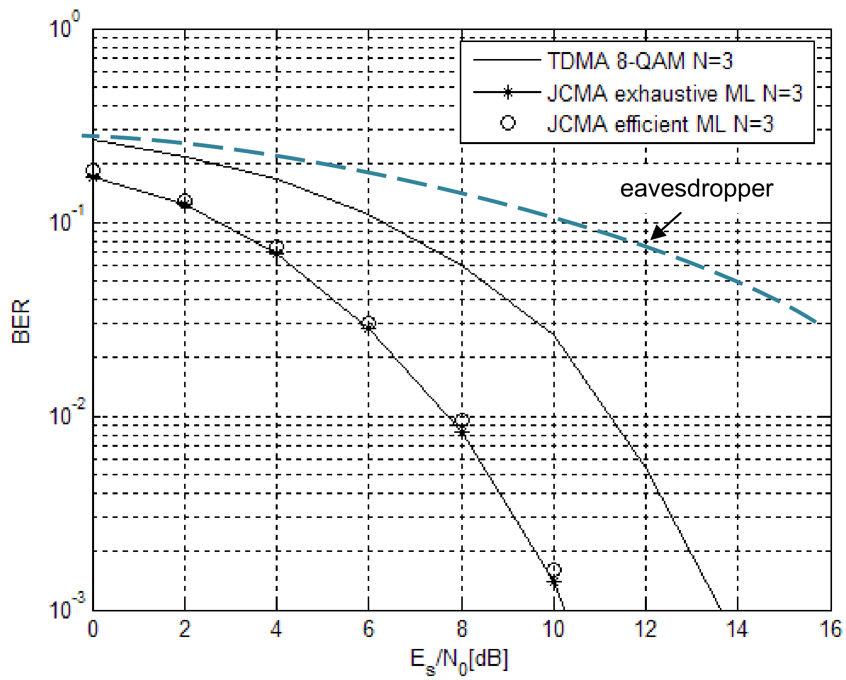


Figure 17– Performance curves for the three transmitters scenario

To gain insight on the impact of security factors 1 and 3 on decoding, representative joint constellations of the eavesdropper are depicted in Fig. 18. Note how the joint constellation varies from pilot to pilot, implying the required high complexity of decoding. In addition, note how close the constellation points are to one another, implying the high probability for decoding errors.

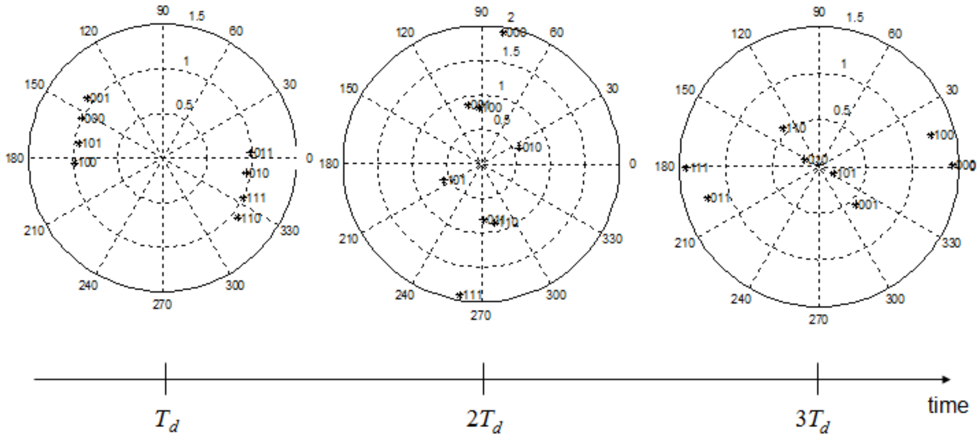


Figure 18 – Consecutive joint constellations of eavesdropper

8 Summary

A multiple access method based on a reverse piloting algorithm, JCMA, was proposed and analyzed. The method uses synchronous super-position modulation coupled with joint decoding at the receiver to overall sub-carriers with multiple transmitters. Each transmitter uses a predefined constellation set, and the receiver decodes all transmitters together from a composite joint symbol formed by channel superposition at its MF output. The method is PCT patent pending at WIPO [32].

JCMA was shown to offer decoding gains for power limited transmitters. It was proven that the minimal Euclidean distance in the joint constellation increases with the number of transmitters. It was demonstrated how an offline random symbol search approach can generate robust constellations. This contribution was published in [33] with an emphasis on network optimization. A general guideline algorithm for computationally efficient ML decoding based on symmetries in the joint constellation was depicted as well.

JCMA was modeled as a Shannon secrecy model and was shown to increase security strength. It enables completely securing simultaneous data bursts from N transmitters which are N times longer by increasing the unicity distance. In addition, other security factors come into play in a JCMA setting, making decoding much more difficult for the eavesdropper even after the unicity distance has been reached: the need for blindly estimating the joint constellation structure, the need for an exhaustive search decoding algorithm, degradation due to the incoherent sum of transmitters signals and the suboptimal joint constellation for decoding. This contribution was published in [34].

It was shown that synchronization, power control and mobility are achievable for the JCMA system. The pilot signaling requirements for supporting the same synchronization and mobility as those of a reference TDMA system was explicitly shown to reduce to feasible demands. To keep the JCMA decoding performance gain, the pilot signal energy has to be N times larger, and the pilot retransmission rate has to be higher up to 2.5 times that of TDMA for $N = 5$ in Rayleigh fading, which is actually good for security because it increases key generating rate. The decoding performance gain can be discarded by having each transmitter use $1/N$ power than that of TDMA, and system performance would be as that of TDMA with no extra demands on pilot signaling. The probability of unit failure was also found in terms of the probability for unit failure in a TDMA system. It was shown that this probability is N times larger for JCMA.

Unpublished contributions are in final preparation for publication [35].

9 Refferences

[1] P. P. Bergmans, "A Simple Converse for Broadcast Channels with Additive White Gaussian Noise", *IE***EE** *Transactions* **on Information Theory**, Vol. IT-20, pp. 279-280, March 1974.

[2] T. Cover, J. Thomas, *Elements of Information Theory*, Wiley, New-York, 1991.

[3] A. Goldsmith, *Wireless Communications*, Cambridge University Press, 2006.

[4] S. Verdu, *Multiuser detection*, Cambridge University Press, 1998.

[5] E. G. Larsson, B. R. Vojcic, "Cooperative transmit diversity based on superposition modulation", *IEEE Communication Letters*, vol. 9, pp. 778-780, Sept. 2005.

[6] F. N. Brännström, T. M. Aulin and L. K. Rasmussen, "Constellation-constrained capacity for trellis code multiple access systems", *IEEE Global Telecommunication Conference*, pp. 791-795, Dec. 2001.

[7] F. N. Brännström, T. M. Aulin and L. K. Rasmussen, Capacity considerations for trellis code multiple access systems, *IEEE Info. Theory Workshop*, pp. 153-155, Sept. 2001.

[8] F. N. Brännström, T. M. Aulin and L. K. Rasmussen, "Iterative detectors for trellis code multiple access", *IEEE Trans. on Communication*, vol. 50, pp. 1478-1485, Sept. 2002.

[9] J. A. F. Ross and D. P. Taylor, "Vector Assignment Scheme for M+N users in N-dimensional Global Additive Channel", *IEEE Electronic Letters*, vol. 28, pp. 1634-1636, August 1992.

[10] J. A. F. Ross and D. P. Taylor, "Multiuser Signaling in the Symbol-Synchronous AWGN Channel", *IEEE Transactions on Information Theory*, vol. 41, pp. 1174-1178, July 1995.

[11] F. Vanhaverbeke "Digital Communications through Oversaturated Channels", *doctoral dissertation, Ghent University*, Belgium, March 2005. (available at: http://telin.ugent.be/~fv/eigen_publicaties.html)

[12] J. G. Proakis, *Digital Communication*, McGraw Hill, 2000.

[13] A. Papoulis. *Probability, Random Variables, and Stochastic Processes,* Third Edition. McGraw-Hill, New York, 1991.

[14] E. A. Lee, D.G Messerschmitt, *Digital Communication*, Kluwer Academic Publishers, 1988.

[15] S. Verdú, "Capacity Region of Gaussian CDMA Channels: The Symbol- Synchronous Case", *Proc. Twenty-fourth Allerton Conf. on Communication, Control and Computing*, Allerton, IL, p. 1025-1034, Oct. 1986

[16] Y. Li, "Pilot-Symbol-Aided Channel Estimation for OFDM in Wireless Systems", *IEEE Transactions on Vehicular Technology*, vol. 49, pp. 1207-1215, July 2000.

[17] O. Edfors, M. Sandell, J. Beek, S. Wilson, P. Borjesson, "OFDM Channel Estimation by Singular Value Decomposition", *IEEE Transactions on Communications*, vol. 46, pp. 931-939, July 1998.

[18] L.Berriche, K.Abed Meraim, J-C.Belfiore, "Cramer-Rao Bounds for MIMO Channel Estimation", *Proc. ICASSP*, May 2004, vol.4, pp. 397–400.

[19] B.Hassibi, B.M.Hochwald, "How Much Training is Needed in Multiple-Antenna Wireless Links", *IEEE Transactions on Information Theory*, vol. 49, pp. 951–963, Apr. 200

[20] M.Dong, L.Tong, "Optimal Design and Placement of Pilot Symbols for Channel Estimation", *IEEE Transactions on Signal Processing*, vol. 50, no. 12, pp. 3055–3069, Dec. 2002.

[21] X. Tang, M. S. Alouini, A. J.Goldsmith, "Effect of Channel Estimation Error on M-QAM BER Performance in Rayleigh Fading", *IEEE Transactions on Communications*, vol. 47, no. 12, December 1999

[22] H. L. Van Trees, *Detection, Estimation, and Modulation Theory, Part I*, Wiley, 2001

[23] M. R. Spiegel, *Mathematical Handbook*, Schaums Outline Series, McGraw-Hill, 1990.

[24] A. Georgiadis, "Gain, Phase Imbalance, and Phase Noise Effects on Error Vector Magnitude", *IEEE Transactions on Vehicular Technology*, vol. 53, no. 2, March 2004.

[25] R. A. Shafik, S. Rahman, A. Razibul Islam, N. S. Ashraf, "On The Error Vector Magnitude As A Performance Metric And Comparative Analysis ", *IEEE ICET International Conference on Emerging Technologies*, 2006.

[26] J.L. Pinto, I. Darwazeh, "Error vector magnitude relation to magnitude and phase distortion in 8-PSK systems", *Electronic Letters*, vol. 37 no. 7, March 2001

[27] B. Sklar, "Rayleigh fading channels in mobile digital communication systems .I. Characterization", *IEEE Communications Magazine*, vol. 35, issue 7, pp. 90–100, July 1997.

[28] D. H. Evans and W. N. McDicken, *Doppler Ultrasound*, Second Edition, John Wiley and Sons, 2000.

[29] Lee W. C., *Mobile Communication Engineering*, McGraw-Hill: New York, 1982.

[30] C. E. Shannon, "Communication Theory of Secrecy Systems", *Bell Systems Technical Journal*, vol. 28, pp. 656–715, 1948.

[31] Data Over Cable Systems 2.0, Part 1: Radio Frequency Interface, ANSI/SCTE 79-1 200

[32] G. R. Tsouri, D. Wulich, SigNexT Comm., (WO/2007/039908) Joint Constellation Multiple Access – PCT patent pending. (available at: http://www.wipo.int/pctdb/en/wo.jsp?IA=WO2007039908)

[33] G. R. Tsouri, D. Wulich, "Wireless Channel Access through Jointly Formed Signal Constellations", *IEEE Annual International Symposium on Personal, Indoor and Mobile Radio Communications* (PIMRC), Sep. 2006.

[34] G. R. Tsouri, D. Wulich, "A Physical Transmission Security Layer for Wireless Multiple Access Communication Systems", *European Signal Processing Conference* (EUSIPCO) – special session, Sep. 2007.

[35] G. R. Tsouri, D. Wulich, "Sub-Carrier Over-Loading for OFDM in Wireless Time-Varying Channels", *in preparation* for *EURASIP Journal on Wireless Communications and Networking* – Special Issue on Wireless Physical Layer Security.