

# Optimum Index modulation for new generation Wireless Networks

<sup>1</sup>M.Subrahmanyeswararao

<sup>2</sup>A.Suresh

<sup>1</sup>Associate Professor, <sup>2</sup> Assistant professor

Department of Electronics and communication Engineering  
Chalapathi Institute of engineering and technology, Guntur

## Abstract:

Index modulation (IM) techniques, which consider innovative ways to convey information compared to traditional communication systems, for next-generation wireless networks due to the attractive advantages they offer in terms of spectral and energy efficiency without increasing the hardware complexity, i.e. increase data rate and save energy while being simple to implement. These modulation schemes belong to two different communication methods. The first scheme known as spatial modulation (SM), is a scheme that uses multiple antennas at the transmitter side where just one antenna is activated at a time and its index is used as means to convey information. The second is known as code-index modulation (CIM), a system that uses multiple spreading codes, where a certain code is selected and its index is used as a mechanism to ferry data. In order to evaluate the advantages and disadvantages of each technique, we compare the energy efficiency, the system complexity, and the bit error rate performance of the SM and CIM schemes.

Keywords: Index Modulation, Spatial modulation(SM), code index Modulation(CIM), OFDM with IM, channel Modulation

## INTRODCUTION:

More specifically, there are three forms of Index Modulation which are i). Spatial modulation ii). Orthogonal frequency division multiplexing (OFDM) with Index Modulation (OFDM-IM) and iii) Channel modulation which consider the transmit antennas of a multiple-input multiple output system, Generally speaking, IM splits the information bits into index bits and constellation bits. *The former* determine which portion of the radio resources (antennas, subcarriers etc.) is active, and *the latter* are mapped to conventional constellation symbols that are to be carried by the active resources. Suppose that  $k$  out of the  $n$  resource indices are active. Therefore the system spectral efficiency (SE) in terms of bps/Hz is Spectral Efficiency

$$(SE) = \left(\frac{k}{n}\right) \log_2(C_n^k) + \left(\frac{k}{n}\right) \log_2 M \quad \text{----(1)}$$

Where  $C_n^k$  denotes binomial Coefficient and  $M$  denotes Cardinality of Symbol Constellation. The Other issue in Index Modulation is Energy efficiency (EE). To evaluate the EE, we derive the coding gain of the IM schemes,  $G_c$  which can be obtained by evaluating the high SNR approximation of the theoretical average bit error probability (ABEP)

$$ABEP \propto (G_c \gamma)^{G_d} \quad \text{----(2)} \quad \text{where } \gamma \text{ denotes the SNR, and } G_d \text{ is the coding gain.}$$

IM in frequency cannot reduce the required RF chain number, and the EE gain solely results from coding gain.

The IM-OFDM system with  $A$  active subcarriers out of  $N$  subcarriers per group is denoted by  $(N, A)$ .

- The coding gain provided by IM is proportional to the ratio of inactive subcarriers and index bits.
- For a fixed modulation order, IM improves the SE and the coding gain simultaneously in comparison with plain OFDM. But both gains degrade as the modulation order increases due to the decrease of the share of index bits among all information bits.
- When considering the realistic frequency selectivity of the channel, for approximate SE and coding gain, smaller group size is more preferable to realize the theoretical performance. From all these, we can see that IM in both space and frequency domains can provide EE and SE gains that are primarily facilitated by the index bits. From the perspective of achievable SE and RF transmit power, IM indeed achieves higher SE and EE while using less RF chains and activating less space and frequency resources.

## SPATIAL MODULATION(SM)

IM concept has started a new wave of alternative digital modulation schemes that considers an innovative approach to transmit information by means of the indices of the transmit antennas of a  $n_T \times n_R$  MIMO system in addition to the conventional  $M$ -ary signal constellations [1]. The conventional MIMO schemes rely on either spatial multiplexing (SMX) to boost the data rate by the transmission of different data symbols from different transmit antennas [2], or spatial diversity to improve the error performance by the reception of multiple copies of the data symbols from different transmit/receive antennas at different time slots [3].

In other words, the multiple transmit antennas of a MIMO system are used for a different purpose in these scenarios compared to SM. More specifically, two information carrying units exist in SM: the indices of the available transmit antennas and the  $M$ -ary constellation symbols. For each transmission interval, a total of  $\log_2(n_T) + \log_2(M)$  bits enter the transmitter of an SM system where  $n_T$  and  $n_R$  denote the number of transmit and receive antennas, respectively, and  $M$  is the size of the considered signal constellation diagram. In a traditional fashion, the first  $\log_2(M)$  bits of the incoming bit sequence are used to modulate the phase and/or amplitude of a carrier signal. On the other hand, the remaining  $\log_2(n_T)$  bits of the incoming bit sequence are considered for the selection of the index ( $I$ ) of the active transmit antenna that performs the transmission of the

corresponding modulated signal .

The receiver of the SM scheme has to deal with the following two major tasks: detection of the active transmit antenna for the demodulation of IM bits and detection of the data symbol transmitted over the activated transmit antenna for the demodulation of the bits mapped to the  $M$ -ary signal constellation. Unfortunately, the optimum ML detector of SM has to search jointly over all transmit antennas and constellation symbols to perform these two tasks [5].

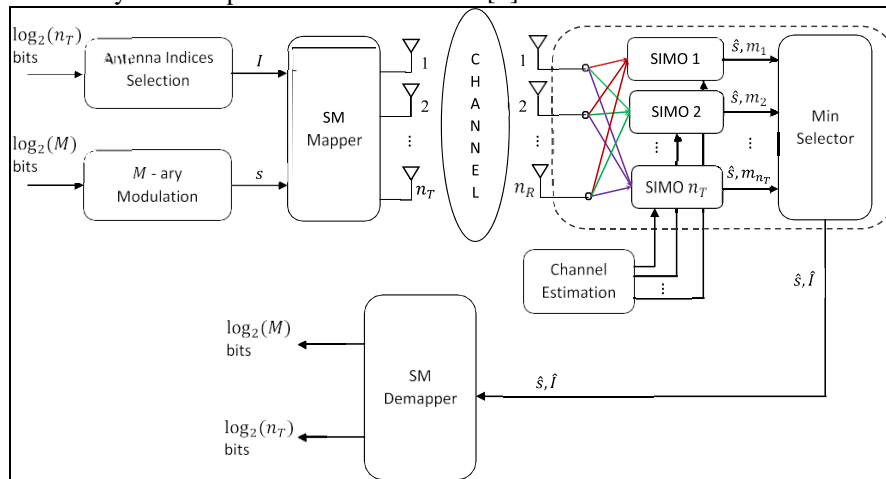


Figure 1. SM system model with  $n_T$  transmit and  $n_R$  receive antennas.

The main **ADVANTAGES** OF SM over classical MIMO systems:

- **High spectral efficiency:** Due to the use of transmit antenna indices as an additional way of conveying information, the spectral efficiency of SM exceeds that of SISO systems and orthogonal space-time block codes (STBCs).
- **High energy efficiency:** The power consumed by the SM transmitter is independent of the number of transmit antennas, while the information can be still transferred via these antennas. In terms of the energy efficiency in Mbits/J, improvements up to 46% compared to V-BLAST are reported for different type of base stations (BSs) equipped with multiple antennas.
- **Simple transceiver design:** Since only a single transmit antenna is activated during transmission, a single RF chain is sufficient for the SM scheme. Furthermore, inter-antenna synchronization (IAS) and inter-channel interference are completely eliminated and the decoding complexity of the SM receiver, in terms of the total number of real multiplications, grows linearly with the constellation size and number of transmit antennas.
- **A much simpler implementation** solution can be obtained by transmitting information with only active transmit antenna indices and the resulting scheme is called space-shift keying (SSK) [19]. Compared to SM, SSK requires neither in-phase and quadrature (IQ) modulation nor pulse shaping.
- **Operation with flexible MIMO systems:** Unlike the V-BLAST scheme, which requires  $n_R > n_T$  to operate with minimum mean square error (MMSE) and zero forcing (ZF) type linear detectors, SM can be implemented for any number of transmit and receive antennas.

**DISADVANTAGES** are as follows:

- The spectral efficiency of SM increases logarithmically with  $n_T$ , while the spectral efficiency of V-BLAST increases linearly with  $n_T$ . Therefore, a larger number of transmit antennas are required for SM to reach the same spectral efficiency as that of V-BLAST.
- The channel coefficients of different transmit antennas must be sufficiently different for an SM scheme to operate effectively. In other words, SM requires rich scattering environments to ensure better error performance. But the bit error rate (BER) performance of SM degrades in contrast to classical systems.
- SM transfers the information using the spatial domain, plain SM cannot provide transmit diversity as STC systems. One solution is to consider transmit precoding, which requires channel state information (CSI) at the transmitter, while another direction is STC techniques that require at least two transmission phases.

**APPLICATION OF SPATIAL MODULATION(SM):**

**SM To Full-Duplex (FD) Networks:** To enable simultaneous transmission and reception at the same time and same frequency band, an FD node must be configured with at least two independent transmit and receive RF chains. Based on this architecture, it is possible to extend the SM concept to an FD node.

**SM To Cooperative Networks** Cooperative communications has been one of the important topics in wireless communications and its basic principle is the transmission of user information not only by its own antenna, but also by the active or passive nodes available in the network.

**SM To Cognitive Radio(CR) Networks :** SM techniques appear as promising alternatives to overcome the main limitations of traditional spectrum sharing systems. Spectrum sharing is a potential technique to use the available limited spectrum in a more efficient way. CR networks, which utilize spectrum sharing, are capable of overcoming the scarcity and inefficient usage of the wireless spectrum.

**SM To Massive MIMO And Multi-User Systems:** Massive MIMO systems have been regarded as one of the potential key technologies for next-generation (5G and beyond) wireless networks due to their appealing advantages such as very high spectral and energy efficiency by the employment of tens to hundreds of antennas at their Base Station. .

OFDM WITH INDEX MODULATION

OFDM has been the most popular multicarrier transmission technique in wireless communications. In the OFDM-IM scheme, the information is conveyed by both of the  $M$ -ary constellation symbols and the indices of the subcarriers that are modulated by these constellation symbols. Here we do not use all of the available subcarriers, we compensate for the loss in the total number of transmitted bits by transmitting additional bits in the spatial domain of the OFDM block. Similarly, multiple-input multiple-output (MIMO) transmission techniques have been implemented in many practical applications, due to their benefits over single antenna systems. Spatial modulation (SM), which uses the spatial domain to convey information in addition to the classical signal constellations, has emerged as a promising MIMO transmission technique. In this scheme, information is conveyed not only by  $M$ -ary signal constellations as in classical OFDM, but also by the indices of the subcarriers, which are activated according to the incoming information bits. A general method, by which the number of active subcarriers can be adjusted, and the incoming bits can be systematically mapped to these active subcarriers, is presented for the OFDM-IM scheme.

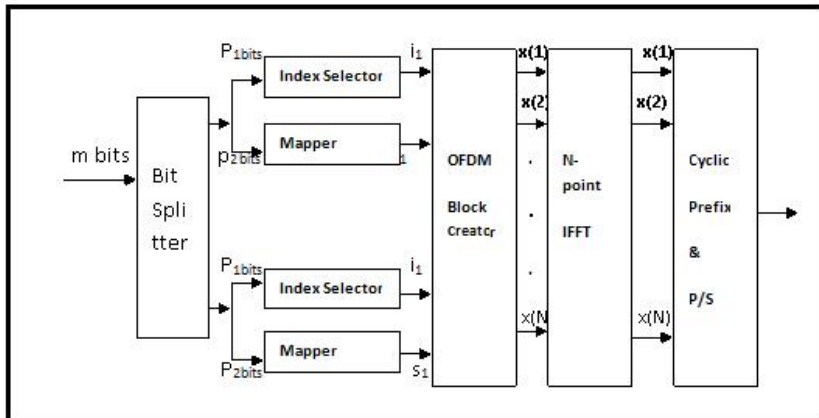


Figure 2. OFDM-IM Block transmitter

An OFDM-IM Transmitter is shown in figure 2. In which a total of  $m$  information bits enter the OFDM-IM transmitter for the transmission of each OFDM block. These  $m$  bits are then split into  $g$  groups each containing  $p$  bits, i.e.,  $m = pg$ . Each group of  $p$ -bits is mapped to an OFDM sub block of length  $n$ , where  $n = N/g$  and  $N$  is the number of OFDM subcarriers. Contrary to the classical OFDM, this mapping operation is not only performed by means of the modulated symbols, but also by the indices of the subcarriers.

Inspiring from the SM concept, additional information bits are transmitted by a subset of the OFDM subcarrier indices. For each subblock, only  $k$  out of  $n$  available indices are employed for this purpose and they are determined by a selection procedure from a predefined set of active indices, based on the first  $p_1$  bits of the incoming  $p$ -bits sequence. We set the symbols corresponding to the inactive subcarriers to zero. The remaining  $p_2 = k \log_2 M$  bits of this sequence are mapped on to the  $M$ -ary signal constellation to determine the data symbols that modulate the subcarriers having active indices, therefore, we have  $p = p_1 + p_2$

**OFDM sub block concept:**

For each subblock  $\beta$ , the incoming  $p_1$  bits are transferred to the index selector, which chooses  $k$  active indices out of  $n$  available indices, where the selected indices are given by  $I_\beta = \{i_{\beta,1}, \dots, i_{\beta,k}\}$  .....(4)  
 where  $i_{\beta,\gamma} \in [1, \dots, n]$  for  $\beta = 1, \dots, g$  and  $\gamma = 1, \dots, k$ .

Therefore, for the total number of information bits carried by the spatial position of the active indices in the OFDM block, we have  $m_1 = p_1 g = \lfloor \log_2 (C(n,k)) \rfloor g$ .

In other words,  $I_\beta$  has  $c = 2^{p_1}$  possible realizations. In other words, On the other hand, the total number of information bits carried by the  $M$ -ary signal constellation symbols are given by

$$m_2 = p_2 g = k (\log_2 (M)) g$$

The total number of active subcarriers is  $K = kg$  in our scheme. Consequently, a total of  $m = m_1 + m_2$  bits are transmitted by a single block of the OFDM-IM scheme.

The equivalent frequency domain input-output relationship of the OFDM scheme is given by

$$y_F(\alpha) = x(\alpha)h_F(\alpha) + w_F(\alpha), \quad \alpha = 1, \dots, N \text{ where } y_F(\alpha): \text{ received signals}$$

$$h_F(\alpha) = CN(0, 1): \text{ the channel fading coefficients}$$

$$w_F(\alpha) = CN(0, N_{0,F}): \text{ noise samples}$$

$$\text{Noise variance in the frequency domain } N_{0,F} = (K/N) N_{0,T} \text{.....(5)}$$

$$\text{Signal-to-noise ratio (SNR): } \rho = E_b/N_{0,T} = [(N+L)/M]/N_{0,T} \text{.....(6)}$$

**The receiver's task** is to detect the indices of the active subcarriers and the corresponding information symbols by processing  $y_F(\alpha)$ ,  $\alpha = 1, \dots, N$ .

Unlike the classical OFDM, a simple maximum likelihood (ML) decision on  $x(\alpha)$  cannot be given by considering only  $y(\alpha)$  in our scheme due to the spatial information carried by the OFDM-IM sub blocks

There are two different type of mapping & detection algorithms for the OFDM-IM scheme:

Look-Up Table Method - Maximum Likelihood (ML) Detector

Combinadics Method - Log-likelihood Ratio (LLR) Detector.

A look-up table of size  $c$  is created to use at both transmitter and receiver sides. At the transmitter, this look-up table provides the corresponding indices for the incoming  $p_1$  bits for each subblock, and it performs the opposite operation at the receiver.

Table-1: A Look-Up table example for n=4;k=2 and P<sub>1</sub>=2

Bits	Indices	Sub Blocks
[0 0]	{1,2}	[S <sub>χ</sub> S <sub>c</sub> 0 0] <sup>T</sup>
[0 1]	{2,3}	[0 S <sub>χ</sub> S <sub>c</sub> 0] <sup>T</sup>
[1 0]	{3,4}	[0 0 S <sub>χ</sub> S <sub>c</sub> ] <sup>T</sup>
[1 1]	{1,4}	[S <sub>χ</sub> 0 0 S <sub>c</sub> ] <sup>T</sup>

Since C(4,2)=6, Two combinations out of six are discarded. The ML detector for the OFDM-IM scheme considers all possible sub block realizations by searching for all possible subcarrier index combinations and signal constellation points.

**Combinadics Method - Log-likelihood Ratio (LLR) Detector:**

The combinational number system (combinadics) provides a one-to-one mapping between natural numbers and k-combinations, for all n and k. It maps a natural number to a strictly decreasing sequence  $J = \{c_k, \dots, c_1\}$  where  $c_k > \dots > c_1 \geq 0$ .

In other words, for fixed n and k, all  $Z \in [0, C(n, k) - 1]$  can be presented by a sequence J of length k, which takes elements from the set  $\{0, \dots, n - 1\}$  according to the following equation:

$$Z = C(c_k, k) + \dots + C(c_2, 2) + C(c_1, 1) \dots \dots \dots (7)$$

The algorithm, which finds the lexicographic ordered J sequences for all n, can be explained as follows:

Start by choosing the maximal c<sub>k</sub> that satisfies  $C(c_k, k) \leq Z$ ,

Choose the maximal c<sub>k-1</sub> that satisfies  $C(c_{k-1}, k-1) \leq Z - C(c_k, k)$  and so on.

In our scheme, for each sub block, we first convert the p<sub>1</sub> bits entering the index selector to a decimal number Z. Then feed this decimal number to the combinadics algorithm to select the active indices as J + 1.

However, it can give a catastrophic result at the exit of the decimal-to-binary converter if  $Z \geq C$  use this detector for the increased bit-rate

**Bit Error Rate (BER):** According to the CIM system, we can see a fact that the total probability of BER, defined as P<sub>T</sub>, is a function of the probability of BER for the modulated bits, denoted as P<sub>eb</sub>, and the probability of BER for mapped bits, given as P<sub>em</sub>. Moreover, in the in-phase branch, the probability of BER for mapped bits P<sub>em</sub> is dependent upon the number of mapped bits N, and the probability associated with erroneous code detection is P<sub>ed</sub>. Each combination may have different number of incorrect bits compared to the correct bit combination. For example, if the mapped bits are 0, 0, 0, the number of bit errors can be either one or three if the detected combination was 0, 0, 1 or 1, 1, 1 respectively.

The probability of detecting one of the remaining (2<sup>N</sup> - 1) incorrect combinations is the same for all codes and it equals to  $\frac{1}{2^N - 1}$ . Therefore, the probability of BER for the mapped bits can be formulated as

$$P_{em} = \frac{P_{ed}}{N(2^N - 1)} \sum_{c=1}^N \binom{N}{c} \dots \dots \dots (8) \text{ where } \binom{N}{c} \text{ represents the number of combinations having c bits}$$

different from the correct bit combination.

As a result, the total probability of BER for the generalized CIM system is formulated as

$$P_T = \frac{n}{n+2N} P_{eb} + \frac{2N}{n+2N} P_{em} \quad (9) \text{ where } (n + 2N) \text{ is total number of transmitted bits in which n}$$

is the number of modulated bits while 2N is the number of mapped bits. It is easy to see that the total probability of BER, P<sub>T</sub>, is obtained only if the probability of BER for the mapped bits P<sub>em</sub> and modulated bits P<sub>eb</sub> are calculated.

We can see that the correct reception of the modulated bits depends on the code detection and the M-ary modulation. The error may occur in two different cases. *Case 1:* there is no error in the spreading code detection (i.e no error in the mapped bits), but the modulated symbol is impossible to detect. *Case 2:* there is an error in the code detection (i.e in the mapped bits) and the modulated symbol is detected based on demodulation of incorrect selected correlator output. Consequently, the probability of BER for the modulated bits can be expressed as

$$P_{eb} = P_{ss} (1 - P_{em}) + \frac{1}{2} P_{em} \dots \dots \dots (10)$$

where P<sub>ss</sub> represents the probability of BER for the conventional SS M-ary system which depends on the number of modulated bits n and P<sub>em</sub> is already calculated in (8). The theoretical expression of P<sub>ss</sub> for the M-PSK can be found in [11,12]. The factor  $\frac{1}{2}$  indicates a fact that with an error in the mapped bit detection P<sub>em</sub>, the bit value detected based on the incorrect demodulated branch still matches the modulated bit half of the times. The error probability spreading code detection P<sub>ed</sub> is obtained.

The only difference is that the CIM system uses two different spreading codes to perform the spreading operation for the in-phase and quadrature components rather than one spreading code for the two components as in the SS M-ary. At the receiver side, 2<sup>2N</sup> de-spreading/correlation operations are required for the in-phase and quadrature branches of the CIM system instead of two operations as in the SS M-ary system. However, while the CIM system requires just two spreading operations at the transmitter and 2<sup>2N</sup> de-spreading operations at the receiver to transmit N<sub>t</sub> bits, the SS M-ary system requires 2 + 2(2N/n) spreading operations and 2+2(2N/n) de-spreading operations at the receiver side where 2N/n represents the number of symbols corresponding to 2N bits. Therefore, the total number of operation required for CIM system to transmit N<sub>t</sub> bits is

$$O_{CIM} = 2 + 2 \times 2 \dots \dots \dots (11)$$

and for SS M-PSK system it is  $O_{M-PSK} = 4 + 4 \times \frac{2N}{n}$  -----(12)

**Throughput analysis :** In order to understand the enhancement behaviour of the CIM system we analyse its throughput. Typically, the throughput is defined as the number of correct bits (i.e bit level analysis) a user receives per unit time which can be written as  $R_t = N_t \frac{(1 - BER)}{T}$  ----- (13)

where  $N_t$  is the number of total transmitted bits per symbol in conventional or CIM modulations, T is the transmission time, BER is the bit error probability, and (1-BER) is the correct bits received during time T.

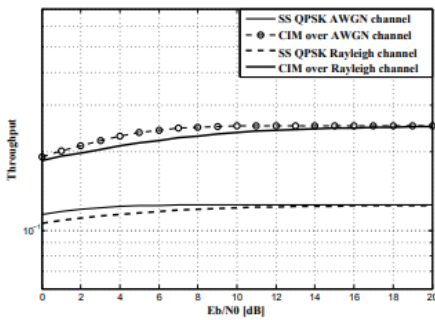


Fig. 3. Throughput of the CIM system modulation n = 2, N = 1 and SSQPSK schemes over an AWGN and Rayleigh channel

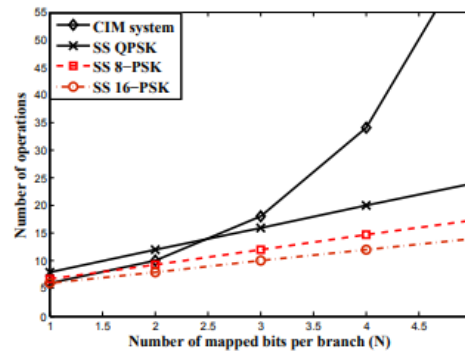


fig.4 Complexity comparison of the CIM and SSM-PSK

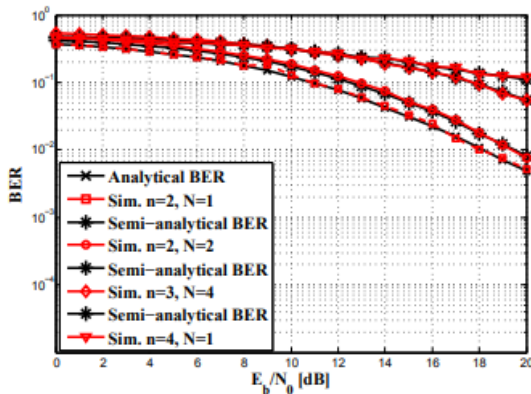


Fig.5 BER analysis for CIM system for rayleigh fading channel

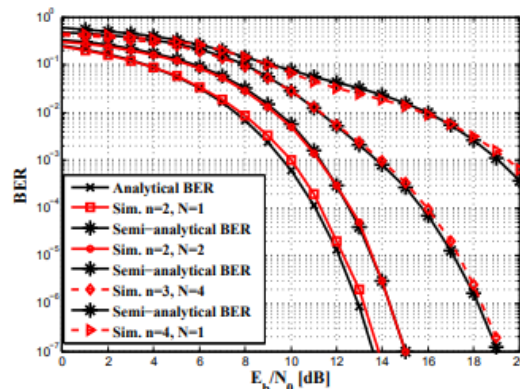


Fig.6 BER analysis for CIM system for AWGN channel

Table:2 comparison between schemes :

	Scheme	spectral efficiency	complexity	BER performance
single carrier Communication systems	SIMO	L	L	L
	SM	M	L	M
	GSM	M	M	M
	QSM	H	L	H
	V-BLAST	H	H	M
Multi carrier communication systems	OFDM	L	L	L
	OFDM-IM	L	M	M
	V-BLASTOFDM	H	M	M

Note: L-LOW;M-MODERATE;H-HIGH

**CHANNEL MODULATION:**

- CDMA forward link uses same frequency spectrum as AMPS i.e. 869-894 MHz. One channel bandwidth is 1.25 MHz
- Modulation scheme used is QPSK.
- Orthogonal Walsh codes are used. Walsh codes are called Hadamard codes and they are used in all CDMA techniques.
- Forward channels are separated from each other using different spreading codes. 64 Walsh codes are used to identify each channel.

Type of forward channel:

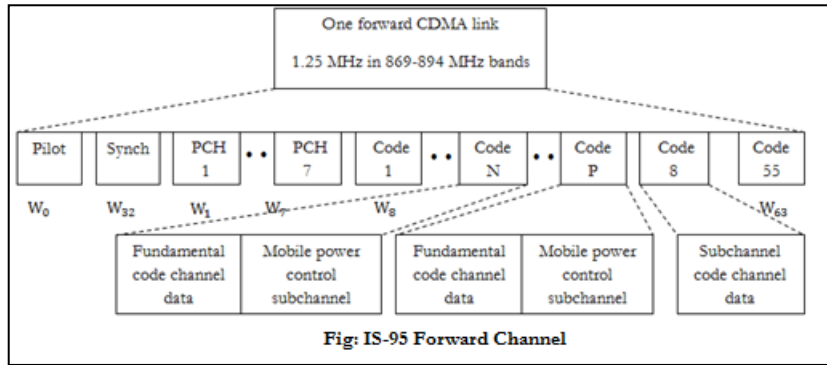


Fig: IS-95 Forward Channel

**A. Pilot channel:**

\* It provides phase for coherent demodulation, time, signal strength, comparison with reference signal for determining when to hand off for all mobile stations.

\* It is used to uniquely identify sectors or cells.

It is 4-6 db stronger than all other channels. It is used to lock onto other channel.

It is obtained using all zero Walsh code i.e. it contains no information except the RF carrier.

**B. Synch channel:**

It is used to acquire initial time synchronization.

Synch messages include System ID (SID), Network ID (NID), the offset of the PN short code and the paging channel data rate.

It broadcasts synch messages to the mobile station and operates at 1200 bps.

It uses Walsh code 32 for spreading.

**C. Paging channel:**

There are 7 paging channels used to page the mobile station in case of an incoming call, or to carry the control messages for call set up.

It uses Walsh code 1-7. There is no power control.

It is additionally scrambled by PN long code, which is generated by LFSR of length 42.

It operates at the rate of 4.8 kbps or 9.6 kbps.

**D. Traffic channel:**

There are 55 traffic channels used to carry actual information.

It supports variable data rates-RS1={9.6, 4.8, 2.4, 1.2 kbps} and RS2={14.4, 7.2, 3.6, 1.8 kbps}

RS1 is mandatory for IS-95. But support for RS2 is optional.

It also carries power control bits for the reverse channel.

**The forward channel modulation process is as follows:**

**A. Convolution encoder and repetition:**

Speech coded voice or user data is encoded using 1/2 rate convolution encoder with constraint length 9.

The speech coder exploits gaps and pauses in speech and reduces its output from 9600 bps to 1200 bps during silent period.

Whenever the user data rate is less than 9600 bps each bit is repeated to maintain a constant symbol rate of 19.2 kbps.

**B. Block interleaver:**

It makes data block of 20 ms in a random way i.e. consecutive bits are not in a same block.

It maps the data bits in a 24 by 16 matrix and then transmit it column wise.

This procedure is helpful in recovering the data back if a block is lost during channel transmission.

**C. Long PN sequence:**

In forward CDMA channel Direct Sequence is used for data scrambling.

Long PN sequence is user specific code of period 242-1242-1 chips.

PN sequence is generated from a 42 bit code also called as the public mask.

Public mask is specified as- M41 through M32 is set to 1100011000 and M31 through M0 is set to mobile station ESN bits. ESN= (E31, E30, E29, E28, ..... , E1, E0), permuted ESN= (E0, E31, E22, E13, E14, E26, E17, E8, ..... , E18, E9)

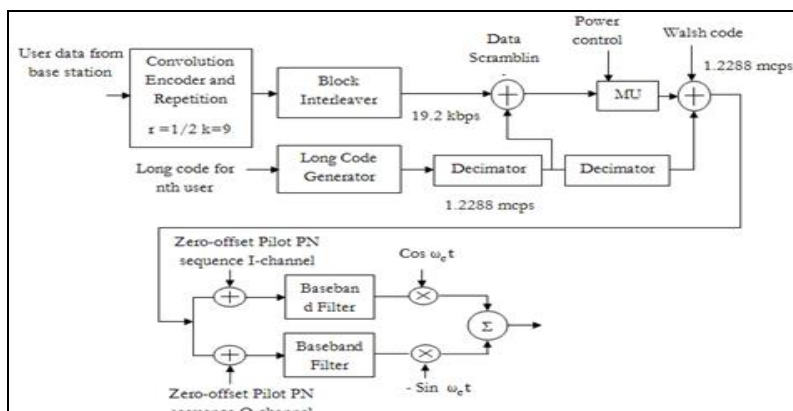


Fig.8 .Block diagram forward channel modulation process

**D. Data scrambler:**

It is performed after block interleaver. The 1.2288 MHz PN sequence is applied to decimator which keeps only the first chip out of every 64 consecutive PN chips.

The data rate from the decimator is 19.2 ksps. The data scrambling is performed by modulo-2 addition of the interleaver output with the decimator output symbol.

**E. Power control sub channel:**

Power control measures are sent by base station every 1.25ms. Power control commands are sent to raise or lower its transmission power in 1 db steps.

If the received signal is low 0 is sent over power control subchannel instructing the mobile station to increase its mean output power level. If mobile's power level is high 1 is sent to indicate that the mobile station should decrease the power level.

**F. Orthogonal covering:**

Orthogonal scrambling is performed following the data scrambling on the forward link.

Each traffic channel is transmitted on the forward CDMA channel is spread with a Walsh function at fixed rate of 1.2288 Mcps.

The Walsh functions consist of 64 binary sequences each of length 64 which are completely orthogonal to each other and provide orthogonal channelization. After orthogonal covering Quadrature modulation is performed.

**Conclusion :** The concept of DM-OFDM is a clever solution to overcome the spectral efficiency limitation of OFDM-IM by activating all subcarriers while still exploiting IM. In DM-OFDM scheme, all subcarriers are modulated and the index information is carried by the signal constellations assigned to the subcarrier groups. Two distinguishable signal constellations, a primary and a secondary constellation, are determined to transmit the data symbols from the active and inactive subcarriers of the OFDM-IM scheme, respectively.

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