NTU Journal of Engineering and Technology (2023) 2 (1) : 16-23
DOI: https://doi.org/10.56286/ntujet.v2i1

IRAQI Academic Scientific Journals

P-ISSN: 2788-9971 E-ISSN: 2788-998X
NTU Journal of Engineering and Technology
Available online at: https://journals.ntu.edu.iq/index.php/NTU-JET/index

Index Modulation OFDM Systems with Direct Pattern of Subcarrier Activation

Zainab Mohammed Abdulkareem[1], Abdulrahman Ikram Siddiq[2]
{ zainab.abdulkaream@ntu.edu.iq[1], draisiddiq@ntu.edu.iq[2] }
1. Northern Technical University Iraq, Technical Engineering College Kirkuk, 2. Northern Technical University Iraq, Technical Engineering College Kirkuk
Zainab Mohammed Abdulkareem, zainab.abdulkareem@ntu.edu.iq
AIS: draisiddiq@ntu.edu.iq

Article Informations

Received: 27-04- 2022,
Accepted: 04-11-2022,
Published online: 15-03-2023

Corresponding author:
Name: Zainab M. Abdulkareem
Affiliation: Technica Engineering College Kirkuk
Email:
zainab.abdulkaream@ntu.edu

Key Words:
Orthogonal frequency division multiplexing,
subcarrier index modulation,
subcarrier activation pattern,
bit error rate,
spectral efficiency.

A B S T R A C T

OFDM-IM is a spatial modulation technique applied to OFDM's block subcarriers, resulting in a modified version of OFDM. Compared to traditional OFDM, OFDM-IM boasts several benefits, such as enhanced bit-error rate (BER) performance and power efficiency. When working with OFDM-IM, the specification of subcarrier-activation-patterns (SAPs) is done by utilizing either look-up tables (LUTs) or a combinatorial approach to conform with data. However, the data-to-SAP mapping methods of both suffer from increased complexity as the number of subcarriers expands. The paper proposes a direct data-to-SAP mapping that eliminates the need for any type of look-up tables. Through the presented analysis and computer simulation results, it is demonstrated that the OFDM-IM system utilizing the proposed mapping scheme outperforms equivalent traditional OFDM-IM systems in both complexity and bit error rate (BER) performance.

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Introduction

OFDM is a popular technique for encoding digital data on multiple carrier frequencies and is widely used in many digital communication systems. The use of multiple subcarriers helps to combat the effects of multi-path propagation, which can cause inter-symbol interference and reduce the performance of the system. By using low symbol rate modulation schemes like PSK and QAM, the signal quality can be maintained in the presence of multi-path propagation. OFDM is widely used in many applications, such as digital television and audio broadcasting, internet access, wireless networks, and 4G mobile communications, because of its ability to provide high data rates and reliable communication over a wide bandwidth [1], [2].

The OFDM-IM is an extension of the traditional OFDM (Orthogonal Frequency-Division Multiplexing) scheme, where the information bits are encoded not only in the amplitude and phase of the subcarriers but also in the index of active subcarriers. This results in an increased spectral efficiency(SE), making it a potential solution for high data rate applications such as 5G cellular networks and wireless communication systems. The use of index modulation also offers benefits such as improved error performance, reduced complexity, and enhanced robustness against fading channels compared to traditional OFDM. In OFDM, it is the result of applying the spatial modulation (SM) technique to the subcarriers in each block. By this scheme, a part of the subcarriers are reactivated in response to incoming information bits so that M-ary symbols can be transmitted while the other subcarriers remain inactive. Activation patterns for subcarriers (SAPs) are determined based on data and are used to carry information as well. When compared to conventional OFDM, this saves power and is more efficient with regard to bit error rate (BER) performance [1], [2]. Despite OFDM-IM's advantages for large numbers of subcarriers, the main problem is that the mapping of data to SAP is complex [1]. A look-up table (LUT) or combinatorial method is typically used to map data to active subcarrier indexes in OFDM-IM systems. Each One of the main advantages of using a large number of subcarriers is that it provides higher spectral efficiency and better error performance. This is because more subcarriers mean more data can be transmitted in a given bandwidth. However, this advantage comes at the cost of increased computational complexity and larger LUT sizes. On the other hand, using a smaller number of subcarriers results in smaller LUT sizes and reduced computational complexity. However, this comes at the cost of reduced spectral efficiency and degraded error performance. Therefore, a trade-off must be made between the number of subcarriers used and the resulting performance and complexity. The choice of mapping scheme depends on the specific requirements of the system and the desired trade-off between performance and complexity.

The computational difficulty of the combinatorial mapping technique grows as n increases [1], [2].

A direct straightforward one-to-one method of determining the state of n subcarriers was used in earlier versions of OFDM-IM, such as [3]. Consequently, spectral efficiency and energy efficiency were affected by variable activation ratios. The data in [3], is separate into two streams. One of the data streams is subdivided, this subdivided data stream is utilized for conformable subcarrier activation with the plurality bit value (0 or 1) as part of a one-to-one relationship. The second stream of data has been used in modulating the active subcarriers. There is an announcement that the system will be capable of improving BER over traditional OFDM systems [3]. The ordinary system is altered in [4] to what is recognized then in the literature as OFDM-IM [1]. Following the introduction of OFDM-IM (Orthogonal Frequency Division Multiplexing with Index Modulation), multiple efforts have been made to address its various issues, such as enhancing the Bit Error Rate (BER) and Spectral Efficiency (SE), developing new index modulation schemes, and exploring its applications in Multiple Input Multiple Output (MIMO) systems, among others. In reference [5], a compact BER expression is derived. The improvement in the Euclidean distance between the received symbols was achieved in [6] through the use of various subblock interleaving techniques, as described in [7] and [8]. The rate, energy efficiency (EE), and spectral efficiency (SE) were addressed in [9], and the BER performance was analyzed in [10]. To improve the Spectral Efficiency (SE), [11] proposes the use of a varying number of effective subcarriers per subblock. The method applies OFDM-IM to both the in-phase and quadrature components independently. However, it results in a decreased Bit Error Rate (BER) performance compared to traditional OFDM-IM. To improve the Spectral Efficiency (SE), [11] proposes the use of a varying number of effective subcarriers per subblock. The method applies OFDM-IM to both the in-phase and quadrature components independently. However, it results in a decreased Bit Error Rate (BER) performance compared to traditional OFDM-IM systems.

The analysis of detection complexity and the proposal of low-complexity substitutes are presented in [12] and [13]. The examination of the use of OFDM-IM in Multiple Input Multiple Output (MIMO) systems is explored in [14] and [15].

This paper introduces a highly efficient data to SAP (Signal to Average Power) scheme. The proposed scheme is based on direct mapping and eliminates the need for storing LUTs or performing complex iterative computations, which are commonly used in other OFDM-IM systems.

The rest of the paper is organized as follows. First section gives a brief description to the determination of a specific SAP in OFDM-IM systems. Second section describes the proposed data-to-SAP mapping scheme. Third , Fourth sections are describing the enhancement in the SE, BER of the proposed scheme over conventional method respectively. Finally, the last section concludes the paper.

1. MODEL SYSTEM OF OFDM-IM

At its core, OFDM-IM separates an N-subcarrier OFDM block into g individual sub-blocks, each of which contains n subcarriers. Out of these n subcarriers, k are selected (activated) to be modulated by a M-ary constellation data symbol for each sub-block. The number of all possible SAPs is $C_k^n(=n!/(n-k)!\,k!)$. The operation of mapping $p_1(=\lfloor\log_2 C_k^n\rfloor)$ bits of data according to established LUT used to determine a nominated SAP, where $\lfloor.\rfloor$ is the greatest or largest lower integer function. Therefore, the actual number of utilized SAPs is 2 to the power of p_1, which is equivalent to the largest integer power of 2 that is less than C_k^n, where C_k^n is greater than 2 to the power of p_1 for all n and k greater than 1. In addition, p_2 $(=k\ \log_2 M)$ bits over the k active subcarriers of a sub-block are modulated. The process involves combining p_1 and p_2 bits to form a total of $p(=p_1+p_2)$ bits. These p bits are then packed into a subblock. After packing the bits, the system transmits one OFDM (Orthogonal Frequency Division Multiplexing) block, the total conveyed bits are equal to $m\ =\ g.$ Following this, the frequency domain of the OFDM-IM block is represented as $\boldsymbol{x}=[x_0,x_1,\dots,x_{N-1}]$T. This block undergoes cyclic prefix (CP) addition operations and inverse fast Fourier transform (IFFT), as performed in a conventional OFDM transmitter. The resulting time-domain block is then transmitted over a multipath Rayleigh fading channel that is subject to variation over time. The fading channel coefficients are assumed to be quasi-static, meaning that they remain fixed for the duration of one block. At the receiver, a replica of x is obtained by extracting the cyclic prefix (CP) and applying an N-point FFT. The frequency domain representation of the channel can be expressed as follows

$$\boldsymbol{y}\ =\ \boldsymbol{Hx}\ +\ \boldsymbol{w} \qquad (1)$$

Where $\boldsymbol{y}\,[y_0,y_1,\dots,y_{N-1}]^T$,$\boldsymbol{H}\ diag(h_0,h_1,\dots,h_{N-1})$, h_i is fading coefficient of a channel with $h_i\sim CN\ (0,1)$ and $\boldsymbol{w}\ =\ [w_0,w_1,\dots,w_{N-1}]^T$ is a separate Additive White Gaussian Noise (AWGN) such that $w_i\sim CN\ (0, N_0)$.

2. PROPOSED SUBCARRIER ACTIVATION SCHEME

The paper presents a revised direct data-to-SAP scheme that maps n bits of data to the state of n in-phase components of n subcarriers in an OFDM-IM subblock. The quadrature components are mapped to the opposite state, resulting in the in-phase and quadrature components of each subcarrier having opposite states. The proposed data-to-SAP mapping scheme eliminates the need for dividing the N-subcarrier OFDM block into subblocks, which is a departure from conventional mapping schemes. Conventional mapping schemes are designed to operate on subblocks of n subcarriers, where n is significantly less than N, with the aim of reducing complexity. However, the proposed scheme simplifies the mapping process by directly mapping n bits of data to the state of n in-phase components of n subcarriers in an OFDM-IM subblock. By avoiding the use of subblocks, the proposed scheme not only reduces complexity but also minimizes the overhead associated with subblock processing. [11].

The inphase components, I_i, of an OFDM block with N subcarriers are determined by a segment of N bits of data, where each bit corresponds to a specific subcarrier, indexed by $0\le i\le N-1$. The activation of the inphase components is one-to-one with the values of the corresponding bits. Conversely, the quadrature components are activated in a complementary fashion to the bits, such that the value of $b_i$determines whether the corresponding quadrature component is active or not, that is

$$I_i=b_i\quad and\ \ Q_i=\overline{b_i}\,,\qquad 0\le i\le N-1 \qquad (2)$$

The activation ratio of subcarriers is 50% with the proposed system, which is the same as the conventional OFDM-IM system when $k=n/2$. In the conventional system, this corresponds to the maximum number of SAPs and index bits. It is important to note that the maximum number of index bits in OFDM-IM systems is calculated using the formula $\frac{N}{n}\lfloor log_2 C_{n/2}^n\rfloor$.

The proposed scheme has a larger number of index bits compared to the conventional OFDM-IM for all values of N, n and k. For any arbitrary values of n and k, the value of p_1 (determined by $\lfloor\log_2 C_k^n\rfloor$) is always less than n [16]. Thus, it can be inferred that the number of index bits per OFDM block is greater in the proposed scheme compared to the conventional OFDM-IM, regardless of the values of N, n and k.

$$N>gp_1$$
$$N>\frac{N}{n}p_1 \qquad (3)$$

The proposed subcarrier activation scheme has a second major advantage, it is simple. It does not require the use of any Look-Up Tables (LUTs) or combinatorial calculations, which are commonly used in other OFDM-IM systems.

Nonetheless, this leads to the activation of N subcarrier components, denoted as c_i , where c_i belongs to the set of $\{I,Q\}$ and $0\le i\le N-1$. These N active components are grouped into $N/2$ pairs to facilitate $N/2$ complex-valued M-QAM constellation symbols, similar to the conventional OFDM-IM active subcarrier modulation. As a result, the proposed and traditional OFDM-IM systems utilize the same amount of data to modulate the active subcarriers.

As is done in usual OFDM systems, the N-subcarrier OFDM block is then processed by applying IFFT and CP additions before being transmitted through the communication channel. The receiver will at first need to remove the CP and do a FFT, which will follow by determining the SAP of the received N-subcarrier block, followed by demodulating the active subcarrier components in order to recover the index and modulating data bits respectively.

By comparing the magnitudes of the $I \, and \, Q$ components of the i^{th} received subcarrier denoted as ($\acute{I_\iota}$ and $\acute{Q_\iota}$) one can easily determine their respective states.

$$\acute{I_\iota} = \begin{cases} 1 & if \, |I_i| > |Q_i| \\ 0 & otherwise \end{cases} \quad (4)$$

and

$$\acute{Q_\iota} = complement \, of \, \acute{I_\iota} \quad (5)$$

The i^{th} recovered index bits, $\acute{b_\iota}$ is calculated as

$$\acute{b_\iota} = \acute{I_\iota} \quad for \, 0 \le i \le N-1 \quad (6)$$

Once the active subcarrier components have been identified, they are paired up in a way that resembles the process in the transmitter. These pairs correspond to individual M-QAM symbols, which are then demodulated to retrieve the modulating data bits.

3. SPECTRAL EFFICIENCY

The spectral efficiency refers to the amount of information that can be transmitted per unit of bandwidth. In the context of OFDM-IM systems, spectral efficiency is commonly expressed as the number of transmitted data bits per subcarrier. This metric is often used to compare different OFDM-IM systems and to evaluate their overall performance.

In this particular case, we are considering two different OFDM-IM systems: proposed SE_p and conventional SE_{im}. The SE_p and SE_{im} OFDM-IM systems that have been presented with their respective spectral efficiencies as:

$$SE_p = (N + \frac{N}{2}\log_2 M)/N$$

$$= 1 + \frac{1}{2}\log_2 M \quad \text{b/s/Hz} \quad (7)$$

And

$$SE_{im} = \frac{p_1 + p_2}{N}$$

$$= \frac{1}{n}\left(\lfloor \log_2 C_k^n \rfloor + k \, \log_2 M \right) \quad \text{b/s/Hz} \quad (8)$$

In the proposed system, the spectral efficiency is solely determined by the symbol modulation order M and is independent of the number of subcarriers n. On the other hand, the spectral efficiency of the SE_{im} system is dependent on both the number of subcarriers, denoted as n, as well as the subcarrier index, denoted as k, in addition to the symbol modulation order M.

Figure 1, illustrates the plots of SE_p and SE_{im} $(for \, k = n/2)$ against different values of M, where it is evident that SE_p is consistently higher than SE_{im} for a given M. However, as n increases, the value of SE_{im} approaches SE_p. It should be highlighted that this increase in SE_{im} comes at a significant cost of increased data to SAP mapping complexity.

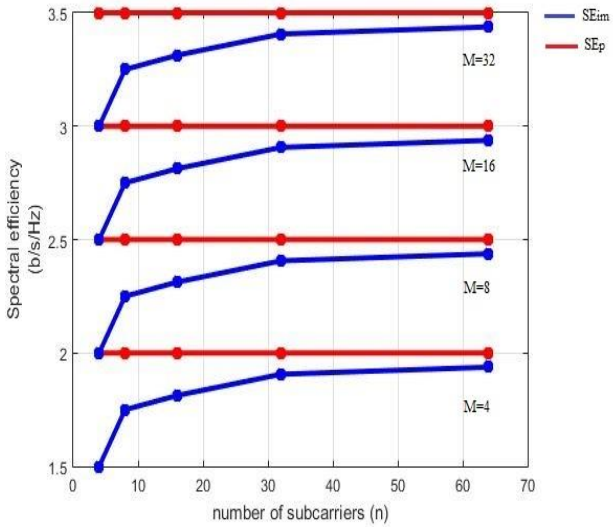


Figure 1. SPECTRAL EFFECIENCY.

4. BER PERFORMANCE

MATLAB simulations were conducted to assess and compare the bit error rate (BER) performance of OFDM-IM systems utilizing both the conventional method and the newly proposed Dir-OFDM-IM mapping scheme to SAP. The simulation parameters were chosen to ensure that the SE of the tested systems was comparable.

Referring to Figure 1, the systems were simulated for the parameters given in Table 1, with $N = 128, n = 4 \, and \, k = 2$, over time varying frequency selective Rayleigh fading channel.

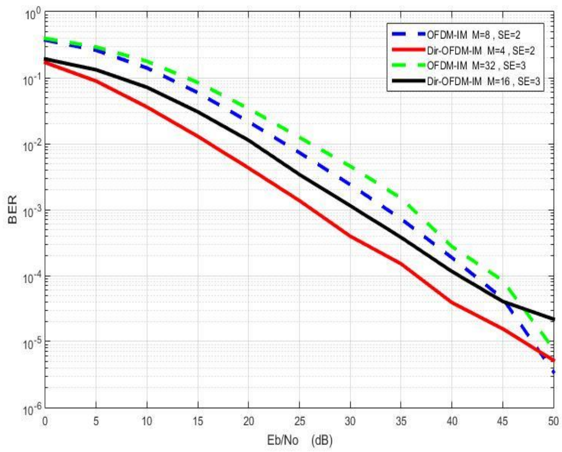
TABLE 1. SIMULATION PARAMETERS

SE (b/s/Hz)	***M***	
	OFDM-IM	**Dir-OFDM-IM**
2	**8**	**4**
3	**32**	**16**
3.5	**64**	**32**
4	**128**	**64**

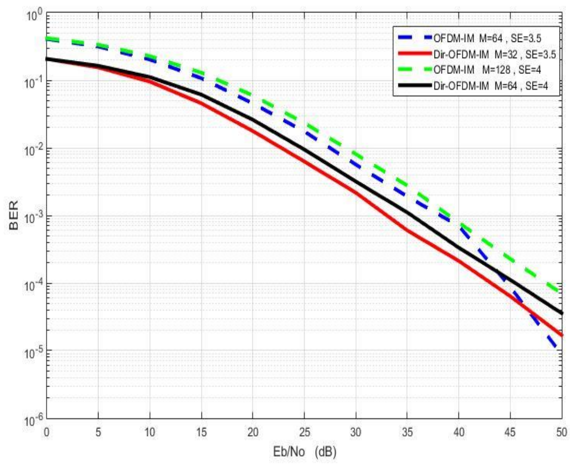
Figure 2, depicts the BER performance of the tested systems, namely the conventional OFDM-IM and the proposed direct mapping OFDM-IM, across different

SNR values ranging from (0 to 50). The plotted curves illustrate the improved BER performance achieved by the proposed system over the traditional OFDM-IM scheme. Furthermore, to attain a BER of 10-4, the Dir-OFDM-IM system requires a lower SNR value than the conventional OFDM-IM system, where the gain (the difference in SNR values) between the two systems is 4 dB, 4.9 dB, 2dB and 1dB when the values of the SE of the two systems is equal to 2, 3, 3.5 and 4 respectively. However, the primary factor contributing to this improvement is the utilization of a lower modulation order M in the proposed system compared to the conventional OFDM-IM, despite maintaining the same spectral efficiency. This is because a smaller M results in fewer errors during symbol demodulation, ultimately leading to better error performance. In addition, the proposed system offers a higher level of simplicity and independence when determining the state of a particular subcarrier, without any impact on the adjacent subcarriers. In conventional OFDM-IM systems, the determination of subcarrier states within a given subblock is typically performed collectively. This is true regardless of whether a look-up table (LUT) or combinatory mapping is used. The issue with this approach is that it may introduce significant errors during the mapping of subcarrier allocation pattern (SAP) to data at the receiver. This is due to the fact that if any of the subcarriers within a subblock are incorrectly identified, it can impact the reception of other subcarriers, leading to erroneous decoding of the transmitted data. The proposed direct mapping scheme in Dir-OFDM-IM, however, provides greater simplicity and independence in determining the state of a specific subcarrier, which in turn, results in more accurate SAP to data mapping at the receiver.

The BER curves of Figure 2, suggest the proposed system as a low complexity alternative of ordinary OFDM-IM.



(a). Comparison of BER performance between two systems at SE=2&3.



(b). Comparison of BER performance between two systems at SE=3.5&4.

Figure 2. BER performance of ordinary OFDM-IM and proposed direct OFDM-IM.

5. COMPLEXITY COMPARISION

In conventional OFDM-IM systems, the active subcarrier indices are determined based on the transmitted data, utilizing either a LUTs or combinatorial mapping method. However, the complexity of these data to subcarrier allocation pattern (SAP) mapping schemes is highly dependent on various parameters, and as the number of subcarriers (n) increases, the complexity of the mapping schemes grows significantly.

Firstly, the LUT-based approach's intricacy can be measured based on the storage memory size required. This involves storing 2^{p1} subcarrier allocation patterns SAPs, each containing n elements, for a given number of subcarriers n and active subcarriers k in a subblock. Additionally, at the receiver end, an exhaustive search is necessary to locate a match in the LUT for each detected SAP. Once a match is found, the corresponding p_1 data can be demapped.

The combinatorial mapping scheme, as previously reported in [17] and [18], enables a unique and direct mapping between natural numbers and k combinations for any given values of n and k. In this scheme, the p_1 data bits are first converted to a decimal number, which is labeled as Z. The combinatorial algorithm then utilizes this decimal number as an input to select the indices of the active subcarriers $C_1, C_2, \dots, C_k$ by using

$$Z = C_k^{Ck} + \dots + C_2^{C2} + C_1^{C1} \quad (9)$$

The process of identifying active indices is accomplished through iterative steps, wherein C_k is selected such that $C_k^{Ck} \leq Z$, followed by the selection of C_{k-1} such that $C_{k-1}^{Ck-1} \leq Z - C_k^{Ck}$, and so on. This algorithm necessitates computing the binomial combinations to map p_1 to the SAP associated with it. Consequently, the combinatorial scheme incurs a substantial computational burden

The proposed scheme is designed to simplify the process of determining the state of each subcarrier by utilizing only a single bit of data. This method is described in detail in section III of the report. The direct subcarrier activation scheme employed in this approach circumvents the need for LUTs and combinatorial calculations, thereby reducing the complexity of the system. Instead of relying on lookup tables or combinatorial algorithms, the proposed scheme maps each subcarrier to a state that corresponds directly to a single data bit. This significantly simplifies the data to subcarrier mapping process, allowing for more efficient and streamlined data transmission. The degree of complexity in mapping these data to SAP schemes is influenced by various parameters, and it intensifies significantly with an increase in n. However, as n increases, SE_{im} also increases. It is important to observe that this rise in SE_{im} comes at the cost of a substantial escalation in the complexity of data to SAP mapping. Overall, the proposed direct subcarrier activation scheme provides a more straightforward and efficient alternative to the conventional LUT and combinatorial mapping schemes used in existing OFDM-IM systems. For different n and m values, Table 2, compares SE between OFDM-IM and direct OFDM-IM.

TABLE 2. SE OF THE OFDM-IM AND DIRECT OFDM-IM FOR DIFFERENT n AND M VALUES:

n	Dir. ofdm-im M=4	ofdm-im		Dir. ofdm-im M=16	ofdm-im	
		M=4	M=8		M=16	M=32
4	2	1.5000	2	3	2.5000	3
8	2	1.7500	2.2500	3	2.7500	3.2500
16	2	1.8125	2.3125	3	2.8125	3.3125
32	2	1.9063	2.4063	3	2.9063	3.4063
64	2	1.9375	2.4375	3	2.9375	3.4375
128	2	1.9688	2.4688	3	2.9688	3.4688

CONCLUSION

The paper introduces a new approach for activating the subcarriers "direct data to SAP mapping scheme" and it is presented as a simpler alternative to existing schemes that require look-up tables or combinatorial calculations. The proposed scheme uses a single bit of data to determine the state of each subcarrier, resulting in a more straightforward activation process. By eliminating the need for complex mapping schemes, the proposed approach aims to improve the efficiency and performance of OFDM-IM systems. The article explains the workings of the proposed scheme and showcases simulation results that exhibit its improved bit error rate (BER) performance as compared to traditional OFDM-IM systems. The analysis presented indicates that the proposed scheme surpasses conventional LUT and combinatorial mapping methods in terms of complexity. Furthermore, the computer simulation results demonstrate that utilizing the proposed scheme in OFDM-IM leads to a superior bit error rate (BER) performance in comparison to equivalent conventional OFDM-IM systems. As a result, one can deduce that the proposed data to SAP scheme exhibits promise and has the potential to be implemented in upcoming generations of communication systems as a more effective and less complex substitute for traditional schemes.

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