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Study of Combination Communication Regime

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ABSTRACT In this paper, to the best of our knowledge, we propose a comprehensive combination communication regime for the first time, which uses the spatial position combination of different physical entities, rather than the change of physical parameters, to represent the information. The maximum information capacity formula for combination communication is present in this paper. Furthermore, several innovative combination communication modes, such as partial combination communication (PCC), inverse combination communication (ICC), and generalized combination communication (GCC), are presented and mathematically analyzed. The results show that the proposed combination communication modes, especially GCC, can effectively enhance the flexibility and transmission efficiency of the communication system, compared to existing spatial modulation schemes. In addition, the computational complexity and BER performance are discussed. Finally, a demonstration application shows that combination communication can address certain specific dilemmas in the traditional Shannon-Nyquist communication regime, such as reducing channel crosstalk in the wavelength division multiplexing (WDM) system while achieving channel capacity beyond the expected level. ICC demonstrates its advantages in maintaining a simple hardware implementation while achieving a high capacity.

INDEX TERMS Combination communication, spatial modulation, Shannon-Nyquist communication regime, channel capacity, WDM.

I. INTRODUCTION

To date, in most communication systems, information transmission is completed by changing physical parameters, such as the amplitude, phase, frequency, light intensity, and polarization of an individual physical entity (e.g., a lightwave with a certain wavelength). However, from our viewpoint, in addition to the conventional communication regime (i.e., the Shannon-Nyquist regime), the combination of physical entities can also be applicable to information transmission.

We make the following definition:

Definition: Combination Communication is a communication regime in which changes in the combinations of physical or logical entities are used to represent information.

An illustrative example will help us to understand this definition. Imagine that two people, Alice and Bob, attend a scheduled concert. There are four scenarios regarding their attendance, that is, four different combinations, as shown in Table 1. From the perspective of information theory, the information capacity of attending the concert equals two bits because there are four combinations(possibilities) in total, and we can use two bits (i.e., 11, 10, 00, 01) to represent all possibilities. Assume that each possibility occurs with the same probability, that is, $\log_2 4 = 2$.

TABLE 1. Associations between information representation and combination (Alice & Bob).

Attendance Scenario	Bit representation	Attendance Scenario	Bit representation
Both Alice and Bob attended	11	Only Alice attended	10
Both Alice and Bob absent	00	Only Bob attended	01

Imagining a wavelength division multiplexing (WDM) system that only consists of two wavelengths, λ_1 and λ_2, let us say $\lambda_1 \rightarrow$ Alice, $\lambda_2 \rightarrow$ Bob, the combination scenarios of λ_1 and λ_2 are listed in Table 2. We assume that the change between different combinations is completed within one unit of time. Thus, such a WDM system is capable of transmitting 2 bits per unit time. It follows a different information transmission regime from its Shannon-Nyquist counterpart.

In the Shannon-Nyquist regime (conventional communication system), information transmission is accomplished by

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TABLE 2. Associations between information representation and combination(wavelengths).

Combination Scenario	Bit representation	Combination Scenario	Bit representation
Both λ_1 and λ_2 transmitted	11	Only λ_1 transmitted	10
Both λ_1 and λ_2 unlaunched	00	Only λ_2 transmitted	01

changing certain physical parameters of physical entities, such as the light intensity of the light wave. Suppose that intensity modulation/direct detection (IM/DD) is completed within one unit time, then, a two-wavelength conventional WDM system can transmit two bits per unit time in total. Although the information transmission rates of the two communication systems above-mentioned are the same, the difference is obvious: Combination Communication uses the changes in the combination status of physical entities to transmit information, rather than the changes in physical parameters (such as amplitude and phase) of a physical entity.

There have been a number of studies involving concepts similar to Combination Communication, mainly in the field of wireless communications. For example, a spatial modulation (SM) scheme was proposed in [1], in which only one transmit antenna is selected and activated from n_t antennas at a time. The novelty of [1] is that it first exploited the location of the antenna as an additional source of information. Information is contained not only in the transmitted symbol, as a traditional communication system does, but also in the physical location of the antenna. In contrast, in previous SM schemes, such as space-time bit-interleaved coded modulation [2], [3], the antenna pattern is only recognized as a spatial constellation, but is not used as a source of information. The shortcoming of [1] is that only one antenna is selected from n_t antennas as the source of information, whereas the remaining $n_t - 1$ antennas are idle. In fact, [1] is concerned with eliminating interchannel interference (ICI) rather than the transmission efficiency. Let R be the information transmission rate in bit, for M-ary QAM modulation, the R of the SM scheme proposed by [1] can be formulated as follows:

$$R = \log_2 n_t + \log_2 M \tag{1}$$

An improved spatial modulation scheme called generalized space shift keying (GSSK) was proposed in [4] and further investigated in [5], where n_a out of n_t LEDs are activated for information transmission each time instant [5], i.e., the combination of LEDs is used as an independent source for information transmission. Thus, there are $\binom{n_t}{n_a}$ possibilities regarding the pattern of activated LEDs, which offers increased spectral efficiency compared to previous SM schemes. However, the light intensity of the LED is not used to carry information in GSSK. Thus, the R of GSSK is:

$$R = \left\lfloor \log_2 \binom{n_t}{n_a} \right\rfloor \tag{2}$$

where $\lfloor\ \rfloor$ represents the rounding down operation. It can be seen that there are $\binom{n_t}{n_a}$ possible constellation points and a maximum of $\left\lfloor \log_2 \binom{n_t}{n_a} \right\rfloor$ bits/symbol in GSSK. Thus, the number of constellation points, i.e., n_t and n_a, should be carefully designed so that $\binom{n_t}{n_a}$ could be, or at least not too far away from, the integer power of 2. Otherwise, the LED resources may be wasted. For example, in the case of $n_t = 6$, $n_a = 2$, we have $\binom{n_t}{n_a} = 15$, which is very close to 16, however, R can only be 3 bits because $\left\lfloor \log_2 \binom{n_t}{n_a} \right\rfloor = \lfloor \log_2 15 \rfloor = 3$, which fails to reach 4 bits. With an increase in power, the number of LEDs undergoes drastic changes between two adjacent powers. For example, to fit 2^5, 32 LEDs are required, whereas to fit 2^6, the number of LEDs must be increased to 64, which means that even when using 63 LEDs, R is still equal to 5, rather than 6. The situation is similar for applications in which LEDs are replaced by antennas. Obviously, GSSK cannot offer flexible resource utilization because it may have to deploy a large number of LEDs or antennas to match a power of 2. This shortcoming wastes hardware resources and restricts the application scope of the existing SM schemes. There are also many other schemes involving SM, as well as index modulation, which can be considered a variant of SM, for example, SSK, GSM, FGSM, GCIM-SM, and QSM [6]–[11], but their utilization efficiency of antenna/LED never exceeds the references [1], [4], [5].

The major contributions of this study are summarized as follows. First, based on theoretical analysis, we propose a Combination Communication regime for the first time. The performance of Combination Communication is comprehensively investigated, including the information capacity, working mechanism, and bit error rate (BER). Second, several innovative Combination Communication modes that can improve the efficiency of resource utilization or increase the flexibility of applications are proposed. Third, an application scenario in which the proposed Combination Communication modes are used to address a dilemma in optical communications is presented, thus demonstrating the advantages of our scheme.

The remainder of this paper is organized as follows. In Section II, we present the Combination Communication regime, and the mechanism is analyzed in mathematics. We then propose several innovative Combination Communication modes that have never been presented before. In Section III, we show the potential and advantages of the proposed Combination Communication modes in an optical communication scenario. The relevant results are analyzed in this section. Finally, Section IV concludes the paper.

II. THEORETICAL ANALYSIS

Although analogous concepts, such as SM and improved SM schemes, have been developed in previous studies, the theoretical basis of Combination Communication has never been discussed in detail. Moreover, existing SM schemes are application-oriented and do not seriously consider Combination Communication as an independent communication regime. In this section, a comprehensive investigation of Combination Communication, including the working mechanism, theoretical analysis, and relevant formulas, will be presented.

Combination Communication uses different combinations of physical entities to represent information. The combinations of physical entities consist of two elements: physical entity and position, and the position can be spatial, temporal, or logical. For simplicity, physical entity is sometimes called "entity" in this paper.

Previous SM schemes only considered taking one physical entity out of i physical entities, that is, $\binom{i}{1}$, or k physical entities out of i physical entities, that is, $\binom{i}{k}$, but did not consider full and partial combination effects. In mathematical language, the full combination can be expressed as: $\sum_{k=0}^{i}\binom{i}{k}$, and the partial combination can be expressed as: $\sum_{k=0}^{j}\binom{i}{k}$, where $0 \leqslant j < i$. We call Combination Communication, which employs the full combination effect, **Full Combination Communication (FCC)**. Unlike other SM schemes, in FCC, the number of selected entities is not fixed each time, but varies from 0 to i. 0 means no entity is selected. For example, for $i = 4$, k could be 0, 1, 2, 3, or 4, thus, the number of combinations is equal to: $\binom{4}{0}+\binom{4}{1}+\binom{4}{2}+\binom{4}{3}+\binom{4}{4}$. From the perspective of information theory, this is equivalent to increasing the information capacity because FCC's number of combinations is greater than that of any fixed k scheme, i.e., other SM schemes. Similarly, we call Combination Communication, which employs the partial combination effect, **Partial Combination Communication (PCC)**. Following the example above, if k is limited up to j, let us say $j = 2$, then the number of combinations of PCC is equal to: $\binom{4}{0}+\binom{4}{1}+\binom{4}{2}$. The advantages of the PCC will be presented in the subsequent paragraphs of this section.

Let C be the information capacity of the communication system (in binary bits), in this article, the meanings of information capacity and information transmission rate are interchangeable, assuming that there are i physical entities available for full combination at the same time, then:

$$C = \left\lfloor \log_2 \sum_{k=0}^{i}\binom{i}{k} \right\rfloor \tag{3}$$

Conclusion 1: Given i entities, the information capacity C of Full Combination Communication (FCC) is equal to i, in mathematics,

$$C = \left\lfloor \log_2 \sum_{k=0}^{i}\binom{i}{k} \right\rfloor = \log_2 2^i = i \tag{4}$$

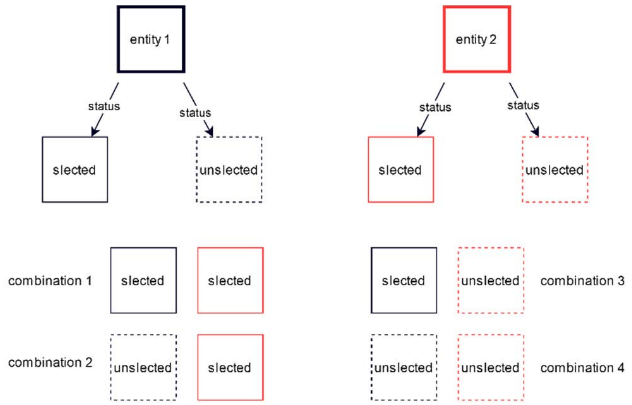

FIGURE 1. The full combination of two entities.

Proof: If i entities are independent of each other, the number of full combinations of i entities is equal to the product of the number of statuses that each entity can have. In the context of this paper, each entity has two statuses, "selected" and "unselected", and the number of all possible combinations is equal to 2^i. Fig.1 shows an illustrative example that includes two entities, each entity has two statuses, "selected" and "unselected", the number of full combination is $2 \times 2 = 4$ as listed from combination 1 to combination 4 in Fig. 1. For more entities, for example, three entities, the situation can be deduced in a similar manner, that is, $2 \times 2 \times 2 = 8$. In this way, we can conclude that for a full combination consisting of i entities, the number is 2^i. Therefore, the corresponding information capacity of the FCC is i.

That is, for Combination Communication employing i entities, the maximum information capacity is no more than i bits. Considering that the number of activated entities in PCC mode is no more than j, $0 \leq j < i$, because of $\sum_{k=0}^{j}\binom{i}{k} < \sum_{k=0}^{i}\binom{i}{k}$, the information capacity of PCC is less than i.

Let W denote the channel bandwidth and assume that the minimum distinguishable frequency space is ΔW, thus the number of distinguishable frequencies (physical entities) i is equal to $W/\Delta W$. According to (4), the information capacity formula of FCC, where the information capacity C is equivalent to the channel capacity, we have,

$$C = \log_2 \sum_{k=0}^{W/\Delta W}\binom{W/\Delta W}{k} = \frac{W}{\Delta W} \tag{5}$$

(5) is the maximum information capacity of the Combination Communication. Compared to a conventional communication system that includes $W/\Delta W$ frequencies, where we assume two-ary modulation is adopted, and let the

standard unit of information capacity be one bit/channel/unit time(bcu), thus, we can conclude that:

Conclusion 2: The information capacities of both conventional communication systems and FCC systems are equal to $W/\Delta W$ bits, in the absence of noise.

The difference between them lies in that: to reach $W/\Delta W$ bits, using a conventional communication system, $W/\Delta W$ entities must be presented in the channel at the same time. By contrast, when using Combination Communication, certain entities may not be presented.

Combination Communication can be used in conjunction with the Shannon-Nyquist regime in the same system. In this case, the information is divided into two parts: one part is used to modulate the physical parameters of the physical entity, for example, the light intensity of the lightwave, and the other part is mapped to the combination of physical entities. Select k out of i entities to represent the combination information, and considering that k entities can carry k bits per unit time in the conventional communication mode, let C_{hybrid} be the total information capacity of the hybrid system, we have,

$$C_{hybrid} = \left\lfloor \log_2 \binom{i}{k} \right\rfloor + k \tag{6}$$

It is worth noting that if the conventional communication mode uses M-ary modulation, then the result of (6) is $\left\lfloor \log_2 \binom{i}{k} \right\rfloor + k \log_2 M$. This article uses the default setting: $M = 2$, thus, $\log_2 M = \log_2 2 = 1$.

In addition to the existence of entities, the absence of entities can also be used to represent information in Combination Communication. For instance, given the prior knowledge as follows: there are i entities, however, k out of i entities are missing at the transmitter, $k \leq i$, and k entities are variable in the next unit time. Thus, the corresponding information can be recognized at the receiver by detecting the combination pattern of missing entities. Such a Combination Communication mode is called **Inverse Combination Communication (ICC)**. In ICC mode, the receiver recognizes information by detecting the combination of missing entities. Suppose k out of i entities are not activated at the transmitter, then the activated $i-k$ entities can carry $i-k$ bits per unit time in the conventional mode, and let C_{hybrid}^{ICC} be the total information capacity of the hybrid ICC system, we have,

$$C_{hybrid}^{ICC} = \left\lfloor \log_2 \binom{i}{k} \right\rfloor + (i-k) \tag{7}$$

The ICC mode has never been proposed before. It has certain advantages of a compact structure and higher capacity, which will be demonstrated in Section III.

Like ICC, PCC is another innovative Combination Communication mode that has never been proposed before. In addition to the above-mentioned form $\sum_{k=0}^{j} \binom{i}{k}$, PCC can be used in other forms, such as $\sum_{k=j}^{l} \binom{i}{k}$, where $0 \leq j < l < i$. $\sum_{k=j}^{l} \binom{i}{k}$ means that the contribution to combination patterns comes from not only $\binom{i}{j}$ but also $\binom{i}{j+1}$, $\binom{i}{j+2}$, ..., and $\binom{i}{l}$. In addition, it is also possible to use only use the specified combinations, such as $\binom{i}{j}$ and $\binom{i}{j+3}$.

SM schemes only use the sole combination form: $\binom{i}{k}$, namely, k is fixed. For example, $\binom{7}{3} = 35 \rightarrow R = 5$. In PCC mode, k can be different each time within a given scope, for example, $\sum_{k=0}^{3} \binom{7}{k}$, where k can be any one of 0, 1, 2, or 3. Thus, $\sum_{k=0}^{3} \binom{7}{k} = 64 \rightarrow R = 6$. It can be seen that PCC is capable of achieving a higher capacity, and especially more flexible resource utilization, at the same time, without increasing the number of physical entities in a channel.

Assume that each combination pattern occurs equiprobably in PCC mode, and the activated entities are also modulated by changing the physical parameter at the same time, let C_{hybrid}^{PCC} be the total information capacity of the hybrid PCC system, then,

$$C_{hybrid}^{PCC} = \left\lfloor \log_2 \sum_{k=j}^{l} \binom{i}{k} \right\rfloor + \xi, \quad 0 \leqslant j \leqslant l < i \tag{8}$$

where,

$$\xi = \frac{j \cdot \binom{i}{j} + (j+1) \cdot \binom{i}{j+1} + \cdots + l \cdot \binom{i}{l}}{\sum_{k=j}^{l} \binom{i}{k}} \tag{9}$$

ξ represents the information capacity transmitted by the conventional communication mode in a hybrid PCC system. The explanation for this is as follows. In an unit time, the number of total possible combination elements is $\sum_{k=j}^{l} \binom{i}{k}$, in which j selected entities contribute $\binom{i}{j}$ possible combination elements, $j+1$ selected entities contribute $\binom{i}{j+1}$ possible combination elements, ..., l entities contribute $\binom{i}{l}$ possible combination elements. Assuming that the number of selected entities, that is, $j, j+1, \ldots, l$, occurs with the same probability, and each entity carries 1 bit in the conventional communication mode, considering that $\binom{i}{j} + \binom{i}{j+1} + \cdots + \binom{i}{l} = \sum_{k=j}^{l} \binom{i}{k}$, from the point of view of probability theory, the information capacity ξ is equal to: $j \cdot \frac{\binom{i}{j}}{\sum_{k=j}^{l}\binom{i}{k}} + (j+1) \cdot \frac{\binom{i}{j+1}}{\sum_{k=j}^{l}\binom{i}{k}} + \cdots + l \cdot \frac{\binom{i}{l}}{\sum_{k=j}^{l}\binom{i}{k}}$, thus, (9) is derived.

It is can be seen that an apparent difference between the proposed PCC mode and the existing SM schemes is that: the number of the selected entities in the SM schemes is fixed, while the number of the selected entities is variable in the PCC mode. This change not only improves the efficiency of resource utilization but also enhances the information capacity of the proposed system.

Furthermore, we propose the **Inverse Partial Combination Communication (IPCC)** mode, which means that the missing entities, rather than the activated entities, are used to represent information in the PCC. When integrating IPCC with the conventional communication mode, in which the activated entities are modulated by changing their physical parameters, let C_{hybrid}^{IPCC} be the total information capacity of the hybrid IPCC system, we have,

$$C_{hybrid}^{IPCC} = \left\lfloor \log_2 \sum_{k=j}^{l} \binom{i}{k} \right\rfloor + \xi'' \tag{10}$$

where k denotes the number of missing entities, and

$$\xi'' = \frac{(i-j)\cdot\binom{i}{j} + (i-j-1)\cdot\binom{i}{j+1} + \cdots + (i-l)\cdot\binom{i}{l}}{\sum_{k=j}^{l}\binom{i}{k}} \tag{11}$$

ξ'' represents the information capacity transmitted by the conventional communication mode in a hybrid IPCC system. The derivation is omitted because it can be referred to that of ξ. It is worth mentioning that $i-j$ is used to replace j in (11) because the actual number of active physical entities is $i-j$ rather than j in ICC mode.

Next, we propose **Generalized Combination Communication (GCC)** as a more general Combination Communication mode. Let S be a complete set of combination elements, where the "complete set" means the number of combination elements is exactly equal to the power of two to match binary applications, let S_r denote the set of combination elements of $\binom{i}{r}$, where r denotes the number of selected entities, $0 \leq r \leq i$, if the elements, all of which together make up a complete set S, come from different S_r, then we call the Combination Communication employing such a complete set GCC. Let N_{S_r} denote the number of elements of S_r, and $\overline{N_{S_r}}$ denote the number of elements that are selected from S_r, obviously, $\overline{N_{S_r}} \leq N_{S_r}$, Assuming that $\sum_{r=0}^{i}\overline{N_{S_r}}$ is able to form a complete set S of GCC, then the information capacity C^{GCC} of GCC can be formulated as follows:

$$C^{GCC} = \left\lfloor \log_2 \sum_{r=0}^{i} \overline{N_{S_r}} \right\rfloor \tag{12}$$

Considering a hybrid system in which the GCC mode is operated in conjunction with a conventional communication system, then the information capacity C_{hybrid}^{GCC} of such a system can be formulated as follows:

$$C_{hybrid}^{GCC} = \left\lfloor \log_2 \sum_{r=0}^{i} \overline{N_{S_r}} \right\rfloor + \xi''' \tag{13}$$

where,

$$\xi''' = \frac{\sum_{r} r \cdot \overline{N_{S_r}}}{\sum_{r} \overline{N_{S_r}}} \tag{14}$$

ξ''' represents the information capacity transmitted by the conventional communication mode in a hybrid GCC system. This derivation is omitted because the methodology can refer to the derivation of ξ.

It can be seen that an apparent difference between the GCC and the other Combination Communication modes is that: in other modes, we have to select all elements of S_r. In GCC, the combination elements are selectable from S_r and thereby the combination elements are variable even both i and r are determined. We can gather specific elements from different S_r to construct a complete set S instead of using all elements in S_r. This difference makes GCC more flexible than the other modes and existing SM schemes.

At the end of this section, let us make a compact discussion regarding the performance of the average bit error rate (ABER) of the pure Combination Communication modes. First, we consider the scenario of Gaussian white noise. Suppose a Gaussian white noise channel in which the symbol error occurs 1 symbol per second (s/s) on average, i.e., the symbol error rate (SER) is 1 s/s. Obviously, if using the two-ary intensity modulation, the ABER of a conventional communication system is 1 bit per second (b/s). With an increase in SER, the ABER of the conventional communication system also increases accordingly. In the proposed Combination Communication modes, any symbol error, that is, the misidentification of any physical entity, will fail in the entire bit block. Specifically, the size of the bit block depends on the information gain achieved by the Combination Communication modes. For example, for the GCC mode, if its combination element number is 32, then its information gain is $\log_2 32 = 5$, and a symbol error will cause the entire bit block to fail, that is, five errors (in bits), i.e., the ABER is 5 b/s. Let Φ be the number of selected combination elements, $\mathbb{G}$ be the information gain of the Combination Communication, then $\mathbb{G} = \log_2 \Phi$. In most cases, Combination Communication systems use multiple channels that are independent of each other. Assuming that the SER of each channel is at the level of ℓ s/s, then the ABER of the Combination Communication systems will be no more than $\ell\mathbb{G}$ b/s even if the multiple channels have symbol errors simultaneously. This is because the physical entities that are accommodated in these channels jointly consist of a complete state space, that is, a complete set of combination elements. Any misidentification of the physical entities, regardless of whether one physical entity or multiple physical entities, will lead to the global failure of the information delivery. In contrast, in a conventional communication system with multiple channels, errors occurring in multiple channels result in the superposition effect. Assuming there are $\mathbb{M}$ channels in the conventional communication system and the SER of each channel is at the level of ℓ s/s, the ABER of such a system is $\ell\mathbb{M}$ b/s.

The Combination Communication regime can be regarded as a band-pass communication system if the ''frequency'' is the parameter that identifies the physical entity. In this case, the detector in Combination Communication acts as a narrow-band filter that can remove noise outside the working frequency band and improve the signal-to-noise ratio (SNR). Thus, narrowing the working bandwidth of the detector is an effective means to improve the ABER performance of Combination Communication systems.

III. DISCUSSION & RESULT ANALYSIS

WDM technology is widely deployed in high-capacity optical communication systems. In WDM, different wavelengths are combined by a multiplexer (MUX), and the combined optical signal is coupled into a single optical fiber and transmitted to the receiver. At the receiver side, the demultiplexer (DEMUX) splits the incoming beam into separate wavelengths, just as before entering the MUX. Fig.2 shows a typical WDM system that consists of eight wavelengths, marked from λ_1 to λ_8. In general, the information capacity of WDM system is directly proportional to the number of wavelengths used in the optical fiber channel. However, the number of wavelengths coexisting in a fiber is limited by factors such as the interchannel interference and four-wave mixing (FWM). If the transmission distance is less than 100 km and no amplifiers are required, coarse WDM (CWDM) can be an option. CWDM allows MUX and DEMUX to have a wider channel spacing relative to dense WDM (DWDM). This is important because a wider channel spacing is helpful in mitigating the interchannel interference and FWM effects.

For specific application scenarios, we use ''channel capacity'' or directly use ''capacity'' to replace the previous term ''information capacity''.

In a WDM system, the expansion of channel capacity when the number of wavelengths is limited by certain factors is a topic worthy of study. Previous studies have confirmed that FWM is a crucial factor that degrades the capacity of WDM system [12]. Although sophisticated DSP (Digital Signal Processing) algorithms can alleviate the FWM effect, at the same time, it is also necessary to deploy various DSP units, such as analog-digital converter (ADC), filter, and related signal processing circuits, which usually increase not only the energy consumption of the system, but also the size

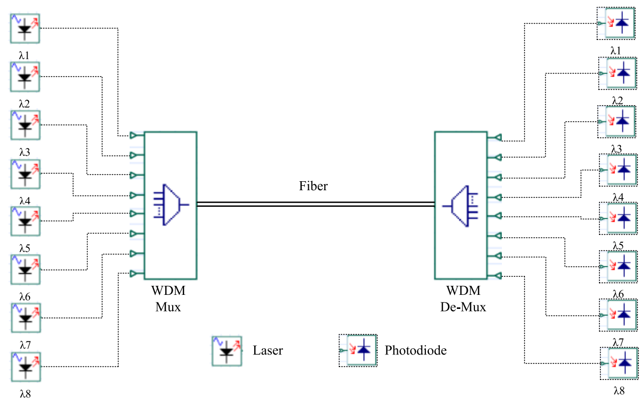

FIGURE 2. WDM system with 8 wavelengths.

of both transmitter and receiver. Thus, the DSP scheme is inapplicable to certain scenarios. For instance, transmitting an analog radio over fiber (RoF) signal via WDM networks is gaining momentum as the most spectrally efficient transport solution for 5G communication [13]. However, to fit ubiquitous 5G deployments, the remote antenna unit (RAU) must be a compact, low-energy-consuming component so that it cannot afford the complex and high-energy-consumed DSP unit inside.

Previous studies have shown that the FWM effect becomes stronger with decreasing channel spacing or increasing signal power [12], [14]. By reducing the channel spacing, the performance of the WDM system worsens owing to an increase in interchannel interference [15]. In addition, compared with the equally spaced channel allocation (ESCA) commonly used in most WDM systems, unequally spaced channel allocation (USCA) has been proven to be an effective way to significantly reduce FWM crosstalk [16],[17].

In conclusion, unequal channel spacing, wider channel spacing, and lower signal power play a positive role in improving the performance of WDM systems. Indeed, a conventional communication system cannot satisfy the above three conditions without reducing the channel capacity. However, Combination Communication can satisfy these requirements while keeping the channel capacity unchanged or even boosting the channel capacity. Let us now examine how Combination Communication achieves this goal.

Suppose a WDM system has eight wavelengths: $\lambda_1 \sim \lambda_8$, as shown in Fig.2, which can normally transmit 8 bits per unit time as the capacity of a single wavelength channel is 1 bcu. However, the use of hybrid Combinatorial Communication, as described in (6), can potentially increase the capacity of the WDM system. Let us say $\binom{8}{4}$, there are $\binom{8}{4} = 70$ possible combination elements by selecting four out of the eight wavelengths. Considering the hybrid system in which the activated entities are used to transmit conventional binary information, according to (6), in this case, $i = 8$, $k = 4$, thus, we obtain $C_{hybrid} = \left\lfloor \log_2 \binom{i}{k} \right\rfloor + k = 6 + 4 = 10$ bits. It can be observed that the system obtains a gain of two bits through hybrid Combination Communication. Using the ICC mode, let us say $\binom{8}{1}$, which means that a certain wavelength is not selected, naturally, it will not be sent from the transmitter, and then the receiver detects which photodiode has no output current and transforms the representation into the corresponding information. Similarly, considering the hybrid system, using (7), in this case $i = 8$, $k = 1$, thus, we can obtain $C^{ICC}_{hybrid} = \left\lfloor \log_2 \binom{i}{k} \right\rfloor + (i - k) = 3 + 7 = 10$ bits. It can be seen that although the results of the above two schemes are the same, the hardware implementation of ICC mode is simpler because it involves a simpler combination pattern.

As discussed above, to improve the performance of the WDM system, it is better to use fewer wavelengths and wider or unequal channel spacing because this can mitigate the FWM effect and interchannel interference. Suppose that the fiber channel can accommodate eight wavelengths, as shown in Fig.2, but the WDM system is only allowed to use at most four wavelengths, owing to the FWM effect and interchannel interference. Thus, the channel capacity of the WDM system is no more than four bits per unit time in conventional communication. Next, let us investigate the performance of the WDM system using the GCC mode.

Selecting three out of the eight wavelengths, that is, $\binom{8}{3}$, means that there are 56 combination elements. To mitigate FWM and interchannel interference, the following rule is stipulated: no two adjacent wavelengths should be selected simultaneously. Such a rule can ensure that unequal channel spacing and wider channel spacing are satisfied, or at least one of them is satisfied. Thus, the 36 combination elements that do not comply with this rule must be removed from the 56 combination elements of $\binom{8}{3}$. We omit this calculation because it is not complicated. Owing to $56 - 36 = 20$, we normally obtain four bits because of $\lfloor \log_2 20 \rfloor = 4$. Next, based on the GCC mechanism, it is not difficult to select 12 combination elements from $\binom{8}{2}$ to meet the above rule. In this way, we obtain a complete set of combination elements S from different S_r to match the powers of the two. Using Equation (12), which formulates the GCC mode, we obtain: $C^{GCC} = \left\lfloor \log_2 \left(\sum_{r=0}^{i} \overline{N_{S_r}} \right) \right\rfloor = \lfloor \log_2(20 + 12) \rfloor = 5$ bits. In contrast, the channel capacity is no more than 4 bits in a conventional WDM system, as mentioned above. Furthermore, using the hybrid GCC formula (13), considering $\xi''' = \frac{\sum_r r \cdot \overline{N_{S_r}}}{\sum_r \overline{N_{S_r}}} = \frac{(3\times 20)+(2\times 12)}{20+12} = 2.625$, we obtain: $C^{GCC}_{hybrid} = 5 + 2.625 = 7.625$ bits in the hybrid GCC system, which is much close to the channel capacity of an eight-wavelength WDM system.

To avoid FWM and interchannel interference, a conventional WDM system can only use no more than four wavelengths, resulting in a channel capacity of 3 or 4 bits per unit time. In contrast, the GCC uses only three wavelengths to achieve almost the same efficiency as eight-wavelength conventional WDM systems. Importantly, by deliberately selecting certain combination elements, the GCC WDM system can effectively eliminate the FWM effect and interchannel interference. The performance comparison of SM, conventional WDM, and GCC is presented in Table 3.

TABLE 3. Performance comparison of SM, conventional WDM, and GCC.

	Mitigating FWM and interchannel interference	Channel Capacity (bit)
SM	NO	N/A
Conventional WDM	YES (no more than 4 wavelengths)	3 (3 wavelengths) 4 (4 wavelengths)
GCC	YES (3 wavelengths used)	5 in pure GCC 7.625 in hybrid GCC

Next, we investigate the computational complexity of the proposed Combination Communication modes in comparison with the conventional WDM and SM schemes. Considering a WDM system that adopts two-ary intensity modulation, as depicted in Fig.2, each wavelength is split by the demultiplexer, and is then directed to the corresponding photodiode in which the information completes the conversion from lightwave to electric current, and the electronic information stream is processed in parallel. Thus, a conventional WDM system can be regarded as a parallel processing system. The computational complexity of such a conventional WDM system is $O(1)$. Considering the simplest SM scheme in which only one wavelength is selected from n wavelengths as the source of information, suppose using the binary search method, then the computational complexity of the SM scheme is $O(\log_2 n)$. Similarly, the binary search method can also be applied to the proposed Combination Communication modes. Let us say FCC, the most complex Combination Communication mode, which employs n wavelengths, according to the proof of conclusion 1, we know there are 2^n combination elements in total, thus, the computational complexity of the FCC mode is $O(\log_2 2^n)$, i.e. $O(n)$. Fig.2 shows a comparison of the computational complexity of SM, FCC, and conventional WDM. It can be seen that the computational complexities of both the SM and FCC increase with an increase in the number of involved physical entities (number of wavelengths). However, the growth of the latter is faster because the FCC has a higher capacity. In the SM scheme, the combination number of physical entities(wavelengths) must be a power of 2, which limits the flexibility of the application. Except for FCC, the other modes do not exploit the full combination effect, so their computational complexities are less than $O(n)$. Specifically, the complexity of the proposed Combination Communication regime is proportional to the size of the selected combination elements, i.e., information gain $\mathbb{G}$. For instance, in the case discussed in Table 3, although the WDM system has eight wavelengths, the complexity of GCC is only 5 rather than FCC's 8 because the GCC only offers 32 selected combination elements.

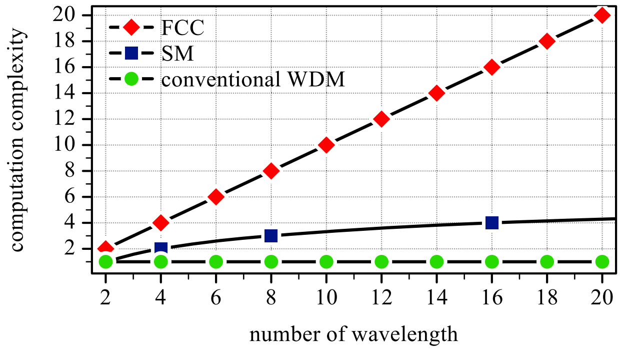

FIGURE 3. Complexity comparison of SM, FCC, and conventional WDM.

TABLE 4. ABER comparison for conventional WDM, SM, QSM, and GCC.

	1 s/s	2 s/s	3 s/s
Conventional WDM	1 b/s	2 b/s	3 b/s
SM	5 b/s	5 b/s	5 b/s
QSM	2.5 b/s	2.5 b/s	2.5 b/s
GCC	5 b/s	5 b/s	5 b/s

Relative to the conventional WDM system, the computational complexity of the proposed combination communication regime is maintained at an acceptable level when the number of physical entities is not very large, for example, no more than 20. In particular, some sophisticated optimization algorithms have been proposed to further reduce the computational complexity of SM [18], [19], and they are also applicable to our proposed regime.

Next, we investigate the ABER performance of the proposed GCC mode, in comparison with the conventional WDM, SM, and quadrature spatial modulation (QSM) [10], [11]. Assume a perfect fiber channel in which only the Gaussian white noise is present, the fiber channel in a WDM system usually contains multiple wavelength channels, and assume the symbol errors are assigned to the occupied wavelength channels with equal probability, following the scenario depicted in Table 3, suppose the SER is 1 s/s in the fiber channel, in the case of selecting 3 wavelengths out of 8 wavelengths, the ABER performance of the conventional WDM, SM, and QSM and GCC is shown in Table 4.

The conventional WDM system consists of three selected wavelength channels, and the information is modulated on each wavelength separately by two-ary intensity modulation. Therefore, when symbol error occurs at a rate of 1 s/s in the fiber channel, the ABER is 1 b/s. With an increase in the symbol error rate, the ABER of the conventional WDM also increases linearly. The ABER of the SM system is stable at 5 b/s when the SER is no more than 3 s/s. This is because the SM scheme has 56 combination elements by employing the combination of $\binom{8}{3}$, which is equivalent to 5 bits. A symbol error that occurs at any selected wavelength channel will result in 5-bits errors. To be more specific, the SM scheme uses three selected wavelengths to represent an indivisible information symbol, which is equivalent to 5 bits. Thus, even though each wavelength channel of the three selected wavelengths has one symbol error per second, that is, the SER of the fiber channel is 3 s/s, the ABER of the SM scheme remains at the level of 5 b/s. In the QSM system, the spatial constellation symbols are expanded to in-phase (X-polarization) and quadrature (Y-polarization) components, and the information loaded in the in-phase and quadrature components are processed in parallel, thus, relative to the SM system, the QSM has a double capacity. In other words, at the same capacity, the ABER of the QSM system is half that of the SM, i.e., 2.5 b/s. The proposed GCC system has 32 selected combination elements: $\log_2 32 = 5$, the information gain $\mathbb{G}$ is 5. According to the principle presented in Section II, the ABER of the proposed GCC system is equal to: $\ell\mathbb{G} = 1 \times 5 = 5$ b/s, where ℓ is the SER of the wavelength channel. It can be seen that the GCC has the same ABER as the SM in Table 4, this is because we set the same information gain for them, and both of them comply with the principle of combination.

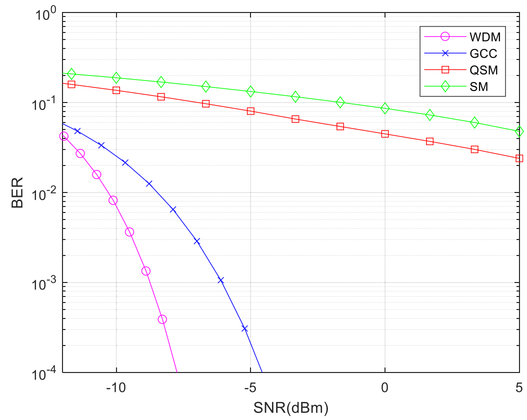

FIGURE 4. BER comparison among WDM, GCC, QSM and SM under FWM effect.

However, when the FWM effect is considered, the situation is different. Neither the SM nor the QSM systems work properly because they do not have a mechanism to prevent the FWM degradation, while our GCC system can work properly because of the well-designed mechanism mentioned before, its performance is close to that of the conventional WDM system, which consists of three selected wavelengths sparsely spaced. The results are shown in Fig.4.

IV. CONCLUSION

Previous SM schemes are self-contained and lack comprehensive regime construction and theoretical analysis. They did not consider full, partial, and generalized combinations. In this study, we formally proposed a comprehensive combination communication regime for the first time, including a theoretical basis and mathematical analysis. Several innovative combination communication modes have been proposed, such as PCC, ICC, IPCC, and GCC, which can either enhance the flexibility or simplify the structure of a combination communication system. Furthermore, we demonstrated that the proposed Combination Communication scheme is capable of addressing the dilemma between a higher channel capacity and degradation of system performance in conventional WDM systems.

REFERENCES

[1] R. Mesleh, H. Haas, C. W. Ahn, and S. Yun, ''Spatial modulation—A new low complexity spectral efficiency enhancing technique,'' in *Proc. 1st Int. Conf. Commun. Netw. China*, Oct. 2006, pp. 1–5.

[2] Z. Hong and B. L. Hughes, ''Bit-interleaved space-time coded modulation with iterative decoding,'' *IEEE Trans. Wireless Commun.*, vol. 3, no. 6, pp. 1912–1917, Nov. 2004.

[3] Y. Li and X.-G. Xia, ''Constellation mapping for space-time matrix modulation with iterative demodulation/decoding,'' *IEEE Trans. Commun.*, vol. 53, no. 5, pp. 764–768, May 2005.

[4] J. Jeganathan, A. Ghrayeb, and L. Szczecinski, ''Generalized space shift keying modulation for MIMO channels,'' in *Proc. IEEE 19th Int. Symp. Pers., Indoor Mobile Radio Commun.*, Sep. 2008, pp. 1–5.

[5] W. O. Popoola, E. Poves, and H. Haas, ''Error performance of generalised space shift keying for indoor visible light communications,'' *IEEE Trans. Commun.*, vol. 61, no. 5, pp. 1968–1976, Mar. 2013.

[6] M. I. Kadir, ''Generalized space-time-frequency index modulation,'' *IEEE Commun. Lett.*, vol. 23, no. 2, pp. 250–253, Feb. 2019.

[7] H. Hai, X.-Q. Jiang, W. Duan, J. Li, M. H. Lee, and Y. Jeong, ''Complex Hadamard matrix-aided generalized space shift keying modulation,'' *IEEE Access*, vol. 5, pp. 21139–21147, 2017.

[8] F. Cogen, E. Aydin, N. Kabaoglu, E. Basar, and H. Ilhan, ''Generalized code index modulation and spatial modulation for high rate and energy-efficient MIMO systems on Rayleigh block-fading channel,'' *IEEE Syst. J.*, vol. 15, no. 1, pp. 538–545, Mar. 2021.

[9] M. Al-Nahhal, E. Basar, and M. Uysal, ''Flexible generalized spatial modulation for visible light communications,'' *IEEE Trans. Veh. Technol.*, vol. 70, no. 1, pp. 1041–1045, Jan. 2021.

[10] R. Mesleh, S. S. Ikki, and H. M. Aggoune, ''Quadrature spatial modulation,'' *IEEE Trans. Veh. Technol.*, vol. 64, no. 6, pp. 2738–2742, Jun. 2015.

[11] E. Basar, M. Wen, R. Mesleh, M. Di Renzo, Y. Xiao, and H. Haas, ''Index modulation techniques for next-generation wireless networks,'' *IEEE Access*, vol. 5, pp. 16693–16746, 2017.

[12] M. W. Maeda, W. B. Sessa, W. I. Way, A. Yi-Yan, L. Curtis, R. Spicer, and R. I. Laming, ''The effect of four-wave mixing in fibers on optical frequency-division multiplexed systems,'' *J. Lightw. Technol.*, vol. 8, no. 9, pp. 1402–1408, Sep. 1990.

[13] E. Ruggeri, A. Tsakyridis, C. Vagionas, G. Kalfas, R. M. Oldenbeuving, P. W. L. van Dijk, C. G. H. Roeloffzen, Y. Leiba, N. Pleros, and A. Miliou, ''A 5G fiber wireless 4 Gb/s WDM fronthaul for flexible 360° coverage in V-band massive MIMO small cells,'' *J. Lightw. Technol.*, vol. 39, no. 4, pp. 1081–1088, Feb. 15, 2021.

[14] S. Song, ''The number of four-wave mixing (FWM) waves in WDM systems and its applications,'' in *Proc. 14th Annu. Meeting IEEE Lasers Electro-Opt. Soc. (LEOS)*, Nov. 2001, pp. 283–284.

[15] J. J. G. Torres, A. M. C. Soto, and N. G. Gonzalez, ''Evaluation and compensation of interchannel interference effects in a 16-QAM Nyquist-WDM system with LMS equalization,'' in *Proc. IEEE Latin-Amer. Conf. Commun. (LATINCOM)*, Nov. 2014, pp. 1–6.

[16] K.-D. Chang, G.-C. Yang, and W. C. Kwong, ''Determination of FWM products in unequal-spaced-channel WDM lightwave systems,'' *J. Lightw. Technol.*, vol. 18, no. 12, pp. 2113–2122, Dec. 1, 2000.

[17] A. Rouf and M. S. Islam, ''A new approach of unequally spaced channel allocation for FWM crosstalk suppression in WDM transmission system,'' in *Proc. 7th Int. Conf. Electr. Comput. Eng.*, Dec. 2012, pp. 35–38.

[18] G. Altin, ''A novel and low-complexity algorithm of EDAS for spatial modulation systems,'' *IEEE Commun. Lett.*, vol. 24, no. 12, pp. 2922–2925, Dec. 2020.

[19] I. Al-Nahhal, E. Basar, O. A. Dobre, and S. Ikki, ''Optimum low-complexity decoder for spatial modulation,'' *IEEE J. Sel. Areas Commun.*, vol. 37, no. 9, pp. 2001–2013, Sep. 2019.

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