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Overview of Multiplexing Techniques in Wireless Networks

Pedram Kheirkhah Sangdeh and Huacheng Zeng

Abstract

Multiplexing is a key technique for wireless communications. In this chapter, we will review the multiplexing techniques that are used in existing wireless systems.

Keywords: wireless networks, multiplexing, CDMA, TDMA, FDMA, NOMA

1. Introduction

With the great advances of communication technologies, the communication paradigm has widely been shifted from point-to-point to multi-user wireless systems to support ever-increasing number of mobile devices being introduced in the market. The proliferation of mobile devices has necessitated an elaborate mechanism to serve multiple users over a shared communication medium. The most important building block in this mechanism is multiplexing approach. The multiplexing refers to a method which aims at combining multiple signals into one signal such that each user would be able to extract its desired data upon receiving the multiplexed signal. **Figure 1** shows a communication system with three sources and corresponding destinations at system level. As shown in **Figure 1(a)**, the system without multiplexing requires three different communication links each of which carrying the signal of single source toward its destination exclusively. Such a system is inefficient since it demands triple times more communication resources than the same system with multiplexer/de-multiplexer shown in **Figure 1(b)**. With the aid of multiplexing, signals of all sources will be superimposed into one signal and sent over single available communication link. Establishing a successful transmission over the single link preserves valuable resources and decreases communication costs. Furthermore, serving multiple users through a channel result in massive connectivity, which paves the way for current and next generation of wireless networks designed for crowded urban areas. In today's communication, multiplexing has penetrated many communication applications ranging from digital broadcasting to Wi-Fi networks. Multiplexing brings the following advantages to wireless communication systems.

- Reducing the communication cost.
- Enhancing the connectivity.
- Saving valuable communication resources.

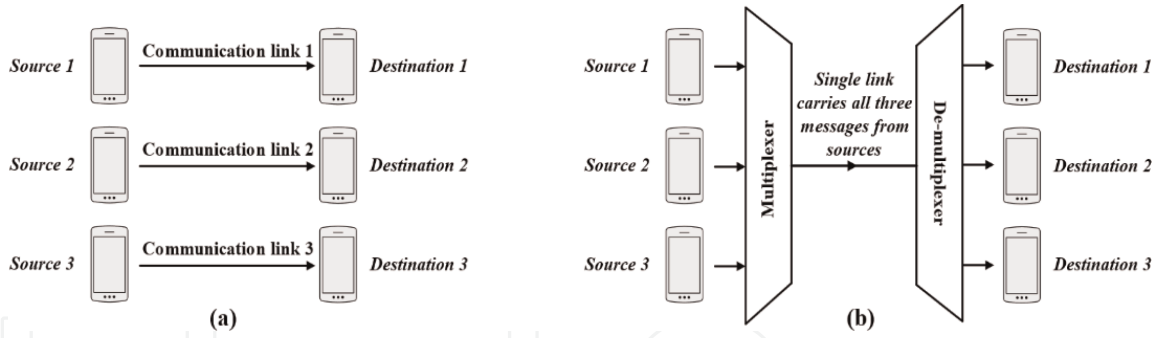


Figure 1. A communication system comprising three sources and destinations: (a) without multiplexing and (b) with multiplexing.

- Improving network capacity.
- Eliminating the need of exclusive links between sources and destinations.

Based on the application requirements, available spectrum, and users' hardware capability, the appropriate multiplexing approach will be designed over the required domain which could be time, frequency, power, code, wavelength or delay-Doppler domain. For example, time division multiplexing is not suitable for a delay-sensitive application, and spatial multiplexing is very amenable for a network with multi-antenna nodes. Among all of the aforementioned domains for multiplexing, only wavelength division multiplexing exclusively targets communication over the fiber cables while others suit wireless communication. In this chapter, the most important multiplexing approaches are studied.

2. Time division multiplexing

Time division multiplexing (TDM) is the first multiplexing scheme has been introduced to be employed in wired and wireless networks. Generally speaking, TDM separates signals from different sources over non-overlapping time slots to share the same spectral medium. At the receiver side, upon detecting the time slots, the desired signals can be recovered through overhearing the related slots. The simplest TDM can be modeled as a switch that periodically moves between multiple sources, and the transition time equals to the slot allocated to a single source. The messages of all sources are combined into a frame and sent over the medium. Based on flexibility of the allocation mechanism, TDM can be implemented in synchronous or asynchronous mode. TDM and its variants have been embedded in plethora of recent technologies, such as WiMAX [1], Tactical data link (TDL) [2], Bluetooth [3], HIPERLAN [4], to name but a few.

2.1 Synchronous time division multiplexing

Synchronous TDM follows a strict approach in time slot allocation. It periodically assigns subsequent time slots to different sources in a predefined order, no matter if some sources have nothing to be sent. As shown in **Figure 2**, the multiplexer and sources can be modeled as a switch and states, respectively. The switch circularly moves between different states and remains in different states for equal amount of time, i.e., a time slot. In a cycle, the switch passes through all states and shares the cycle time between all sources fairly. For the sake of simplicity, the transition time of switching is ignored.

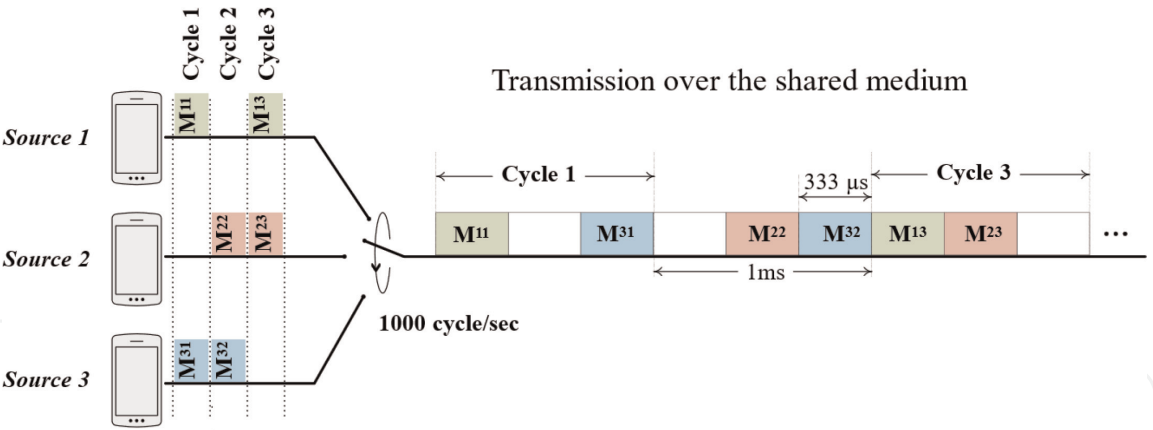


Figure 2.
Synchronous time division multiplexing.

Figure 2 depicts an example of synchronous TDM for three independent sources in three cycles. The switch rotates between states (sources) with the rate of 1000 cycle per second. Hence, the cycle time is 1 ms, and each time slot equals to 333.3 μs. In the j th cycle, the i th source may have message M_{ij} or nothing to be transmitted. For instance, in second cycle, source one remains idle while source two and source three have M_{22} and M_{32} for transmission, respectively. Therefore, these messages occupy the second and third time slots in the second cycle while the second time slot will be wasted without conveying any message. An unused time slot is shown with hatched rectangular. Each cycle could be preceded/terminated with a preamble/postamble enabling destinations to detect beginning/end of a cycle. The detail of each cycle is shown in the figure. Obviously, in each cycle, one third of the airtime will be wasted which drastically degrades the throughput of the system. To prevent squandering airtime, asynchronous TDM has emerged.

2.2 Asynchronous time division multiplexing

Asynchronous TDM, also known as statistical TDM, pursues a more dynamic approach by giving the airtime to sources that have data for transmission. In this manner, the messages of different sources occupy all subsequent time slots, which yield improvement of spectrum utilization in turn. As a well-known application, asynchronous TDM is used in asynchronous transfer mode (ATM) networks [5]. To demonstrate the possible gain of the asynchronous TDM over synchronous TDM, let us consider the sources previously shown in **Figure 2**. This time, the asynchronous TDM is applied on the system, as shown in **Figure 3**. In each cycle, the switch passes through all sources and transfers the existing messages to frame assembler. The frame assembler tags a preamble to each message. The preambles include an ID or address field to notify the origin or intended destination of the message attached to the preamble. Then, the frame assembler aggregates the tagged messages and disregards the idle time intervals related to silent sources. The tagged messages occupy subsequent time slots and are transmitted sequentially. As shown in the figure, each cycle carries messages of sources that have something to transmit; hence, the cycles include two-time slots which improves the spectral utilization by 33%. Although the cycles duration are equal in the example, the transmission duration may vary depending on the number of messages to be carried. Clearly, asynchronous TDM demands more processing capability at multiplexer and de-multiplexer, and it may cause a delay up to one cycle for buffering and aggregating the existing messages. However, it is worthwhile since it yields higher spectral efficiency and saving valuable resources. As another advantage,

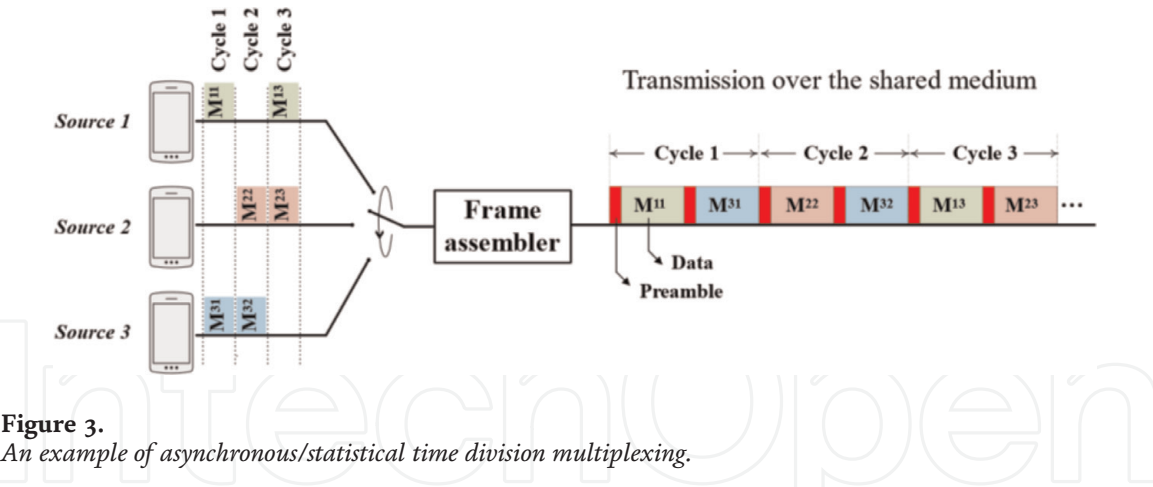


Figure 3.
An example of asynchronous/statistical time division multiplexing.

using the preambles diminishes the need of synchronized clocks between multiplexer and de-multiplexer.

3. Frequency division multiplexing

Frequency division multiplexing (FDM) is a multiplexing technique which divides the available bandwidth into multiple sub-bands each of which is able to carry a signal. Therefore, FDM enables concurrent transmissions over a shared communication medium. As another common use, FDM enables the system to send a huge amount of data through several segments transmitted over independent frequency sub-bands.

Figure 4 reveals basic principles of the conventional FDM. In the figure, signal of three independent sources are multiplexed to be sent over the medium. Each source has a flat signal with large width in time domain. Depending the value of the information bit, the signals can be $x(t) = \pm 1$. Hence, the spectrum of each signal is approximated by $X(f) \approx \pm \delta(f)$. The baseband signals are converted to well-separated bandpass signals by multiplexer. The signals are conveyed by carriers with different frequencies such that each signal is located within a non-overlapping sub-band and does not leak onto other signals. The carrier frequencies spacing, and sub-band width are application-specific and depend on the available bandwidth. The multiplexed signal will be transmitted over the medium. At the receiver side, de-multiplexer employs proper filters to extract the desired bandpass signals. The intended bandpass signals will be converted to baseband signals for further processes at destinations.

The spectrum of a communication system with N sources benefiting from FDM is depicted in **Figure 5**. The multiplexer uses N equally spaced carrier frequencies. The carrier frequency for the i th user is f_{ci} . For further simplicity, consider that

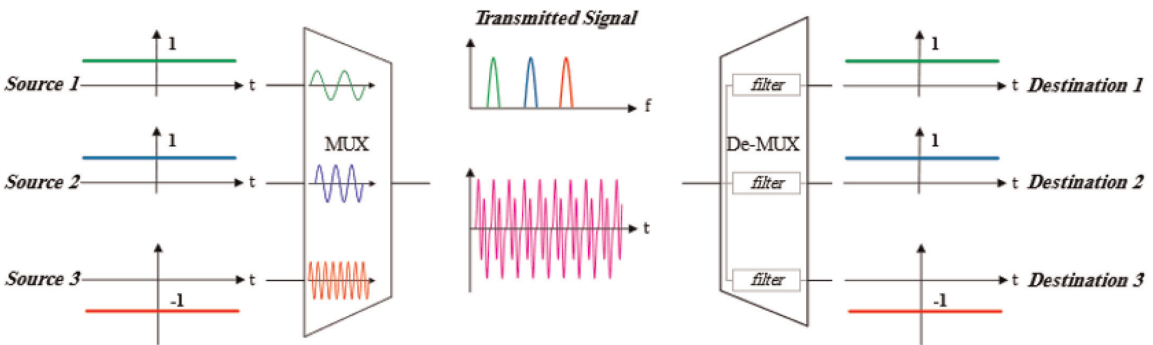


Figure 4.
Frequency division multiplexing.

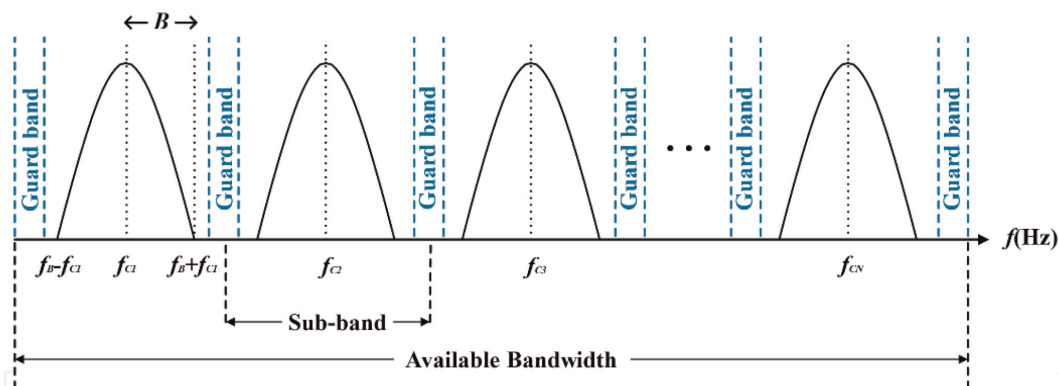


Figure 5.
 Spectrum of multiplexed signals via FDM for a system with N sources.

sources use the same pulses for data transmission. Signals from the i th source lies within the i th frequency sub-band centered around f_{ci} . Bandwidth of the base-band signals is $B = f_B$ Hz which is less than sub-bands' width, i.e., $SB = f_{c(i+1)} - f_{ci}$. To prevent leaking signals into adjacent sub-bands, the sub-bands are separated by a guard band $G = f_G$ Hz. Clearly, for appropriate signal transmission, the carrier frequency spacing should be designed such that $f_{ci} + f_B < f_{c(i+1)} - f_B$.

3.1 Orthogonal frequency division multiplexing (OFDM)

Conventional FDM allocates the available spectrum to the sources very generously, and the spectral efficiency is not among its concerns. With this motivation, OFDM has been introduced for efficient use of spectrum. OFDM is a multi-carrier modulation through which a data stream, like voice, video, or data, is distributed among multiple subcarriers separated closely and precisely. In a simple OFDM-based system, the modulated samples over frequency domain, i.e., $x[k]$, are distributed over different subcarriers via Inverse Fast Fourier Transform (IFFT) as follows.

$$x(t) = \sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1} x[k] e^{j2\pi kt} \quad (1)$$

where $x(t)$ denotes the time domain signal which is sum of multiple sinusoids and $x[k]$ is the k th modulated sample. Since the basis of the transformation is unit vectors with equally angular separated in polar plane, the spectrum of OFDM signal is composed of N shifted *sinc* functions. **Figure 6** illustrates the spectral basis of an OFDM signal with four orthogonal subcarriers. The subcarrier spacing, i.e., $\Delta f = f_{i+1} - f_i$, is chosen such that the center frequency of each subcarrier is located on a null point of other subcarriers. Therefore, at the moment of sampling from the center of subcarriers, no interference is experienced from others. The time domain signal goes through another process called cyclic prefix (CP) insertion to be immune against multipath fading. In this step, a certain amount of the time-domain signal's tail is copied and attached to the beginning of the time-domain signal. If the maximum delay in multipath environment does not exceed the time duration CP, the signal can be recovered perfectly. The CP-inserted OFDM signal is fed into a D/A converter. The baseband analog signal is then converted to a bandpass signal to be sent over the communication medium.

At the receiver side, the superimposition of the analog signals received from different paths within reception interval is sampled and converted to a baseband

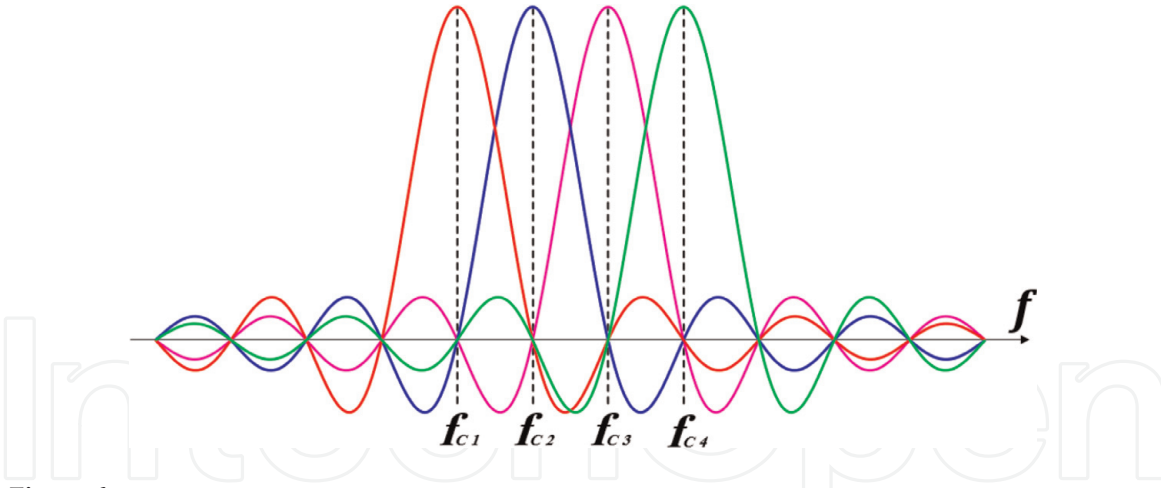


Figure 6.
Bandwidth requirement for an OFDM system using four orthogonally spaced subcarriers.

digital signal. The parallel to serial unit maps the sequence of received OFDM samples into N parallel samples. Then, the CP added by transmitter is removed. The remaining samples go through Fast Fourier Transform (FFT). The resulting series of modulated samples is fed into demodulator, and the desired data is recovered.

Due to promising performance of the OFDM technique and its very low computational complexity, this technique has been embedded in many wireless communication systems like IEEE WLAN standards [6–8], LTE/LTE-A [9–11]. The popularity of this technique stems from following advantages which make it highly amenable for real world application.

- *Resilience in frequency selective environments:* OFDM decomposes whole available spectrum to several narrow channel in frequency domain. It is very likely that signals carried over a subcarrier experience a relatively flat channel although the channel may be frequency selective.
- *Resilience to inter-symbol interference (ISI):* single-carrier communication is vulnerable to ISI specially when the data rate grows. OFDM tackle this problem with dispatching signals over multiple sub-channels. Indeed, OFDM technique changes a transmission with high rate into multiple low-rate transmissions. In this manner, it increases the symbol duration and push the duration beyond maximum delay of the channels. Lack of ISI also means simpler equalization mechanism and reduction in hardware cost of the OFDM receiver. At the end of this section, example 1 reveals how OFDM technique combats the frequency selectivity of the channel.
- *Resilience to narrow-band interference:* narrow-band interference drastically diminishes the throughput of single-carrier systems either by blurring the reference signals for synchronization or corrupting the data. However, if the signal is transmitted using OFDM, only a portion of symbols is contaminated by interference. The erroneous parts caused by interference can be recovered with the aid of error correction codes and interleaving to isolate errors.
- *Spectral efficiency:* comparing **Figures 5** and **6**, it is clear that closely separated frequency sub-channels yields higher spectral efficiency for OFDM.
- *Low-computational complexity:* although OFDM technique is more complex than conventional FDM, it intrinsically demands low-computational capability

since it possesses simple mathematical operations. It can be simply implanted with FFT and IFFT modules containing nothing more than adders, multipliers, and registers.

Example 1: Consider a transmission which requires 1 Mbps data rate and RMS delay spread is $10\ \mu\text{s}$ and frequency selectivity condition is $\tau_{rms} > T_{sym}/10$ where T_{sym} denotes symbol duration. The comparison of single-carrier transmission and OFDM technique with 128 subcarriers is as follows:

- *Single-carrier case:* $T_{sym} = 1\ \mu\text{s}$ and $\tau_{rms} > 1\ \mu\text{s}/10$. Therefore, ISI is imminent.
- *Multi-carrier case:* in this case, data rate of a subcarrier is 7.8125 kbps. The T_{sym} for a subcarrier equals to $128\ \mu\text{s}$. Then, $\tau_{rms} < 128\ \mu\text{s}/10$, and the signal carried by each subcarrier experiences a flat fading channel.

In spite of aforementioned advantages, the OFDM technique suffers from two main disadvantages. High peak-to-average power ratio (PAPR) stems from the large range of amplitude of the OFDM signal and impedes proper performance of amplifiers at OFDM transceivers. Also, OFDM technique is very sensitive to carrier frequency offset (CFO). This effect emerges due to hardware impairment between transmitter and receiver local oscillators and cause inter-carrier interference (ICI).

4. Code division multiplexing

Code division multiplexing (CDM), also called spread-spectrum technique, is a multiplexing technique which has been widely implemented in third generation of wireless network. It takes full advantage of the available spectrum. Through several concurrent transmissions over the spectrum, this technique has enhanced the capacity of network 18 times compared to first generation and 6 times compared to the second generation of wireless communication technologies. For transmitting multiple messages over the channel simultaneously, the multiplexer assigns a separate spreading code from a set of orthogonal pseudo-random sequences to each user. The orthogonality of these sequences will help users to recover their desired signals from the multiplexed signals.

Consider a system with 4 users as depicted in **Figure 7**. AP intends to send one bit to each user, say b_i for user i . The sequence c_i is used to encode/decode the bits

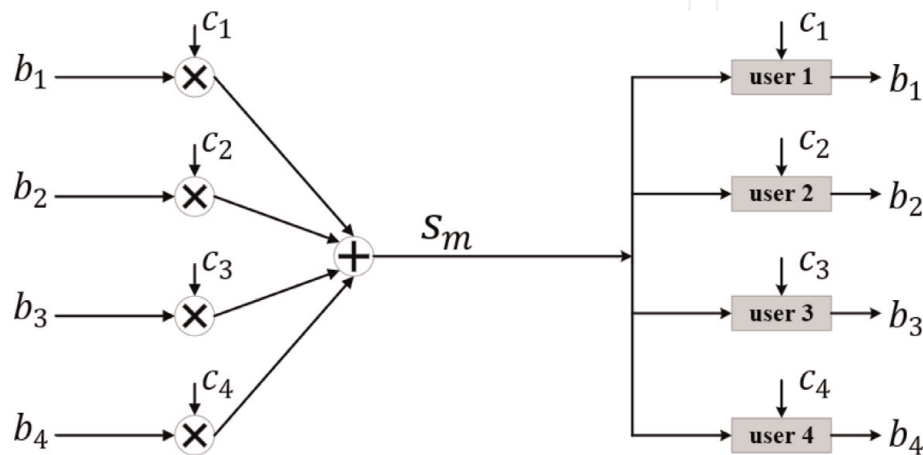


Figure 7.
An example of CDM for a network with four users.

to/from user i . These sequences are devised such that the inner product of two different sequences is zero, i.e., $c_i \cdot c_j = 0$ $i \neq j$. The inner product of a sequence with itself is M which is the number of users. Also, the '0' is mapped to -1 , and 1 is mapped to $+1$. The multiplexed sequence is $s_m = \sum_{i=1}^4 b_i c_i$. Upon receiving the multiplexed sequence, user i recovers its desired information by multiplying its corresponding spreading sequence and received sequence and dividing the result by the length of sequences. The key component in CDM is the spreading code. Walsh code is among the most popular sequences used for CDM. Walsh codes with length of 2^n , $n \in \mathbb{N}$, can be constructed with Hadamard matrices as follows.

$$H_1 = [1] \rightarrow H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \rightarrow \dots \rightarrow H_{2N} = \begin{bmatrix} H_N & H_N \\ H_N & -H_N \end{bmatrix} \quad (2)$$

where each row of H_{2N} can be used as a sequence with length $2N$. This procedure results four orthogonal sequences as follows.

$$c_1 = [1, 1, 1, 1], c_2 = [1, -1, 1, -1], c_3 = [1, 1, -1, -1], c_4 = [1, -1, -1, 1] \quad (3)$$

Consider the following set of bits as an example, $b_1=b_2=b_3=1$, and $b_4=-1$. Therefore, the multiplexed signal is:

$$s_m = \sum_{i=1}^4 b_i c_i = [+2, +2, +2, -2]. \quad (4)$$

The first user recovers its desired data $\hat{b}_1 = s_m \cdot c_1^T / 4$. And other users do the same procedure with their own sequences.

$$\hat{b}_1 = \frac{1}{4} [1, 1, 1, 1] \times [2, 2, 2, -2]^T = \frac{4}{4} = +1. \quad (5)$$

Similarly, $\hat{b}_2=1$, $\hat{b}_3=1$, and $\hat{b}_4=-1$. As seen in the example the Walsh code is used as spreading code. However, a variety of codes can be utilized for this purpose, which can be classified into two major categories.

- *PN codes*: pseudo-random noise code is a sequence of pulses which shows the appropriate features to be used in CDM. Although PN sequences look like noise, they can be exactly generated at both multiplexer and demultiplexer locally using a finite number of shift registers with a pre-defined initial state. The finite length of linear shift registers makes these codes deterministic. A local sequence has a high correlation with itself, but almost zero correlation with other sequences or a time-shifted version of itself. The term "pseudo" refers to the fact that a sequence starts to repeat a certain pattern after its period. In cryptography applications, to ensure security, using PN codes with very large period is a necessity. However, this is not a strict requirement for CDM.
- *Non-random orthogonal codes*: this kind of codes is designed in a specific and predefined manner and has a special set for desired length while satisfying primary features required by CDM. An instance of these codes is Walsh code shown in the previous example. Walsh code is used in the IS95/CDMA 2000 system.

As described, choosing a well-defined code plays a critical role in spreading process. The question may arise here is why the process of multiplying the code sequences to bits is called spreading process. To find the answer of this question, **Figure 8** illustrates an insightful example where the base-band information is converted to the transmitted signal via spreading code. Every bit in the information flow is represented by a pulse with T_b width in time domain. Hence, the effective bandwidth of the original data is proportional to $1/T_b$. Then, the information flow goes through spreading process where the pulses of data flow will be multiplied (in some systems it is XOR) by the spreading code sequence. Since the pulse duration for the spreading code is T_c which is smaller than the T_b , the generated signal by spreading signal is affected by T_c and it becomes a series of pulses with T_c width in time domain. The bandwidth of the transmitted signal is proportional to $1/T_c$ called chip rate. Therefore, the bandwidth of the transmitted signal is larger than original baseband signal. The ratio of spread spectrum and original base-band information is called spreading factor and can be expressed as follows.

$$\text{Spreading Factor} = \frac{\text{chip rate}}{\text{bit rate}} = \frac{T_b}{T_c} \tag{6}$$

Clearly, the spreading for the example illustrated in **Figure 8** is four since the chip rate is fourfold of bit rate.

Until this point, it seems very easy to decode the signal at the intended receiver by using the same spreading code with pre-known chip rate. The de-spreading process, i.e., multiplying the multiplexed signal with a spreading code needs a delicate requirement. At a node in the network, all the received signals multiplied by different spreading codes should be received with equal strength, otherwise the de-spreading process causes interference due to non-zero mutual correlation of spreading codes. This impedes recovering desired signal at that node. This problem is called near-far problem. The near far problem originally refers to a situation where reception of some strong signals makes it impossible to recover weak signals. Here, the unbalanced signal strength causes this intricate challenge. To cope with this problem, a power control mechanism is mandatory to ensure that all the signals from different sources will be received with equal strength. This matter brings two main challenges:

- High power consumption for far users: the power of a signal emitted on the air is attenuated by factor of d^α where d is the amount of distance the signal passes

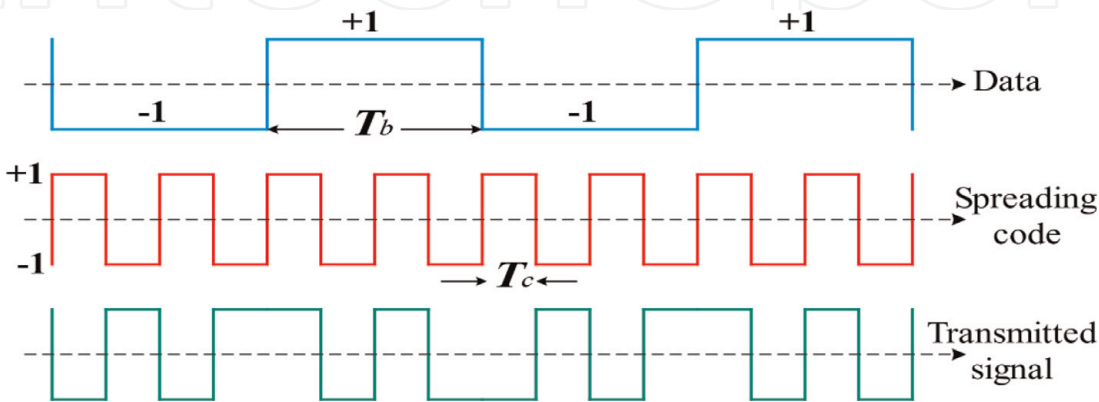


Figure 8.
Spreading process on $(-1, 1, -1, 1)$ via spreading code of $(-1, 1, 1, 1)$ with spreading factor of 4.

and α is pathloss coefficient which depends on the surrounding area and object within there. For an open area and line of sight communication $\alpha \approx 2$. So, if a user wants to adjust its power to maintain a certain signal strength at destination, it takes the distance into the account. Hence, the emitted power of users far from the destination is pretty high. This is very probable in cellular network where some users may be located at cell-edge.

- Communication overhead and reduced overhead: to measure pathloss effect and adjust power, a sounding mechanism should be established to launch a two-way communication between source and destination. This sounding consumes available over-the-air time and reduces the overall throughput of the network.

Despite this challenge along with its other challenges like self-jamming and need for precise synchronization, CDMA have shown some prominent advantages, as follows, paving the way for implementing it in several real-world communication.

- Efficient channelization and enhanced spectrum reuse
- Soft hand-off
- Immunity to interference
- Security

5. Power division multiplexing

Non-orthogonal multiplexing access (NOMA) is key enabler of the next generation wireless communication. Although the concept of NOMA is very broad, the power domain NOMA is the simplest and most popular NOMA. In contrast to orthogonal multiplexing access (OMA) approaches, like TDM and FDM, which separate the signals in frequency or time domain in order to avoid interference, NOMA embraces interference in both time and frequency domains. NOMA establishes multiple concurrent transmissions over the shared medium by adjusting the power levels of different signals.

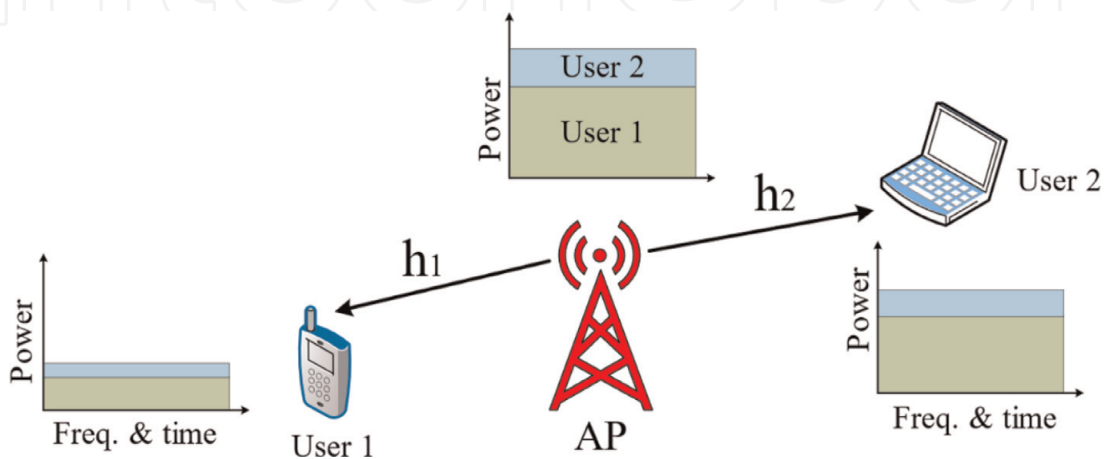


Figure 9.
An example of two-user network using power-domain NOMA in downlink transmission.

NOMA brings the massive connectivity, spectral efficiency, high throughput, and improved fairness all together and it is the key enabler of the fifth generation of wireless networks. By serving several users with available resources concurrently, it improves the connectivity and spectral efficiency. Also, it improves the network capacity, and prevent wasting the resources caused by assigning equal amount of resources to users with low data rate requirement or bad channel conditions. Another, brilliant feature of the NOMA is that it can be easily integrated into existing wireless communication technologies. For example, see its integration with LTE-A [12] and digital TV standard [13].

To illustrate how NOMA works, **Figure 9** shows a simple example of NOMA usage in a two-user network. In this example user 1 goes in the deep fade while user two hears the signal coming from the access point (AP) very clearly. All nodes are equipped with a single omni-directional antenna. Assume the channel between the AP and the i th user is h_i . Therefore, $h_1 \ll h_2$. The AP knows the global Channel State Information (CSI) perfectly. The AP intends to send message s_i to user i . To do so, it scales the s_i with power allocation factor α_i such that more power is assigned to the message of weak user. The superimposed message is as follows.

$$s_m = \sqrt{\alpha_1}s_1 + \sqrt{\alpha_2}s_2 \quad (7)$$

The received signal at the i th user is Y_i .

$$Y_i = s_m h_i + n_i = \sqrt{\alpha_1}s_1 h_i + \sqrt{\alpha_2}s_2 h_i + n_i \quad (8)$$

where n_i is additive white Gaussian noise. At the first user, i.e., weak user, the desired signal has a high power compared to the interference which is $\sqrt{\alpha_2}s_2 h_1$ to be decoded. This user decodes its desired signal by treating interference as noise. However, at the second user, i.e., strong user, the desired signal is drawn into strong interference. This user will pursue a decoding procedure called successive interference cancellation (SIC). Since the strong user knows the codebook used at the AP, it is able to decode interference, \hat{s}_1 . Then, it subtracts the decoded interference from received signal. In the next step, the strong user endeavors to recover its desired signal from $Y_2^{(2)}$.

$$Y_2^{(2)} = \left(\sqrt{\alpha_1}s_1 h_2 - \sqrt{\alpha_1}\hat{s}_1 \hat{h}_2 \right) + \sqrt{\alpha_2}s_2 h_2 + n_2 = e_1 + \sqrt{\alpha_2}s_2 h_2 + n_2 \quad (9)$$

If the channel is estimated perfectly and the interference is decoded flawless, error $e_1 = 0$, and the desired signal, s_2 can be recovered successfully. Assuming perfect CSI estimation, the sum-rate of the network is as follows.

$$R_{sum} = R_1 + R_2 = \log_2 \left(1 + \frac{\alpha_1 |h_1|^2}{\alpha_2 |h_1|^2 + 1/\rho} \right) + \log_2 \left(1 + \alpha_2 \rho |h_2|^2 \right) \quad (10)$$

where $\rho = P_t/N_0$ and P_t is available power budget. This approach can be easily extended to N -user case. Assuming that channels' strength are sorted in ascending order, $|h_i|^2 < |h_j|^2$ for any $i < j$ and $i, j \in \{1, 2, \dots, N\}$, the decoding order is $(1, 2, \dots, N)$. It means the SIC at user l begins with decoding interference s_1 , and then decodes the second powerful interference, i.e., s_2 , and follows the interference subtraction until removing s_{i-1} . After subtracting all interferences which are stronger than desired signal, the user is capable of recovering its intended signal s_i . The R_{sum} can be expressed as follows.

$$R_{sum} = \sum_{i=1}^N \log_2 \left(1 + \frac{\alpha_i |h_i|^2}{\frac{1}{\rho} + \sum_{j=i+1}^N \alpha_j |h_j|^2} \right) \quad (11)$$

For better illustration of NOMA gain over conventional OMA schemes, like TDM and FDM, let us look at the following example.

Example 2: Consider two asymptotic cases with high power budget in two-user scenario: (i) the users' channel are equally strong ($h_1 = h_2 = h$); (ii) one channel is very strong while the other one is very weak ($h_1 \ll h_2$). The power is proportionally allocated to messages. The gain of power domain NOMA over OMA in each case is as follows.

Case 1: Let us say the power budget is P_T and $\rho = P_T/N_0$ where N_0 stands for variance of additive white Gaussian noise. In this case, the sum-capacity of network using OMA is C_{OMA} .

$$C_{OMA} = 0.5 \log_2(1 + \rho |h|^2) + 0.5 \log_2(1 + \rho |h|^2) \approx \log_2(\rho |h|^2) \quad (12)$$

where 0.5 coefficients lie in the fact that OMA shares the resources between users equally. In the NOMA approach, the whole spectrum is shared among both users. Due to power allocation strategy and equally strong channels $\alpha_1 = \alpha_2 = 1/2$. The sum-capacity of the network using the NOMA is C_{NOMA} .

$$\begin{aligned} C_{NOMA} &= \log_2(1 + \rho |h|^2 \alpha_2) + \log_2\left(1 + |h|^2 \alpha_1 / \left(|h|^2 \alpha_2 + \frac{1}{\rho}\right)\right) \\ &\approx \log_2(1 + \rho |h|^2 / 2) + \log_2(2) \approx \log_2(\rho |h|^2) \end{aligned} \quad (13)$$

Therefore, OMA reaches to the performance of NOMA.

Case 2: In this case, $h_1 \ll h_2$ and $\rho |h_1|^2 \rightarrow 0$ and $\alpha_1 \rightarrow 1$.

$$C_{OMA} = 0.5 \log_2(1 + \rho |h_1|^2) + 0.5 \log_2(1 + \rho |h_2|^2) \approx 0.5 \log_2(1 + \rho |h_2|^2) \quad (14)$$

$$\begin{aligned} C_{NOMA} &= \log_2(1 + \rho |h_2|^2 \alpha_2) + \log_2\left(1 + |h_1|^2 \alpha_1 / \left(|h_2|^2 \alpha_2 + \frac{1}{\rho}\right)\right) \\ &\approx \log_2(1 + \rho |h_2|^2 \alpha_2) + \log_2\left(1 + \frac{\alpha_1}{\alpha_2}\right) = \log_2(\rho |h_2|^2) \end{aligned} \quad (15)$$

Obviously, in the latter case, $C_{NOMA} = 2 \times C_{OMA}$. Based on these bounds, the performance of the NOMA for two users can be expressed as follows:

$$C_{OMA} \leq C_{NOMA} \leq 2 \times C_{OMA} \quad (16)$$

The previous example shows that the performance of NOMA is highly dependent on the channel difference among serving users. Therefore, when an AP serves many active users, it is very critical to employ a grouping mechanism to pair a strong and weak user among all possible choices such that the overall throughput of the network is maximized. Each pair will be served separately in different time slot. When the AP has just one antenna, best strategy is measuring the magnitude of the channels of different users, sorting the users based on their channel strength, and then choosing a N -user group in which the channel strength difference among two adjacent users in decoding order is larger than a certain threshold.

To put it briefly, the performance of NOMA depends on its three key components: (i) grouping mechanism; (ii) power allocation scheme; and (iii) SIC at all user except the weakest one. While the grouping mechanism aims at finding best pairs among all users to be fed into power allocator, the power allocation scheme should assign a portion of available power to intended messages of user included in the pairs such that the minimum required data rate of all users is met and the decoding order at the user side is preserved. At the AP, depending on the application, there are two main strategies for power allocation. The first one is maximization of throughput using all available power budget. The second strategy is minimization of the power consumption while requirements of all users are met. After a proper power allocation, all users except the weakest one should be able to recover all strong interference based on decoding order through and accurate and reliable SIC. Although NOMA shows a promising performance theoretically, it faces several challenges in practice. These challenges are described in what follows.

- *Privacy of weak users*: the first and foremost problem of the NOMA is privacy of weak user since their message will be decoded by all users possessing higher decoding order. Indeed, at the end of a cycle of NOMA, the i th user knows the messages of all weaker user, i.e., s_j if $|h_j| < |h_i|$. For example, after SIC completion, the strongest user identifies all the messages sent by the AP for other users
- *Long processing delay for strong users*: in SIC approach, a user first removes all the interference messages stronger than desired signal. This inflicts a huge amount of computational complexity and long processing delay to strong users which must iterate this process several times.
- *Error propagation*: the performance of SIC is highly intertwined with accurate interference reconstruction on subtraction. This fact mandates reliable channel estimation and accurate interference decoding. Failure in these steps for one of strong interferences will introduce an error which impacts the SIC operation for decoding and removing the weaker interferences at the same user. Accumulation of errors within the whole process makes it very difficult to recover the desired signal polluted by errors and residual interferences.
- *Non-trivial grouping*: although the grouping mechanism seems very straightforward for single-antenna AP and single-antenna users (SISO network), the channel strength concept becomes ambiguous for more complicated scenarios, like MISO and MIMO. For example, in MISO case, the channel between a user, say user i , and one of AP's antennas may be so weak while the channel of the same user and other antennas at the AP is very strong. In these cases, to sort the users' strength, the different measures are taken into account, like distance from AP, norm of the channel vector, etc. These metrics stem from theoretical aspects of wireless channels and may show unacceptable outcome when implemented in practice.
- *Sub-optimal performance*: at the AP side, power allocation problem becomes a non-trivial task for large pairs and nodes with multiple antenna (see, e.g., [14]). Due to several requirements imposed by either user or nature of SIC, the problem is a non-convex problem with several variable. In almost all cases, there is no closed-form solution for optimal power allocation. To reach a solution, the problem will be relaxed into a simpler problem, or a heuristic algorithm reaches to a near optimal solution. So, the power allocation problem

entails high computational cost and may yields a non-optimal solution which diminish the gain of the NOMA over OMA.

Although, the term NOMA has referred to power domain multiplexing through this section, the concept of NOMA is much broader and includes other kind of schemes which are totally different from presented one. Actually, in this section, the power domain NOMA is presented. To read more about other variation of NOMA, see [15, 16].

6. Conclusion


In this chapter, we briefly studied the important multiplexing/de-multiplexing techniques, including TDM, CDM, FDM, OFDM, and power-domain NOMA. These techniques play important roles in the past, current, and future generations of wireless communication networks. The main objectives of these techniques are providing the opportunity of concurrent multi-user transmissions and effective utilization of available communication resources. However, the multiplexing approaches are not limited to the investigated techniques, and other techniques, such as spatial multiplexing, delay-Doppler spread multiplexing, pattern division multiplexing can be found in the communication territory. Also, it is very common in communication technologies to employ more than one multiplexing technique for transmission.

Author details

Pedram Kheirkhah Sangdeh and Huacheng Zeng*
University of Louisville, Louisville, KY, USA

*Address all correspondence to: huacheng.zeng@louisville.edu

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