Multi-level modulation scheme based on PAK algorithm for optical camera communications*

WU Jing, CHI Xuefen, JI Fenglei, JIANG Keyu, CHEN Shaoqi, and LI Shuai**
Department of Communications Engineering, Jilin University, Changchun 130012, China

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In an optical camera communication (OCC) system, multi-level modulation is essential for data rate enhancement with the finite frame rate of the receiving camera constraint, where the K-means algorithm is widely used as a thresholding scheme. The result of K-means clustering is sensitive to initial cluster centers. In this paper, we propose a multi-level modulation scheme utilizing the pilot-aided K-means (PAK) algorithm. PAK algorithm innovates in both obtaining the state of the stripes propagated through the optical channel under different environments and overcoming the susceptibility of K-means. Our scheme could prompt data rate and improve the performance of OCC. Finally, non-orthogonal multiple access (NOMA) pattern is designed based on the proposed scheme to achieve multiplex communications.
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The widespread use of wireless technologies based on radio frequencies causes many applications emergent all over the world. Nevertheless, they have some adverse effects on human health[1]. Thus, the researchers are dedicated to finding new wireless technologies to substitute radio frequency technologies. Optical camera communication (OCC) which is regarded as a candidate for the standardization of issues in IEEE 802.15.7r1 has its unique advantages on receiver characteristics[2]. Embedded complementary metal-oxide semiconductor (CMOS) image sensor can be extensively utilized as an OCC receiver because it can offer the flexibility and cheapness of wireless communication[3,4], which facilitates high data transmission rate supply relying on natural spatial features and larger field of view than a photodiode. However, the frame rate is the most critical factor to limit the data transmission rate of the OCC system. The researchers divided image sensor-based camera OCC systems into two types, namely high frame rate camera (HFR) OCC and low frame rate camera (LFR) OCC. In an HFR OCC, the camera with the rate of more than 200 frames is usually regarded as the receiver, while the camera with the rate of fewer than 60 frames is considered in LFR[5]. The most commercial camera can support 30 or 60 frames per second, falling into the LFR OCC category. Therefore, to propose a universality strategy, we focus on LFR OCC, although HFR OCC can provide a higher transmission rate. In the OCC system, binary modulation is broadly applied[6-8]. It judges that the strip only has two states, dark and light (represent “0” and “1”, respectively), which restricts the rate of the OCC system. Some researchers have proposed many multi-level modulation methods. JIN et al[9] proposed a strategy that uses two light emitting diode (LED) lights to achieve multiple levels. LED1 is modulated by on-off keying (OOK), and LED2 is modulated by Manchester code. According to the characteristics of Manchester encoding, the brightness of the two lights is superimposed to produce three amplitudes. Their scheme can achieve a net data rate of 4.32 kbit/s. LIN et al[10] proposed a multi-level brightness modulation (MBM) that used global shutter to combine the states of two LED lights to obtain four levels of multi-level modulation. It can be seen that the current common multi-level OCC systems mostly use two LEDs. Considering the complexity of the hardware and the data rate of the OCC system, it is imperative to combine the rolling shutter with a single LED multi-level modulation.

In traditional communications, the pilot is mainly used for channel estimation, which is an inevitable requirement of the actual communication environment. What’s more, K-means clustering is a classic algorithm that is highly susceptible to the initial clustering center. Facing the above problems, we bring the pilot into the OCC system.

In this paper, we propose a multi-level modulation scheme utilizing the pilot-aided K-means (PAK) algorithm. PAK algorithm innovates in both obtaining the state of the stripes propagated through the optical channel and overcoming the susceptibility of K-means. At the transmitter, LED light is modulated by pulse width modulation (PWM) waves with four different duty cycles

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** E-mail: chixf@jlu.edu.cn

and the pilot is inserted into each packet. At the receiver, we apply the PAK algorithm to complete multi-level demodulation. Finally, we design non-orthogonal multiple access (NOMA) pattern based on our proposed scheme to achieve multiplex communications.

The system block diagram is illustrated in Fig.1. The proposed OCC system consists of two main components, an LED luminaire as the stationary transmitter to emit intensity-modulated light and a smartphone as the receiver.

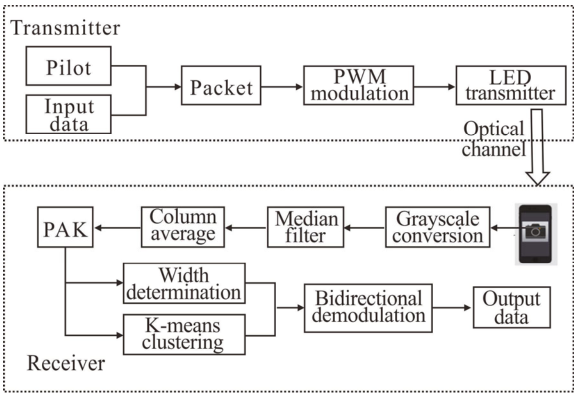

Fig.1 System block diagram

PWM is to adjust the duty cycle of the switch circuit to obtain a series of pulses with equal amplitude but inconsistent width at the output. At the transmitter, we generate PWM waves by controlling the high-resolution counter in the microcontroller. Four appropriate duty cycles are set as 0%, 40%, 60% and 100% to represent symbol “0”, symbol “1”, symbol “2” and symbol “3” respectively, which are shown in Fig.2(a). Thus, four brightness levels emerge. At the receiver, there are four grayscale strips, namely dark strip, dark gray strip, light gray strip, and bright strip correspondingly. Theoretically, the image captured by the camera could be shown in Fig.2(b). One strip represents two bits, so the rate of the OCC system is doubled. The frame structure designed in our system is presented in Fig.3. Each packet contains a header with 12 symbols that carry the pilot information, the data payload with 61 symbols and a packet sequence number (PSN) occupying 8 symbols coming after the preamble.

We traverse each symbol of one period to produce four types of the strip and define each strip as a unit strip. Then send them three times in a row as the pilot, also known as a header. We conduct experiments on all permutations and combinations of four-level gray-scale strips, trying to find the permutation with the highest successful recognition rate. At the same time, to avoid ambiguity and interference between adjacent-level strips due to low contrast, we hope to select adjacent strips separated by one or two levels as the pilot. To sum up, we chose the permutation combination of sending "0213" repeated three times as our pilot strips. The above described pilot strips are shown in Fig.4.

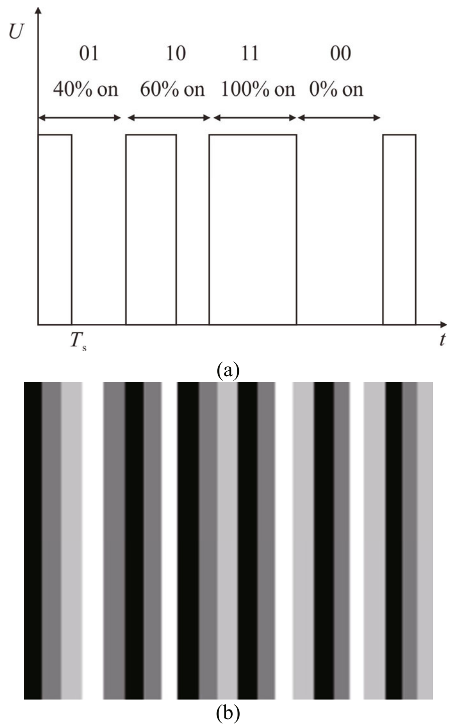

Fig.2 (a) PWM control for symbol in multi-level modulation; (b) Strips under ideal conditions

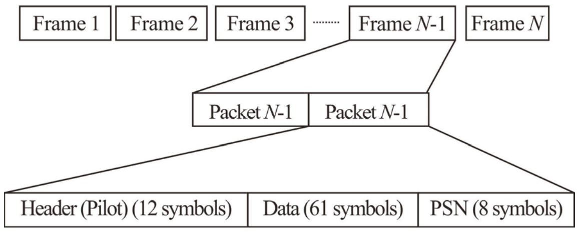

Fig.3 Structure of the data frame

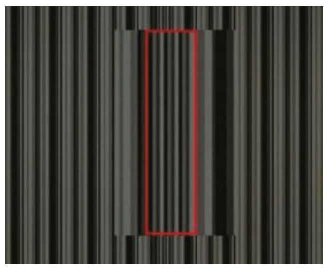

Fig.4 Received pilot strips

The effective functions of the pilot in our proposed scheme are as follows.

(1) Since the pilot signal is known on both sides of the transceiver, it can perform the basic synchronization. When we find the pilot strips, it means that the packet has arrived and completed the synchronization of the communications.

(2) The purpose of using the pilot in communications is to carry some specific prior information to estimate the propagation environment of the signal precisely. Therefore, we can capture how much the gray value of each symbol decays after being transmitted through the optical

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channel under the circumstance of users.

(3) In the OCC system, the interference between stripes is a common factor leading to inaccurate judgment. At our receiver, the pixel width occupied by each stripe can be extracted from the pilot. The width of the unit strip is obtained during demodulation to weaken the interference and prompt the accuracy of demodulating.

(4) It is well known that K-means clustering is susceptible to the initial cluster center selection causing unstable results. Based on the pilot, we know the gray mean value of each strip under the current environment, and take advantage of it as the initial centroid of K-means clustering to keep K-means clustering stable.

At the receiver, the video captured by the camera is processed by frame splitting. Firstly, the image is converted to a grayscale image, and then we apply a median filter with a window of 3×3 to the entire image to eliminate image noise. On account of the row-by-row exposure in the rolling shutter mode, each column of pixels is exposed in the same time period, so the gray value of each column will be within a small fluctuation interval. Therefore, we take the average value of the one dimensional column to replace the data carried by the entire two dimensional strip picture, as shown in Fig.5, which we called column average.

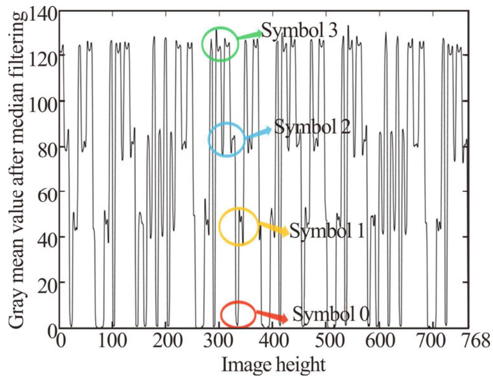


Fig.5 Gray mean value after median filtering

To acquire the gray values from the pilot for K-means clustering, we come up with a PAK algorithm whose sequential function chart is shown in Fig.6. First, the column average is processed by forward difference processing and the difference values are smoothed again to make the position of the change of the strip state clearer. Then, we gain each peak and valley of the difference values. The peak represents the change of the strip from dark to light, and the valley represents the change of the strip from light to dark. Next, we take the absolute values of the difference values to unify the changes of the strips, and the position of the peaks obtained is the position where the state changes. In other words, the location of the data symbol conversion is also found. Reshape every four elements in the peak array into one column to generate matrix $\boldsymbol{P}$. The Pearson correlation coefficient between one column of $\boldsymbol{P}$ and the next column is calculated according to Eq.(1).

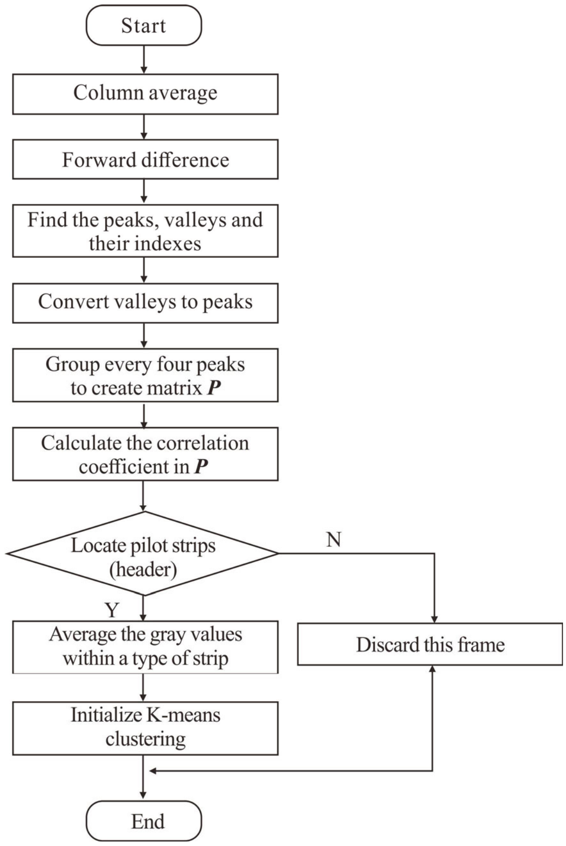


Fig.6 Sequential function chart of PAK

$$\rho_{X,Y}=\frac{\operatorname{cov}(\boldsymbol{X},\boldsymbol{Y})}{\sigma_X\sigma_Y}=\frac{\sum_{i=1}^{4}(x_i-\mu_X)(y_i-\mu_Y)}{\sqrt{\sum_{i=1}^{4}(x_i-\mu_X)^2}\sqrt{\sum_{i=1}^{4}(y_i-\mu_Y)^2}}, \tag{1}$$

where $\boldsymbol{X}$ and $\boldsymbol{Y}$ denote the preceding column and the following columns of the matrix $\boldsymbol{P}$, respectively. x_i and y_i are their elements. $\mu_{\boldsymbol{X}}$ and $\mu_{\boldsymbol{Y}}$ are the means of $\boldsymbol{X}$ and $\boldsymbol{Y}$. $\sigma_{\boldsymbol{X}}$ and $\sigma_{\boldsymbol{Y}}$ are the variances of $\boldsymbol{X}$ and $\boldsymbol{Y}$. When the covariance cov($\boldsymbol{X}$, $\boldsymbol{Y}$) exists, it is called as the correlation coefficient between the random variables $\boldsymbol{X}$ and $\boldsymbol{Y}$.

The repeat transmission of the pilot three times causes the correlation. The pilot position can be determined when the correlation coefficient is greater than or equal to 0.98. What's more, the difference between the index positions of adjacent crests is the pixel width of each strip. The average pixel width of these four strips is taken as the width of the unit strip. Ultimately, treat the column average gray values of each pilot strip as the initial clustering centroids of the K-means clustering.

In the final analysis, multi-level demodulation is a matter of classification. Whereas earlier proposals suggest using polynomial regression to determine the threshold, we choose an iterative clustering analysis algorithm K-means to recover the sent data. The steps are as follows.

Step 1. To divide the data into K groups, K objects are randomly selected as the initial clustering center.

Step 2. The distance between each object and each seed clustering center is calculated, and each object is assigned to the clustering center closest to it. The cluster centers and the objects assigned to them represent a cluster.

Step 3. When an object is allocated into a cluster, the center of this cluster will be recalculated based on the existing objects.

Step 4. The termination condition can be that no (or minimum number of) objects are reassigned to different clusters, no (or minimum number of) cluster centers change again, and the sum of squared errors is locally minimum. The error function can be express as

$$SSE=\sum_{i=1}^{k}\sum_{c_j\in S_i}\left|c_j-u_i\right|^2, \tag{2}$$

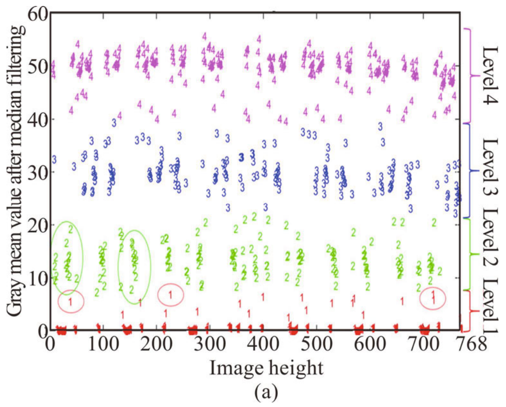
where SSE denotes the sum of error squared, k denotes the number of clustering centers, S_i denotes the ith group of k groups, u_i is the mean value of the points in the group and c_j is an element in S_i. In our experiment, the received signal is partitioned into 4 clusters until the SSE is minimized.

In the K-means algorithm, it is essential to determine an initial partition based on the initial cluster center and then optimize the initial partition. Different initial values give rise to quite different consequences. So we advise a better initial cluster center u_i' as Eq.(3) to make K-means come to convergence faster and more accurately.

$$u_i'=\frac{\sum_{j=1}^{L_{i+1}-L_i}V_j}{L_{i+1}-L_i},(i=1,2,3,4), \tag{3}$$

where L_i denotes the column when the ith pilot strip appears for the first time, and V_j is the gray value of each column in the interval of $[L_i, L_{i+1})$.

Two false classification results for the same frame are shown in Fig.7(a) and (b). In Fig.7(a), one symbol is misjudged, while in Fig.7(b), all the symbols should be discarded. It can be seen that due to the instability of K-means clustering, the same image is clustered into two results. The pilot we designed can just make up for the shortcoming of K-means. The accurate result is shown in Fig.7(c). In this way, the clustering instability, which is caused by the initial clustering center selection in K-means, is solved.



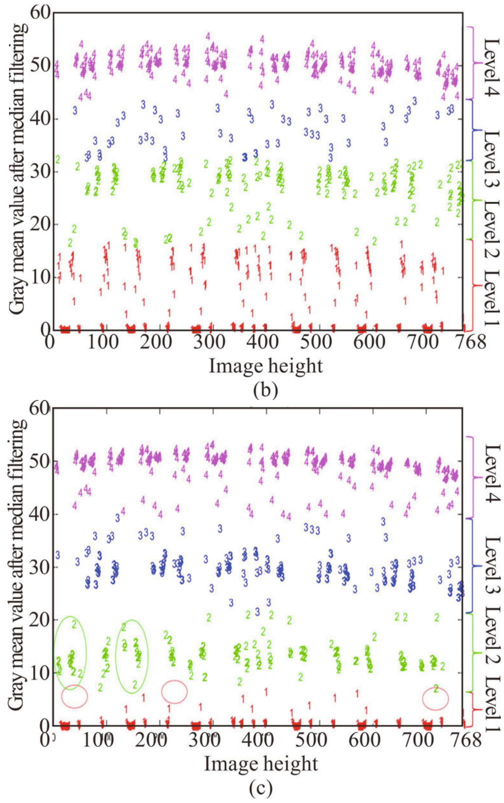


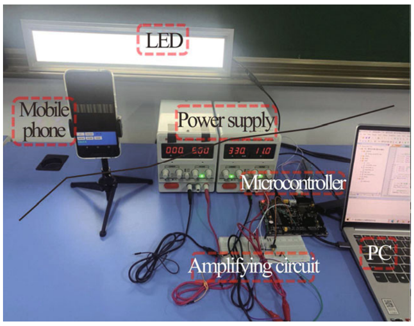
Fig.7 (a) K-means clustering result 1; (b) K-means clustering result 2; (c) K-means clustering result after PAK

Besides, we employ bidirectional demodulation[11]. The length of a packet is half of the number of strips that an image could hold, to ensure that each frame contained a complete data packet. If two pilot headers are detected in the image, the data between the two headers is directly taken out. When a header is detected, the bidirectional demodulation mechanism is adopted.

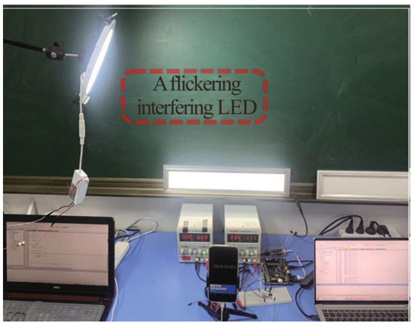
The proposed experimental setup is shown in Fig.8(a). For the transmitting part, the drive circuit is composed of a microcontroller, amplifying circuit and switching circuit. An LED light with a size of 100 mm×500 mm serves as our sender. In our system, the microcontroller is the STM32F103 single-chip microcomputer. The amplifying circuit is MAX4427 chip (the amplified output current is 0.9 A) and the switch is the IRF540N field-effect tube with a shorter response time (about 20 ns). The microcontroller generates the information to be transmitted as a signal source and modulates the information into a digital signal. Since the output voltage of the microcontroller is too small to meet the normal use of the LED, we add an amplifying circuit to amplify the output signal of the microcontroller. For the receiving part, a Google phone NEXUS 5 is used to capture the transmitted light signal. The key parameters of our system are shown in Tab.1.

To analyze the performance of our proposed multi-level modulation scheme, we shot a five-minute video that was continuously demodulated and sent ~1.4×10^6 bits for each given transmission distance. The demodulated algorithm is simulated in Matlab, and the bit error rate (*BER*) performance is analyzed. Each frame of the video contains 166 symbols considering the strip is too thin to demodulate. Therefore, the rate of our multi-level modulation scheme could be expressed as Eq.(4). The data rate can be enhanced by using a mobile phone with a higher frame rate.

$$Rate=\frac{166\ \text{symbols}}{\text{frame}}\times\frac{30\ \text{frames}}{\text{second}}\times\frac{2\ \text{bits}}{\text{symbol}}=9.96\ \text{kbit/s}. \tag{4}$$



(a)



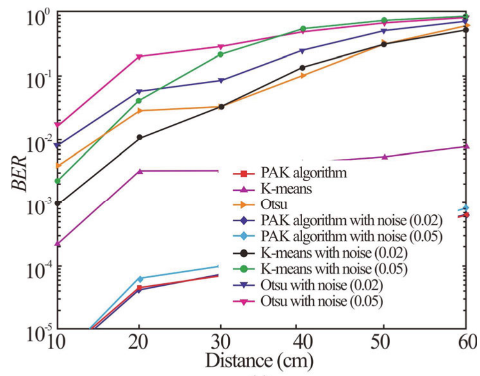
(b)

Fig.8 (a) Experimental setup; (b) The environment with a flickering interfering LED

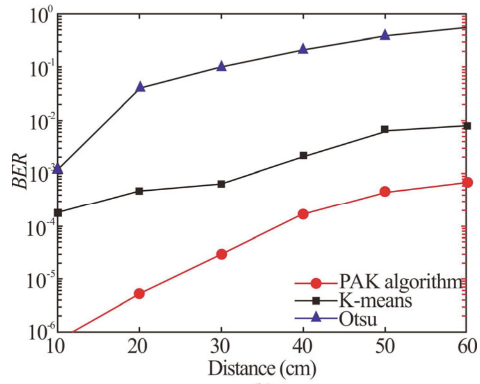
Tab.1 Key parameters of the experiment

Parameter	Value
Image resolution	1 024×768
Frame rate of the camera	30 fps
Camera ISO	400
Symbol interval	200 μs
Number of strips per image	166
Width of a strip	5 pixels

We control the input voltage at 11 V, and then measure the relationship between the *BER* of our system versus the communication distance under different scenarios. The relationship curves are shown in Fig.9. It can be seen that the PAK algorithm we proposed is obviously superior to K-means clustering since our pilot suppresses the instability of K-means clustering. What's more, we also tested the Otsu algorithm based on the principle of maximum between-cluster variance. The results show that our algorithm performs better than Otsu. In general, the *BER* increases with distance, which is due to the signal noise ratio degrades with the increase of distance. To test the performance of the pilot in the OCC system, we added the salt-and-pepper noise, one of the common image noises. The mean of the noise is 0, and the variance is 0.02 and 0.05. The outcomes shown in Fig.9(a) suggest our scheme has noise immunity to some degree. Furthermore, we introduced a flashing LED as the interference light source which is shown in Fig.8(b). The results in Fig.9(b) indicate that the PAK algorithm can correctly demodulate even exposed to the flickering interference light source. The performance of the PAK algorithm is better than that of K-means and Otsu.



(a)



(b)

Fig.9 (a) *BER* under different noises; (b) *BER* in a flickering interfering LED

NOMA can allow resource reuse among multiple users. It uses the power domain to distinguish different users, which increases spectrum utilization and access quantity. NOMA which supports two users in the OCC system was proposed recently[12]. However, their scheme is based on time division multiple access (TDMA). When demodulating, two users use the same frequency in different time slots. Instead, our proposed multi-level system can work out two channels' information simultaneously. The schematic diagram of NOMA in OCC is displayed in Fig.10. The transmitter drives the LED with the

PWM wave of different duty cycles. The different brightness emitted by the LED is equivalent to the different power. Therefore, we apply the proposed multi-level modulation in OCC to NOMA to realize multiplex communications.

Two channels are assumed in an OCC system with communication demands. PWM waves with a duty cycle of 60% and 40% are assigned to channel 1 and channel 2, respectively. This means that the "1" code of server 1 is sent with a PWM wave of 60% duty cycle, the "0" code is sent with 0% duty cycle. Meanwhile, the "1" code of server 2 is sent with a PWM wave of 40% duty cycle, and the "0" code is also sent with 0% duty cycle. The duty cycle of 0%, 40%, 60% and 100% can be formed by superposition of the two channels of information, which respectively represent the two servers to send "00", "01", "10" and "11". For this reason, the system simultaneously shares resources at the same frequency and sends duplex information to the LED lights. The power allocated to the two servers is different, which is in line with NOMA's idea. When demodulating, the receiver obtains the superimposed signal, and it can work out two channels' information simultaneously. At this point, NOMA in OCC is completed.

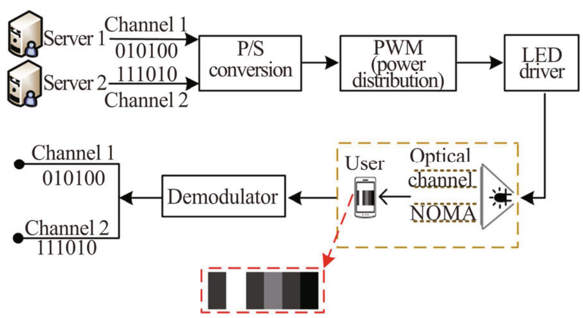


Fig.10 Schematic diagram of NOMA in OCC

In this paper, an effective multi-level modulation scheme was introduced to support a faster smartphone-based OCC system that can achieve a physical layer rate of 9.96 kbit/s with 4-level modulation using a camera of 30 fps. What's more, we propose and demonstrate an efficient algorithm named PAK which implements the pilot to solve the susceptibility of K-means clustering. Under the noise and interference environment, our PAK algorithm also achieves a better demodulation effect. Furthermore, we combine NOMA with multi-level and apply it in OCC to realize multiplex communications.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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