The CEEFQPSK Scheme for Two-Way Relay Communication Systems with Physical-Layer Network Coding

Hongjuan Yang, Jinxiang Song, Bo Li(✉), and Xiyuan Peng

School of Information and Electrical Engineering,
Harbin Institute of Technology (Weihai), 264209 Weihai, China
{hjyang, songjinxiang, libo1983, pxy}@hit.edu.cn

Abstract. A physical-layer network coding (PNC) scheme based on CEEFQPSK (constant envelope enhanced FQPSK) is established for satellite communications. The scheme is implemented for uplink and downlink. In the uplink, the two signals to be sent are modulated into electromagnetic wave signal by CEEFQPSK in two channels (I, Q) and broadcasted to the relay node. At the same time, the electromagnetic wave signal is superimposed on the relay node and mapped into a binary bit, and then it will be modulated and broadcasted to the two terminals. In the downlink, soft information is received according to the maximum posterior probability criterion, and the required information is de-mapped with its own information. The bit-error rate (BER) and throughput of the entire system are analyzed by simulation. Theoretical analysis and simulation results show that the BER of the physical-layer network coding scheme using this method is close to that of the traditional scheme and network coding scheme, but the throughput is higher than the other two.

Keywords: Physical-layer network coding (PNC) · FQPSK modulation · Two-way relay communication · Relay mapping

1 Introduction

With the continuous development of global network information, communications on the ground can no longer satisfy the people's growing demands for information acquisition and transmission, to extend the space resources for communications has been increasingly focused on by more and more people. Therefore, the theory of transmitting information via satellite becomes the focus of people's attention. As with other types of networks, network capacity is one of the important performance parameters for satellite communication networks. Based on Shannon's maximum flow minimum cut theory [1]: "the minimum cut of network determines its maximum end-to-end information flow." finding a way to get close to or reach the upper bound of network capacity has become a heated research. In 2000, researchers like Ahlswede [2] brought up the theory of network coding (NC) and theoretically proved that the top capacity determined by maximum flow minimum cut theorem can be reached through coding information on each code of the network, and NC is a break-through in communication field. Different from traditional information transmission scheme, NC

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technology is no longer just store-and-forward, its core idea is to allow the relay nodes to process the received packets by combining or coding, thus immensely increase the network's transmission capacity.

As the research on NC gets deeper and deeper, people find that NC technology has good compatibility and ability of information extraction when applied to wireless communication network, but it still can't get rid of the problem of interference, especially the interference caused by electromagnetic wave of the same frequency, like traditional coding scheme, TDMA is applied in NC. As data transmitted in the form of electromagnetic waves are all transmitted in the physical layer of wireless link, people naturally get the idea of applying NC in physical layer. In 2006, researchers like Zhang put forward physical-layer network coding (PNC) theorem [3], whose principle is: the transmitted electromagnetic waves are superposed in the airspace, map the superposed signal on the relay node, and make the interference part of the encoding algorithm, then broadcast the mapped signal to both sides, and demodulate the mapped signal at the terminals. Once this theory is brought up, great attention was drawn to it. PNC theory dramatically increases the throughput of the network system, and it help to reach the maximum of spectrum efficiency. For the three-node two-way relay communication system, the throughput of physical-layer network coding is improved a lot, which increased 100% than that of traditional scheme and 50% than that of NC scheme [4].

The idea of PNC is to process the electromagnetic wave signals superposed in wireless channel, and the modulation technology adapted is its key point when applied to satellite communications. Different rules of modulation have different mapping mechanism on the relay nodes. [3] introduced such modulation mapping rules like QPSK and QAM. [5] firstly explored a PNC system suitable for deep-space communications, which applies FQPSK modulation, and its relay mapping uses waveform classification criteria. [6] was the improvement of FQPSK and then brought up CEEFQPSK. This paper will focus on analyzing the performance of PNC based on CEEFQPSK.

2 The Modulation Model of CEEFQPSK

CEEFQPSK is an improvement of IJF-OQPSK, which adds a cross correlation after IJF coding to decrease the envelop fluctuation, its modulation diagram is shown in Fig. 1.

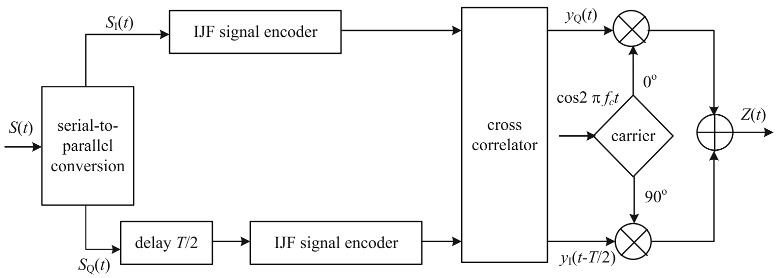

Fig. 1. The modulation diagram of CEEFQPSK

16 kinds of waveform, $s_i(t)$, $i = 0, 1, 2, \ldots, 15$ are defined, whose interval is $-TS/2 \leq t \leq TS/2$. They form the signal set of channel I and Q. For arbitrary interval T_s on each channel, the selection of waveform on channel I and Q depends on its data jump and two continuous data jumps on another channel. Therefore, FQPSK is a modulation type with memory. As the slope of basic waveform is not continuous in the midpoint in FQPSK, which only achieves quasi constant envelope, we make an improvement on FQPSK and then propose CEEFQPSK, and its basic waveform is defined as follow [6]:

$$
\begin{aligned}
&s_0(t) = A, && -\tfrac{Ts}{2} \leq t \leq \tfrac{Ts}{2} && s_8(t) = -s0(t)\\
&s_1(t) = \begin{cases} A, & -\tfrac{Ts}{2} \leq t \leq 0 \\ \sqrt{1 - \left(\sin\frac{\pi(t+\mathrm{Ts}/2)}{\mathrm{Ts}} - (1-A)\sin^2\frac{\pi(t+\mathrm{Ts}/2)}{\mathrm{Ts}}\right)^2}, & 0 \leq t \leq \tfrac{Ts}{2} \end{cases} && && s_9(t) = -s1(t)\\
&s_2(t) = \begin{cases} \sqrt{1 - \left(\sin\frac{\pi(t+\mathrm{Ts}/2)}{\mathrm{Ts}} - (1-A)\sin^2\frac{\pi(t+\mathrm{Ts}/2)}{\mathrm{Ts}}\right)^2}, & -\tfrac{Ts}{2} \leq t \leq 0 \\ A, & 0 \leq t \leq \tfrac{Ts}{2} \end{cases} && && s_{10}(t) = -s2(t)\\
&s_3(t) = \sqrt{1 - \left(\sin\frac{\pi(t+\mathrm{Ts}/2)}{\mathrm{Ts}} - (1-A)\sin^2\frac{\pi(t+\mathrm{Ts}/2)}{\mathrm{Ts}}\right)^2}, && -\tfrac{Ts}{2} \leq t \leq \tfrac{Ts}{2} && s_{11}(t) = -s3(t)\\
&s_4(t) = \begin{cases} \sin\frac{\pi t}{\mathrm{Ts}} + (1-A)\sin^2\frac{\pi t}{\mathrm{Ts}}, & -\tfrac{Ts}{2} \leq t \leq 0 \\ \sin\frac{\pi t}{\mathrm{Ts}} - (1-A)\sin^2\frac{\pi t}{\mathrm{Ts}}, & 0 \leq t \leq \tfrac{Ts}{2} \end{cases} && && s_{12}(t) = -s4(t)\\
&s_5(t) = \begin{cases} \sin\frac{\pi t}{\mathrm{Ts}} + (1-A)\sin^2\frac{\pi t}{\mathrm{Ts}}, & -\tfrac{Ts}{2} \leq t \leq 0 \\ \sin\frac{\pi t}{\mathrm{Ts}}, & 0 \leq t \leq \tfrac{Ts}{2} \end{cases} && && s_{13}(t) = -s5(t)\\
&s_6(t) = \begin{cases} \sin\frac{\pi t}{\mathrm{Ts}}, & -\tfrac{Ts}{2} \leq t \leq 0 \\ \sin\frac{\pi t}{\mathrm{Ts}} - (1-A)\sin^2\frac{\pi t}{\mathrm{Ts}}, & 0 \leq t \leq \tfrac{Ts}{2} \end{cases} && && s_{14}(t) = -s6(t)\\
&s_7(t) = \sin\frac{\pi t}{\mathrm{Ts}}, && -\tfrac{Ts}{2} \leq t \leq \tfrac{Ts}{2} && s_{15}(t) = -s7(t)
\end{aligned}
\tag{1}
$$

After this improvement, the slope is now continuous on the midpoint. So, the slope of the signal is continuous between intervals, and keeps zero-slope at the border, which promises the signal continuous whenever. Meanwhile, as the roll-off speed of signal frequency spectrum is relevant to its smoothness, the frequency spectrum roll-off speed of the modified signal outstanding increases, this tremendously enhances the spectrum efficiency. And this makes FQPSK into constant envelop modulation.

3 System Model for Two-Way Relay Communications

Two-Way Relay Communications model is shown in Fig. 2. There is no direct link between node A and B, information is exchanged via the node R. As shown in Fig. 2, node A and node B stand for two ground stations, node R stands for the relay satellite. Under the condition of half duplex, it only needs two time slots to complete once information transmission. During uplink phase, A and B send its packets S_1 and S_2 to R at the same time; during downlink phase, R will map the received superposed signal according to the waveform classification criteria and generate the network coding packet S_3, then broadcast the generated packet to A and B. Node A and B will demodulate the packets from node B and node A according to the received packet S_3 and the original data they have. Then, a data transmission cycle is completed.

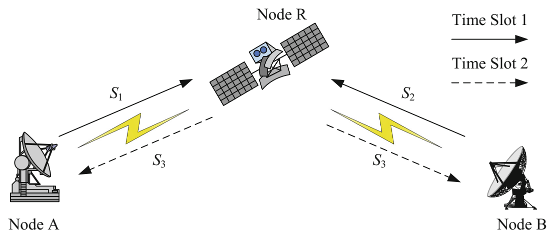

Fig. 2. System model for two-way relay communications

4 The Schemes of Relay Mapping and Terminal De-mapping

4.1 The Mapping Scheme

As the phase constellation points of FQPSK are irregular distributed on the unit circle, the traditional constellation classification criteria is no longer suitable for this system. The scheme of relay mapping adapted in this system is the mapping scheme based on waveform cluster classification criteria, which introduced in [5]. The superposed signal received at the relay node can be described as:

$$y_{\mathrm{R}}(t) = z_{\mathrm{A}}(t) + z_{\mathrm{B}}(t) + n(t) \tag{2}$$

n(t) stands for Gaussian noise with zero mean and variance σ^2, the variance is relevant to the average power of each signal. $z_{\mathrm{A}}(t)$ and $z_{\mathrm{B}}(t)$ stand for the signal from node A and B. Assuming that in the n^{th} time slot, $x_{\mathrm{I}}(t)$ and $x_{\mathrm{Q}}(t)$, the envelope of baseband signal of channel I and Q, are formed by $s_i(t)$ and $s_j(t)$, i and j are decided by the modulation rule. Set $x_{\mathrm{I}}(t) = s_i(t - nT_{\mathrm{s}})$ and $x_{\mathrm{Q}}(t) = s_j(t - nT_{\mathrm{s}} + T_{\mathrm{s}}/2)$, then the transmitted signal envelop can be expressed as:

$$\begin{aligned} z_{\mathrm{A}}(t) &= x_{\mathrm{I}}(t) + jx_{\mathrm{Q}}(t) = \sum_n s_i(t - nT_{\mathrm{s}}) + j\sum_n s_j(t - nT_{\mathrm{s}} + T_{\mathrm{s}}/2) \\ z_{\mathrm{B}}(t) &= x'_{\mathrm{I}}(t) + jx'_{\mathrm{Q}}(t) = \sum_n s'_i(t - nT_{\mathrm{s}}) + j\sum_n s'_j(t - nT_{\mathrm{s}} + T_{\mathrm{s}}/2) \end{aligned} \tag{3}$$

For convenience, the superposed signal can be expressed as:

$$\begin{aligned} S_{\mathrm{I}} &= \sum_n s_i(t - nT_s) + \sum_n s'_i(t - nT_s) \\ S_{\mathrm{Q}} &= \sum_n s_j(t - nT_s + T_s/2) + \sum_n s'_j(t - nT_s + T_s/2) \end{aligned} \tag{4}$$

The idea of classifying the 16 kinds of basic waveform into 4 categories in FQPSK receiver is applied to the received signal on relay nodes. We separate the two channels and then detect the signal S_{I} and S_{Q} of channel I and Q according to energy offset theorem. According to the principle brought up above, all possible waveform combination of the superposed signal S_{I} received at the relay node, interfered by no noise in channel I, is displayed in Table 1.

Table 1. All possible waveform combination

superposed signal (station A \ station B)	$q_0(t)$	$q_1(t)$	$q_2(t)$	$q_3(t)$
$q_0(t)$	$p_{00}(t)$	$p_{01}(t)$	$p_{02}(t)$	$p_{03}(t)$
$q_1(t)$	$p_{10}(t)$	$p_{11}(t)$	$p_{12}(t)$	$p_{13}(t)$
$q_2(t)$	$p_{20}(t)$	$p_{21}(t)$	$p_{22}(t)$	$p_{23}(t)$
$q_3(t)$	$p_{30}(t)$	$p_{31}(t)$	$p_{32}(t)$	$p_{33}(t)$

During each symbol period, energy offset is carried out on baseband signal $S_k(t)$:

$$V_{ii}^{'}(t) = \int_{-\frac{Ts}{2}}^{\frac{Ts}{2}} p_{ii}^{'}(t) \cdot S_k(t)dt - \frac{1}{2}\int_{-\frac{Ts}{2}}^{\frac{Ts}{2}} p_{ii}^{'}(t) \cdot p_{ii}^{'}(t)dt \; k \in \{\text{I,Q}\} \tag{5}$$

Then the maximum offset energy $V_{\max}(t)$ is picked up, which is also the biggest value of $V_{ii}'(t)$. A new standard symbol $\Gamma_k(\bullet)$ for mapping is now defined, and the mapping rule is as follow:

$$\Gamma_k(V_{\max}(t)) = \begin{cases} 0, \; V_{\max}(t) = \begin{Bmatrix} V_{00}(t), V_{01}(t), V_{10}(t), \; V_{11}(t) \\ V_{22}(t), V_{23}(t), V_{32}(t), \; V_{33}(t) \end{Bmatrix} \\ 1, \; V_{\max}(t) = \begin{Bmatrix} V_{02}(t), V_{20}(t), V_{03}(t), \; V_{30}(t) \\ V_{12}(t), V_{21}(t), V_{13}(t), \; V_{31}(t) \end{Bmatrix} \end{cases} \tag{6}$$

Then, we get a new code word sequence $x_r(t) = \Gamma_k(V_{\max}(t)) \in \{0{,}1\}$.

After mapping, $x_r(t)$ is modulated by CEEFQPSK, and then broadcasted to the two ground receiving stations.

4.2 The De-mapping Scheme

According to the symmetry of the system, we take ground station A as an example for information recovery, and it's also appropriate for ground station B. Assuming that the downlink signal received by station A is $y_r(t) = \{r_1, r_2, \ldots, r_L\}$, the soft information carried by the signal is estimated by MAP algorithm. While this information is not what we expect from station B, but the codon formed by the superposed signal which is mapped on the relay node, it only carries the relationship between the two signals form station A and B.

Station A will obtain the information from station B according to its own information and the information demodulated from the codon. The de-mapping algorithm is just like an inversed process of the mapping process. Therefore, we can decide the scope of the superposed signal $p_{ii}'(t)$ according to the Eq. (6), then get the scope of information from station B according to its own information and Table 1.

However, the operation above can neither certainly make sure that, q_0 and q_1, which one is the electromagnetic wave envelop from station B, nor distinguish q_2 and q_3. But according to the interweave chart of simplified CEEFQPSK, we can see that when adapting Viterbi demodulation to the signal from station B, the demodulation output is always 0, whatever the signal is q_0 or q_1. Besides, the output is always 1 whatever the signal is q_2 or q_3. In conclusion, there is no need to distinguish between q_0 and q_1 or q_2 and q_3.

Therefore, Table 2 shows the resumed information at station A (which is also adaptable to station B).

Table 2. The resumed information at station A

If $\Gamma(V_{\max}(t)) = 0$ and $q_i \in \{q_0,q_1\}$, the output is $y_b = 0$;
If $\Gamma(V_{\max}(t)) = 0$ and $q_i \in \{q_2,q_3\}$, the output is $y_b = 1$;
If $\Gamma(V_{\max}(t)) = 1$ and $q_i \in \{q_0,q_1\}$, the output is $y_b = 1$;
if $\Gamma(V_{\max}(t)) = 1$ and $q_i \in \{q_2,q_3\}$, the output is $y_b = 0$;

In conclusion, we can make it easier to de-mapping and demodulate the information from station B by applying intertwined de-mapping and demodulation mechanism. It not only reduces the complexity of the system, but also effectively enhances the fault-tolerance of the whole system, which make the operability of whole system stronger.

5 Simulation Results and Analysis

In this section, we study the performances of the PNC based on CEEFQPSK modulation, as discussed above, by using computer simulation in terms of BER and system throughput.

5.1 BER Performance of the Two-Way Relay System

Figure 3 shows the BER comparison between the traditional scheme, network coding scheme and physical-layer network coding scheme. Because of the integral of BER formula of CEEFQPSK is too complex, its BER performance can be understand through the curve in the Fig. 3.

Form Fig. 3, it can be seen that the changing tendency along with SNR is in consistence between the 3 schemes, all improve with SNR, and the BERs of the 3 schemes are quite similar. Besides, we can see that the traditional scheme has better performance. However, it only needs 2 time slots for physical-layer network coding scheme to accomplish once two-way relay communication, while 4 time slots for traditional scheme and 3 time slots for network coding scheme. So, we can see that physical-layer network coding scheme can help to increase the system throughput.

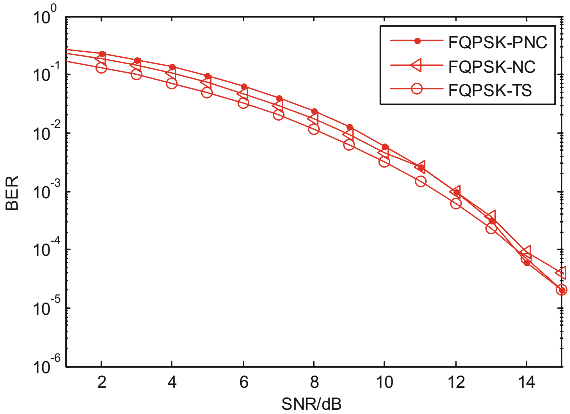

Fig. 3. BER performance comparison

5.2 Throughput Performance of the Two-Way Relay System

In this paper, the system throughput for the two-way relay system is defined as:

$$T = \frac{(1 - BER)^L \cdot 2LR\log_2 M}{n\frac{d}{c}} \tag{7}$$

where BER stands for the bit-error rate of a given scheme; L stands for the length of the data frame transmitted, and we assume that L to be 1024 bits; R stands for the bit rate of the encoded channel, here we assume that the end-to-end channel coding is adapted, and R equals 1/2; M is the modulation order; n stands for the number of time slots required for once two-way relay communication, and the n is to be 4, 3, 2 in traditional scheme, network coding scheme and physical-layer networking scheme, respectively. d stands for the distance between the two communicating stations, here we set d = 30 km; c stands for the travelling speed of the electromagnetic wave, which is close to the speed of light, and d/c equals one time slot. To normalize formula (7), we get:

$$T = \frac{(1 - BER)^L}{n} \tag{8}$$

The throughputs of these three schemes are shown in Fig. 4.

Figure 4 shows that the throughput of physical-layer network coding scheme is much better than that of traditional scheme and network coding scheme. With the SNR increasing, once the system works in stable condition, the throughput of PNC is increased by 100% and 50% than that of traditional scheme and network coding scheme, respectively. This improvement is mainly own to the decreasing of the transmission time slot. As these three schemes have similar BER, the decreasing of the transmission time slot will tremendously increase the throughput performance.

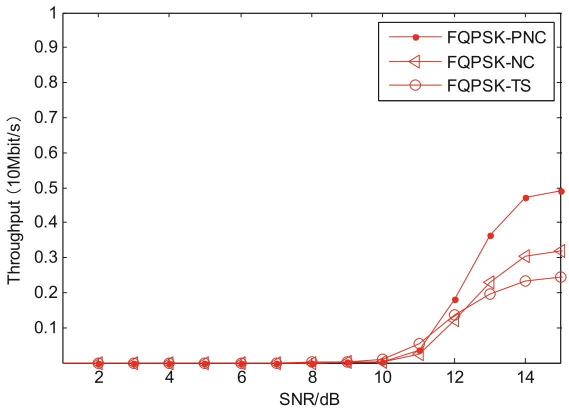

Fig. 4. Throughputs for different schemes

6 Conclusions

This article mainly focuses on researching the performances of physical-layer network coding scheme based on CEEQPSK when applied to satellite communication. During the research process of the PNC system based on CEEFQPSK modulation, signals from the two channels are modulated by CEEFQPSK and then transmitted to the relay node. The signals are superposed on the relay node, and then being processed according to the relay-mapping scheme based on waveform classification criteria before being broadcast. Then, the required information is recovered on the terminal by demodulation and de-mapping. Finally, the system is verified by software simulation.

According to the comparison among traditional scheme, network coding scheme and physical-layer network coding scheme, it can be seen that the BER performances of the three systems are quite close when using CEEFQPSK and the traditional scheme has better performance.

A method for calculating the throughput of the two-way relay communication system is brought up. The simulation results show that when the system works in stable condition, PNC can provide up to 100% and 50% throughput gains compared with traditional scheme and network coding scheme, respectively.

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