PULSE POSITION MODULATION CODING SCHEMES FOR OPTICAL INTERSATELLITE LINKS

F. Ghosna and M. J. N. Sibley
University of Huddersfield, Queensgate, Huddersfield HD1 3DH, UK

ABSTRACT

The rapid and significant development of communications links between satellites has made it possible to use various applications such as relay voice, video, multimedia, etc. As a result, a great deal of research has been done in this field during the last few years to reduce power consumption and increase transmission reliability.

This research project work is concerned with intersatellite links in free space, with optical links using laser sources being considered in particular. This paper discusses the use of several different coding schemes for use in such links: digital pulse position modulation (DPPM); multiple pulse position modulation (MPPM); Dicode pulse position modulation (Dicode PPM). A comparison is made using error rate performance and coding efficiency.

1 INTRODUCTION

A literature survey has been carried out in which the competing technologies of optical and microwave inter-satellite systems were examined by McCullagh et al (1993) & Ekberg (1970). These studies show that, in general, microwave radio systems can receive much lower power levels and operate in the atmosphere more efficiently than optical ones (McCullagh et al (1993)). However, optical systems can operate with much lower path loss and are considered superior to microwave ones in space (Ekberg (1970)). In addition, they have the potential of operation at Gbit/s data rates (McCullagh et al (1993)). Therefore, according to these considerations, optical links in space are receiving a great deal of attention.

The transmitter in an optical link is the laser. The first significant optical intersatellite link was SILEX (Semiconductor laser Intersatellite Link Experiment) by ESA (European Space Agency) using semiconductor laser diode technology (2000) (Lutz (1997)), and the most recent project is OICETS (Optical Inter-orbit Communications Engineering Test Satellite) "Kirari" by JAXA (Japan Aerospace Exploration Agency)using LUCE (Laser Utilizing Communications Equipment) (2005) (Japan Aerospace Exploration Agency (JAXA) (2006)), which enabled optical inter-orbit communications system using a high-power semiconductor laser in free space and between satellites that are tens of thousands of kilometers apart achieved various advantages: more stable communications with less interference; lighter, more compact communications equipment; and higher data transmission rates. These tests led to new technologies that will support the development and utilization of space, including global data reception from Earth Observation satellites and continuous communication links with a manned space station (Japan Aerospace Exploration Agency (JAXA) (2006)). Therefore, for many applications, laser diodes have many advantages: small size; high electrical to optical efficiencies (50 percent); tightly focused beam. In addition, it is possible to adapt the technology used in fiber optic links to free-space communications and so multi-Gbit/s transmission is possible using readily available integrated driver chips.

At the receiver, a photodetector is needed to convert the modulated light signal back into an electrical one. There are two types of detector in use at present: avalanche photodiodes (APDs) or PIN photodiodes (Keiser (2000) & Sibley (1995)). The optimum choice depends on the wavelength of operation which, in turn, depends on how the laser source is to be modulated. In optical fibre communications, it is common practice to modulate a c.w. laser with an external Mach- Zehnder interferometer (Sibley (1995)). As these devices operate at a wavelength of 1.55 μm, this must be the wavelength of operation for the link. Therefore, work is currently being carried out to study the possibility of using a PIN photodiode with a semiconductor optical amplifier (SOA), or APD photodiode with SOA, and then select the best design for an inter-satellite link in free space at a speed of 1 Gbit/s.

2 CODING SCHEMES

According to Sibley (2004, December), digital PPM is the preferred coding scheme for use in optical inter-satellite links. This is because it operates with very low average power and offers high sensitivity. However, it does suffer from a very large bandwidth expansion problem in that a scheme coding 5 bits of PCM will have a final line rate of 6.4 times the original PCM rate (Sibley (2004, December)). This places great strain on the processing electronics and can be prohibitive.

Many alternatives have been proposed that operate with a smaller bandwidth expansion, Zwillinger (1988), Shiu & Kahn (1999) & Shalaby (1999). Of these, multiple PPM (Sugiyama & Nosu (1989), Atkin & Fung (1994), Park & Barry (1995), Park & Barry (1996) & Park & Barry (2003)) and dicode PPM (Sibley (2003) & Sibley (2004)) appear to offer the lowest bandwidth expansion. Multiple PPM uses two or more pulses in a frame to convey the original PCM word, whereas dicode PPM only transmits a pulse when there is a transition between levels. All PPM coding schemes suffer from two types of error: false alarm and erasure. A false alarm is caused by noise in an empty time slot generating a threshold crossing and an erasure is caused by noise obliterating a valid pulse. As the original PCM code is converted into another code, these errors will cause the original PCM to be corrupted.

The timing diagram of figure 1 shows examples of the MPPM, Dicode PPM and DPPM signals:

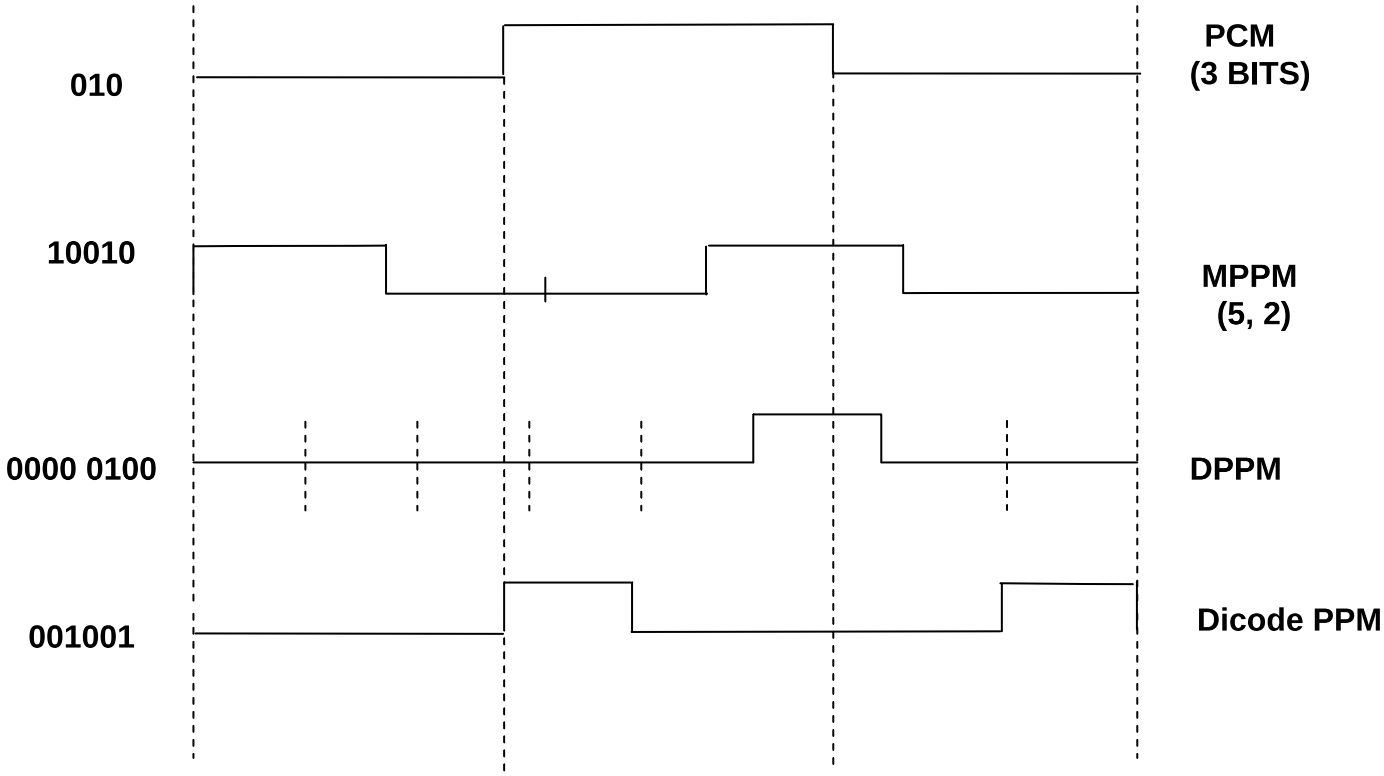

Figure 1: Examples of timing diagram for the MPPM, DPPM and Dicode PPM signals

The coding alphabet for digital PPM and multiple PPM for 3 and 4 bits of PCM is shown in tables 1 and 2.

PCM (3 Bits)	**DPPM**	**MPPM (5,2)**
000	0000 0001	11000 (1,2)
001	0000 0010	10100 (1,3)
010	0000 0100	10010 (1,4)
011	0000 1000	10001 (1,5)
100	0001 0000	01100 (2,3)
101	0010 0000	01010 (2,4)
110	0100 0000	01001 (2,5)
111	1000 0000	00110 (3,4)

Table 1. Alphabet for coding 3 bits of PCM into digital PPM and multiple PPM

As regards the coding alphabet, digital PPM codes *n* bits of PCM into a single pulse which occupies one of 2^n time slots. So, table 1 shows digital PPM in which a single pulse occupies one of 8 time slots to code 3 bits of PCM. However, multiple PPM scheme uses a number of pulses in a frame, with the pulse positions being determined by the original PCM word. Table 1 shows (5, 2) multiple PPM in which a 5-slot frame uses two data pulses to code 3 bits of PCM.

PCM (4 Bits)	**DPPM**	**MPPM (7,2)**
0000	0000 0000 0000 0001	1100000 (1,2)
0001	0000 0000 0000 0010	1010000 (1,3)
0010	0000 0000 0000 0100	1001000 (1,4)
0011	0000 0000 0000 1000	1000100 (1,5)
0100	0000 0000 0001 0000	1000010 (1,6)
0101	0000 0000 0010 0000	1000001 (1,7)
0110	0000 0000 0100 0000	0110000 (2,3)
0111	0000 0000 1000 0000	0101000 (2,4)
1000	0000 0001 0000 0000	0100100 (2,5)
1001	0000 0010 0000 0000	0100010 (2,6)
1010	0000 0100 0000 0000	0100001 (2,7)
1011	0000 1000 0000 0000	0011000 (3,4)
1100	0001 0000 0000 0000	0010100 (3,5)
1101	0010 0000 0000 0000	0010010 (3,6)
1110	0100 0000 0000 0000	0010001 (3,7)
1111	1000 0000 0000 0000	0001100 (4,5)

Table 2. Alphabet for coding 4 bits of PCM into digital PPM and multiple PPM

Table 2 shows digital PPM in which a single pulse occupies one of 16 time slots to code 4 bits of PCM and (7, 2) multiple PPM in which a 7-slot frame uses two data pulses to code 4 bits of PCM.

Work was carried out to show how the PCM error rate is affected by false alarm and erasure errors for digital, multiple and Dicode PPM operating with 3, 4, 5 and 6 bits of PCM.

A maximum likelihood sequence detector (MLSD) is used in the decoder and so the PCM error rate is stet as shown in tables 3, 4 and 5.

Original PCM Word	**MPPM Code**	**MLD**	**Probabilities of False Alarm errors**
000	11000	11100	01100 (100)
			10100 (001)
			11000 (000)
			Average of error = 0.666
		11010	01010 (101)
			10010 (010)
			11000 (000)
			Average of error = 1
		11001	01001 (110)
			10001 (011)
			11000 (000)
			Average of error = 1.333
Final average of error			**0.999 for 3 bits** **0.333 per bit**

Table 3 Determination of PCM error when a false alarm occurs in (5,2) multiple PPM

As an example, if the code 11000 MPPM, which is the code for 000 PCM, has a false alarm occurring in an empty slot in the code-word, three pulses are present and the treatment is shown in table 3. The process is repeated for all vacant slots and the average error obtained. Consideration of all possible code-words yields the total average false alarm error as can be seen in table 6.

Original PCM Word	**DPPM Code**	**MLD**	**Probabilities of False Alarm errors**
000	0000 0001	1000 0001	1000 0000 (111)
			0000 0001 (000)
			Average of error = 1.5
		0100 0001	0100 0000 (110)
			0000 0001 (000)
			Average of error = 1
		0010 0001	0010 0000 (101)
			0000 0001 (000)
			Average of error = 1
		0001 0001	0001 0000 (100)
			0000 0001 (000)
			Average of error = 0.5
		0000 1001	0000 1000 (011)
			0000 0001 (000)
			Average of error = 1
		0000 0101	0000 0100 (010)
			0000 0001 (000)
			Average of error = 0.5
		0000 0011	0000 0010 (001)
			0000 0001 (000)
			Average of error = 0.5
Final average of error			**0.86 for 3 bits 0.286 per bit**

Table 4 Determination of PCM error when a false alarm occurs in digital PPM

If the code 0000 0001 DPPM, which is the code for 000 PCM, experiences a false alarm in an empty slot in the code-word, seven pulses are present and the treatment is shown in table 4. The process is repeated for all vacant slots and the average error obtained. Consideration of all possible code-words yields the total average false alarm error as can be seen in table 6.

Original PCM Word	**MPPM Code**	**MLD**	**Probabilities of Erasure errors**
000	11000	01000	11000 (000)
			01100 (100)
			01010 (101)
			01001 (110)
		10000	11000 (000)
			10100 (001)
			10010 (010)
			10001 (011)
Final average of error			**1.125 for 3 Bits 0.375 per bit**

Table 5 Determination of PCM error when an erasure occurs in (5,2) multiple PPM

Taking the code 11000 MPPM, which is the code for 000 PCM, an erasure error leaves only one pulse in the detected code-word. As two pulses have to be present, the maximum likelihood sequence detector (MLSD) operates as shown in table 5.The same procedure applies if the second pulse is erased and the average error rate is obtained by taking each possible code-word in turn and averaging. Consideration of all possible code-words yields the total average erasure error as can be seen in table 6.

When a digital PPM pulse is erased, the decoded word is all zeroes. So the maximum likelihood decoder assumes it could have been any word at all. Thus the output word will be the average word – 111 (max) 000 (min) giving an average of 1.5 errors. For a 4 bit digital PPM word it would be 1111 (max) 0000 (min) average of 2 errors, etc.

Note. As regards to the errors for dicode PPM, the erasure and false alarm errors rates would be constant independent of the coding level because the Dicode system operates continuously.

3 RESULTS AND DISCUSSION

Table 6 shows how the PCM error rate is affected by false alarms and erasures for digital, multiple and dicode PPM operating with 3, 4, 5 and 6 bits of PCM.

	False Alarm (Per Bit PCM)			Erasure (Per Bit PCM)		
	Digital	Multiple	Dicode	Digital	Multiple	Dicode
PCM (3 bits)	0.286	o.309	0.249	0.5	0.382	0.193
PCM (4 bits)	0.266	0.3088	0.249	0.5	0.419	0.193
PCM (5 bits)	0.258	0.305	0.249	0.5	0.440	0.193
PCM (6 bits)	0.253	0.310	0.249	0.5	0.433	0.193

Table 6 Summary of PCM errors caused by false alarm and erasures in digital, multiple and dicode PPM

As can be seen, dicode PPM is the best coding scheme in terms of error rate because it has the lowest false alarm and erasure error rates. In addition, digital PPM is better than multiple PPM in terms of false alarm error rate because it has fewer errors than multiple PPM. Multiple PPM is better than digital PPM in terms of erasure error rate. However, this data neglects the effects of bandwidth expansion and power efficiency in terms of photons per pulse and average power.

From table 6, it appears that dicode PPM is better than the other two. However, the coding and decoding complexity of all three schemes has yet to be determined. In addition, the power consumption has yet to be analyzed and these areas of work will form the rest of this investigation.

4 CONCLUSION

Digital PPM coding can operate with very low average power and offer a high sensitivity, thus it is the preferred choice for optical inter-satellite links. However, it does suffer from a very large bandwidth expansion problem. Many alternative schemes have been proposed such as differential PPM, overlapping PPM, dicode PPM and multiple PPM. The most bandwidth-efficient of these are dicode PPM and multiple PPM.

This paper has compared the false alarm and erasure error performance of digital, multiple and dicode PPM. Results show that dicode PPM has the lowest error rate. In addition, it offers a small bandwidth expansion of twice the PCM rate. Although, multiple PPM can run at lower speed

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