Tunable Pulse Amplitude and Position Modulation Technique for Reliable Optical Wireless Communication Channels

Yu Zeng, Roger.J.Green, Shaobo Sun and Mark.S.Leeson
Communications and Signal Processing Research Group, School of Engineering, University of Warwick, Coventry, United Kingdom
Email: {yu.zeng, roger.green, s.sun.1, mark.leeson}@warwick.ac.uk

***Abstract*—Modulation techniques have attracted increasing attention in optical wireless communications. Basic schemes such as on off keying (OOK), pulse amplitude modulation (PAM) and pulse position modulation (PPM) have been validated as suitable for the optical wireless channel. This paper starts from the analysis of these three modulation schemes in terms of their power and bandwidth requirements. As a result, a new tunable hybrid modulation technique is proposed. The proposed modulation scheme takes the real time channel conditions into account, which is different from other schemes. By employing amplitude and position modulation selectively, a guaranteed system performance can be secured, without compromising power and bandwidth efficiency. This is also a new approach to realize reliable optical wireless links.**

***Index Terms*—tunable modulation technique, papm, optical wireless, reliable communication channels**

I. INTRODUCTION

High-speed wireless optical communication links have become more popular for personal mobile applications such as PDAs and mobile phones. This is a consequence of the increasing demand from the personal information service boom. Compared to the radio frequency domain, optical wireless communication offers much higher speeds and bit rates per watt. As stated by the official infrared standards body, the IrDA [1], optical communication enjoys much lower power consumption than Bluetooth, with an inherent security feature whilst in Line of Sight (LOS) applications. The only drawback is that infrared radiation cannot penetrate walls as radio frequencies do.

Nevertheless, the optical channel is somewhat noisy for real time applications; it suffers from thermal noise, shot noise and periodic background ambient noise. Due to the nature of personal mobile communication, the established optical link is exposed to a dynamic environment with various noise sources. In optical communication applications, there are always trade offs between system performance and costs. There is thus a pressing need to design a modulation technique for the real time situation.

In this paper, the characteristics of basic modulation schemes are analyzed. The combined power and bandwidth requirements suggest that the basic modulation schemes cannot provide reliability when deployed in a real time channel, resulting in compromised system performance. Starting from actively tuning the modulation scheme parameter, a hybrid modulation scheme is proposed. Extensive simulations of operation in severe noise interference have been carried out to validate the new scheme. A fuzzy logic control module has been developed to realise the tuning mechanism. The simulation results indicate that the new scheme can provide increased immunity against channel noise fluctuation at a relatively low cost. The scheme obtained formed a basis to support reliable mobile optical wireless communication applications.

The rest of this paper is organized as follows: Section II reviews the basic modulation schemes suitable for optical wireless channel. Section III introduces the new tunable modulation scheme, and carries out comparative simulations with the basic schemes. Section IV develops a fuzzy logic control module for the proposed modulation scheme. Section V addresses the reliability prospect of the proposed modulation schemes. Section VI concludes the paper.

II. MODULATION SCHEMES

A. Optical Channels

The optical channel is generally optimal while employing intensity modulation and direct detection (IM/DD) [2]. When the background noise is low, the channel can be modeled as a Poisson process. In the presence of substantial background light, the additive white Gaussian noise (AWGN) model is more appropriate [3]. In terms of calculation complexity, the Gaussian approximation is much simpler than more accurate moment generating function based approaches.

Based on “Adaptive Pulse Amplitude and Position Modulation for Optical Wireless Channels”, by Y. Zeng, R.J. Green and M.S. Leeson which appeared in the Proceedings of the IET International Conference on Access Technologies 2006, Cambridge, UK, June 2006. © 2006 IET.

Using the Gaussian model, the output current at the receiver, *y(t)*, is given by

$$y(t) = \int_{-\infty}^{+\infty} x(\tau)h(t-\tau) + n(t) \quad (1)$$

Where *x(t)* is the optical power of the transmitted signal, *h(t)* represents the factor of multi-path dispersion and *n(t)* represents the white Gaussian noise. Also, *x(t)* must satisfy:

$$x(t) \geq 0 \quad and \quad \lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{T} x(t)dt \leq P \quad (2)$$

Where *P* is the average optical power constraint of the transmitter. These constraints greatly influence the choice of modulation scheme.

B. On Off Keying

The OOK modulation scheme is used for its easy implementation. The transmitter, operating at a bit rate R_b, emits rectangular pulses of duration $1/R_b$ and intensity *2P* to generate bit 'one', and no pulse to generate bit 'zero'. The bandwidth required by OOK is roughly $R_b = 1/T$, the inverse of the pulse width. Assuming matched filtering with a maximum likelihood receiver, the bit error rate (BER) of a OOK system is [2]:

$$BER_{OOK} = Q\left(\frac{P}{\sqrt{N_0 R_b}}\right) \quad (3)$$

Where N_0 is the power spectral density of the white Gaussian noise and *Q(x)* is the customary Q-function of digital telecommunications. By inverting (3), the power requirement for OOK easily seen to be:

$$P_{OOK} = \sqrt{N_0 R_b} Q^{-1}(BER_{OOK}) \quad (4)$$

As $x \in \Re$, and *Q(x)* is monotonically decreasing, the inverse $Q^{-1}(x)$ $\{0,1\} \rightarrow \Re$ is straightforward to obtain via a built in MATLAB function [4].

Furthermore, the OOK modulation scheme can be regarded as a benchmark to other modulation schemes, which can make comparison among different modulation schemes easy. Fig. 1 shows the bandwidth and power efficiencies of the OOK, L-PAM and L-PPM modulation schemes.

C. L level Pulse Amplitude Modulation

For L-PAM, L usually represents amplitude levels. That is, one of L possible amplitude levels transmitted from the transmitter to represent a specific value. The bandwidth requirement of L-PAM is[2]:

$$B_{L-PAM} = \frac{R_b}{\log_2 L} = \frac{1}{\log_2 L} B_{OOK} \quad (5)$$

The BER is:

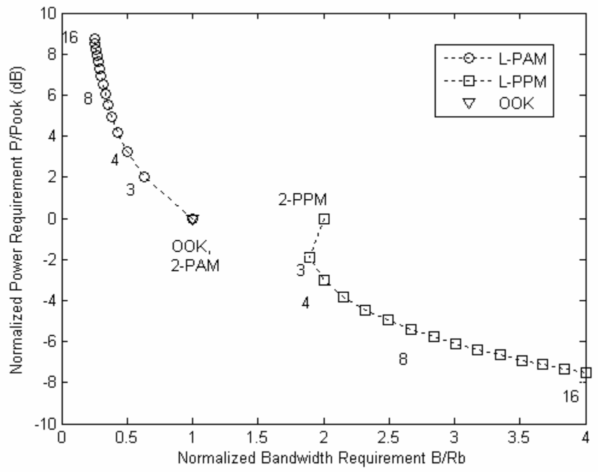

Figure 1. Normalized power requirement and bandwidth requirement for OOK, L-PAM and L-PPM on IM/DD channel

$$BER_{L-PAM} \approx Q\left(\frac{P_{L-PAM}}{L-1}\sqrt{\frac{\log_2 L}{N_0 R_b}}\right) \quad (6)$$

Thus the power requirement of L-PAM schemes is:

$$P_{L-PAM} = \frac{L-1}{\sqrt{\log_2 L}} \cdot \sqrt{N_0 R_0} Q^{-1}(BER_{L-PAM}) \quad (7)$$

To compare with the OOK system, when achieving the same BER:

$$BER_{OOK} = BER_{L-PAM} \quad (8)$$

The Power requirement of the L-PAM is therefore:

$$P_{L-PAM} = \frac{L-1}{\sqrt{\log_2 L}} P_{OOK} \quad (9)$$

The above equation is with the assumptions of high Signal to Noise Ratio (SNR), moderate values of L (L≥2), and a given BER.

D. L level Pulse Position Modulation

In L-PPM, transmitted optical signals are represented by the location of the pulse within a clock cycle. As a result, synchronization between transmitter and receiver is required or assumed when comparing PPM schemes with other schemes[5]. In addition, L represents pulse slots numbers. Note that this is different from L-PAM, though they all use 'L'. The power requirement of an L-PPM system can be approximated by[2]:

$$P_{L-PPM} = \sqrt{\frac{2}{L\log_2 L}} P_{OOK} \quad (10)$$

The bandwidth requirement for L-PPM is:

$$B_{L-PPM} = \frac{L}{\log_2 L} B_{OOK} \quad (11)$$

Sugiyama and Nosu have reported multiple-pulse position modulation (MPPM) and overlapping pulse position modulation (OPPM) as relatives of PPM[6]. Both improve the bandwidth or power requirement at a cost of code calculation redundancy [7]. Alahmari discovered a hybrid modulation scheme: 2 level 2 pulse position modulation (2L2PPM), that has a 0.6 increase in the spectral efficiency with the same power requirement [8].

In addition to the above modulation schemes, there are others such as quadrature amplitude modulation (QAM), quadrature phase shift keying, and binary phase shift keying (Q/BPSK). However, according to the combined power and bandwidth requirement, they are not strong candidates for the optical wireless channel.

The L-PAM and L-PPM modulation schemes have been validated as suitable for the optical wireless channel as basic modulation techniques. The presence of a gap between L-PAM and L-PPM suggests that it is possible to utilize a new modulation scheme to provide a bridge between the two modulation schemes. It must satisfy both the L-PAM and L-PPM requirements, or at least share the features of the two modulation schemes if such scheme exists. From [9] the properties of a potential modulation scheme, Pulse Amplitude and Position Modulation (PAPM) can be found.

E. Pulse Amplitude and Position Modulation

In PAPM modulation, the information is represented both by the amplitude and by the position of the pulse. PAPM is thus also a multi-level modulation scheme. It can be expressed as M-n-PAPM, where M is the number of amplitude levels, and n is the number of pulses within a clock cycle. The bandwidth requirement of the M-n-PAPM is[9]:

$$B_{M-n-PAPM} = \frac{n}{\log_2 nM} B_{OOK} \qquad (12)$$

The power requirement is:

$$P_{M-n-PAPM} = \sqrt{\frac{2M^2}{n\log_2 nM}} P_{OOK} \qquad (13)$$

Since M-n-PAPM has two variables, a family of 2 dimensional curves can be obtained as shown in Fig.2. The vertical curves are constant pulse numbers, with amplitude level M increasing from 2 to 16, and the horizontal curves are constant amplitude levels, with pulse numbers *n* increasing from 2 to 16. M-n-PAPM modulation covers the space above the L-PAM, OOK and L-PAM modulation schemes, with the lower bottom edge being of most interest from the point of power and bandwidth efficiency. The curve jointly formed by M-2-PAPM and 2-n-PAPM crosses the L-PPM at 4-PPM, and reaches the upwards near side of the OOK (2-PAM).

In Fig. 2, a family of curves formed a matrix to cover the space above OOK, L-PAM and L-PPM. This leads to the design of a new hybrid modulation scheme: the tunable PAPM.

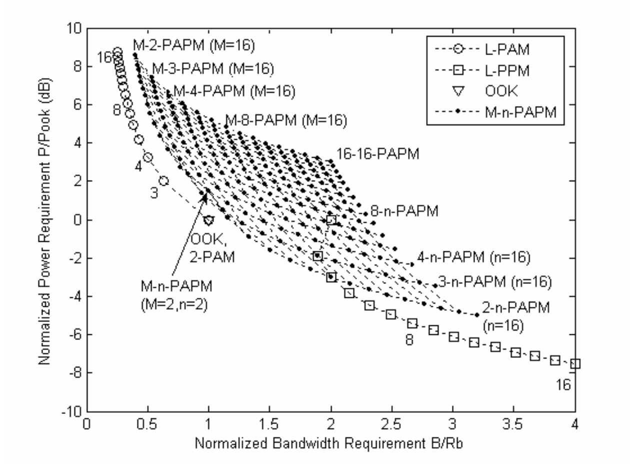

Figure 2. Normalized power requirement and bandwidth requirement for OOK, L-PAM, L-PPM and M-n-PAPM on IM/DD channel

III. TUNABLE MODULATION TECHNIQUE

A. Tunable PAPM

The tunable PAPM signal set can be written as:

$$x(t) = nAP\sum_{i=0}^{n-1} c_i\, p(t - iT/n) \qquad (14)$$

Where n is the number of slots, A is the amplitude thresholds, A=1/M, P is the average signal power, c_i is the code word of L-PPM, p(t) is the rectangular pulse of duration T/n with unity height.

The BER of the tunable PAPM scheme is bounded by its pairing L-PAM and L-PPM. The upper bound is given by (6), using the method in (8), from (10) and (11), upper and the lower bound is given by the following:

$$BER_{Tunable-PPM} \geq Q\left(\sqrt{\frac{1}{2} n \log_2 n}\, \frac{P_{L-PPM}}{\sqrt{N_0 R_b}}\right) \qquad (15)$$

$$BER_{Tunable-PAM} \leq Q\left(\sqrt{\frac{\log_2 M}{(M-1)^2}}\, \frac{P_{L-PAM}}{\sqrt{N_0 R_b}}\right) \qquad (16)$$

The condition for switching between different pulse numbers depends on the requirement of the expected power and the bandwidth efficiency. In another words, the fewer the number of pulses the lower the bandwidth requirement and the greater the number of pulses the lower the power consumption.

Switching among different modulation levels is dependent on the circumstances in which the modulation scheme is used. For power limited mobile applications, it is likely the system will switch to higher-level PPM for a reduced power requirement and thus extend the battery life. For bandwidth-limited applications in high-speed data communications, power is not the major restriction but better bandwidth efficiency and speed are preferable. In this case the lower level of the modulation scheme will be applied. The tunable PAPM scheme provides the flexibility of varying modulation levels without the considerable complexity of MPPM or OPPM.

B. Channel with variable BER

As evidenced by (4), the BER reflects the channel condition. When the BER is increasing, R_b will reduce to maintain the same power consumption *P* (battery life), and vice versa. For multi level PAM and PPM, there is the possibility of maintaining constant *P* whilst the BER changes by altering modulation levels. In any free space links, the conditions will constantly change as a result of obstacles, optical turbulence and the like. As a benchmark, can BER change from 10^{-6} to 10^{-2}, in a constant power situation. For each scheme, Table I lists the relevant performance. The first row indicates the level change needed to maintain the bit rate at the maximum for the channel. The second row shows the resulting multiplication factor from the bit rate without adaptation to that when the system adapts. It should be noted that PPM is unable to fully compensate for the poor BER, as 16-PPM was the maximum complexity considered. The resulting accuracy in the bit rate is a shown as a percentage in the third row, whilst the fourth row explicitly states the number of levels changed in the adaptation.

In Table I, the L-PAM and tunable PAPM are similar in performance, but, by plotting the cost normalized to the adaptive target, as shown in Fig. 3, it becomes apparent that tunable PAPM is more efficient. To demonstrate the benefit of the tunable modulation scheme, Fig. 4 shows the data rates obtainable for the different modulation schemes over a 250 Mbps direct LOS optical link, whilst the BER varies from 10^{-6} to 10^{-2} and the required optical power *P* is fixed.

From Fig. 4, it is clear that under severe BER conditions, tunable PAPM and L-PAM provide a better prevention from dropping the R_b than L-PPM and OOK, which suffer an extremely large penalty.

IV. Applying Fuzzy logic control

A. Fuzzy logic control

Fuzzy logic (FL) is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth, that is truth values between "completely true" and "completely false" [10]. FL incorporates a simple, rule-based IF X AND Y THEN Z approach to a solving control problem rather than attempting to model a system mathematically.

The standard definitions in fuzzy logic are:

truth (not x) = 1.0 - truth (x)
truth (x and y) = minimum (truth(x), truth(y))
truth (x or y) = maximum (truth(x), truth(y))

Traditional control systems are based on mathematical models to define a relationship that transforms the desired state and observed state of the system into inputs that will alter the future state of that system. Fuzzy machines work the same way, but the decision and the means of choosing that decision are replaced by fuzzy sets and rules. Fuzzy control, which directly uses fuzzy rules, has the purpose of influencing the operation of a system by changing inputs to that system via rules that model how the system operates [11].

B. Applying Fuzzy logic control

The System status can be modeled as membership functions in FL. The rules set in the FL system will come from the requirements of the ideal system.

While BER varies across the range, FL can be used to set up rules according to different circumstances such as applications which need prolonged battery power, while the system power consumption is the main concern. In a system where data rate is more vital than others, such as in a bank or government offices, the selection of system

TABLE I.
Comparison of adaptive accuracy between L-PAM, L-PPM and Tunable PAPM

BER ($10^{-6} \rightarrow 10^{-2}$)	L-PAM	L-PPM	Tunable PAPM
Level change	5→11	16→3	3L4→4L2
Adaptive Target (2.04)	2.05	1.45	2.06
Accuracy (%)	0.5	28.9	1
Cost (level)	6	13	3

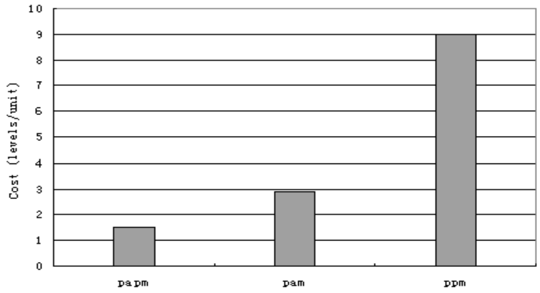

Figure 3. Cost comparison of tunable PAPM, PAM and PPM

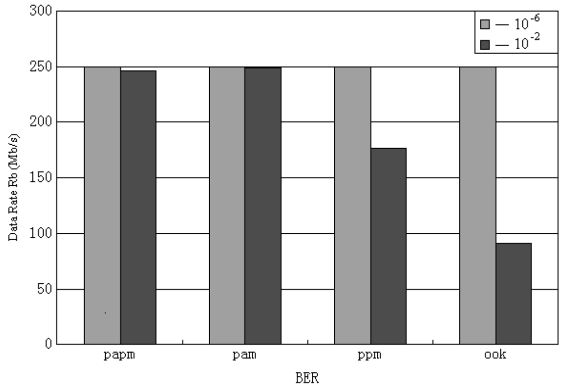

Figure 4. Comparison of R_b recovery between tunable PAPM, PAM, PPM and OOK modulation schemes under different BER conditions.

status will be weighted more towards R_b to satisfy the need for high performance data transmission.

The following section will develop a fuzzy logic control model for the tunable modulation system. The example model will stabilise the BER by establishing a set of rules properly rather than purely control parameters affecting the BER in terms of performance, such as dealing with the bandwidth or power budget. Assuming the system being discussed is possessed of a tunable modulation technique, the BER is affected by several factors, which are stated in (15) and (16). This produces a highly nonlinear characteristic.

It can be acknowledged that the BER will be affected not only by noise and transmitted signal power but also by the system modulation state. A controller in the system needs to know the current BER level and needs to be able to set the state. Therefore, the controller's input will be the BER level difference (compared to 10^{-6}, expressed in dB) and its output will be the rate, or the trend at which the M or n is changing. Since the BER level tends to oscillate around the desired level, it is also worth considering adding another input, the BER level's rate of change, to slow down the state change when the BER is close to the right level.

The rules for the fuzzy controller for this model are the following.

1. If (BER is ok) then (state is no_change)
2. If (BER is low) then (M is change_fast)
3. If (BER is high) then (n is change_fast)
4. If (BER is ok) and (rate is negative), then (M is change_slow)
5. If (BER is ok) and (rate is positive), then (n is change_slow)

These rules are shown as a fuzzy inference diagram in Fig. 5.

According to the rules set above, the system performs a self-adaptation when BER degrades more than a certain threshold. Since high BER states are usually not acceptable from the communication system design point of view, the system states will be changed based on a calculation within available candidate states. This can be dealt with by setting the low membership function to be more influential on the high value settings. The surface of *M* and *n* demanded versus the BER change rate, and the relative BER difference is shown in Fig. 6.

C. Discussion

The modulation requirement will be derived according to the fuzzy logic control output, which can be set at a value between -1 and 1. For the tunable PAPM scheme, *M* can be changed when the fuzzy controller has a positive output, and *n* changes when the output is negative. The operation could be inverted, dependent on the importance given to *M* and *n*. The system under such a control mechanism can perform a search among modulation variables, which provides an added flexibility when dealing with the changing environment. It is also feasible to manipulate other factors, which affect the whole BER but every effort is made to keep the system

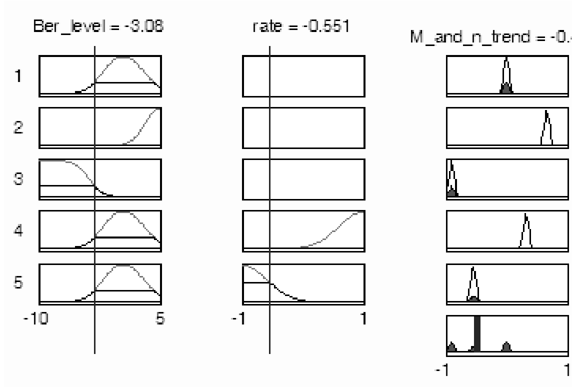

Figure 5. The rules of fuzzy controller to change the system status and stabilise the BER

performance stable. Utilizing fuzzy systems in a dynamic control environment reduces potential stability problems, and this is the benefit of applying fuzzy logic control over a modulation channel.

V. Reliable Communications

The reliability or robustness of a communication channel usually refers to the adaptation ability of the system itself under severe conditions. Researchers have been seeking techniques to combat causes of system instability with the mainstream being focused on the coding theorem [12].

As stated by Barry in 1994 [2], modulation schemes other than the basic ones are needed in the optical wireless environment. Following a comprehensive analysis by Park [13], trellis-coded multiple pulse position modulation (MPPM) stands out from the simulation results. The capacity of the intensity modulation channel remained an open problem until recent work by Hranilovic and Kschishang [14].

Apart from error correction codes, attempts have been made to find alternative techniques to realize reliability and robustness [12]. Among these, the tunable

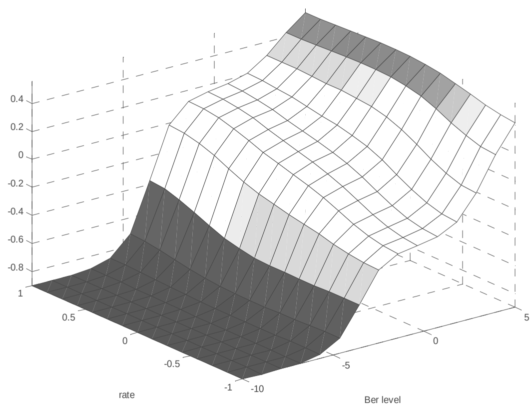

Figure 6. System state changing trend on the basis of fuzzy control rules

modulation scheme is very promising.

From a system design point of view, the desired reliability one system can provide mainly depends on the system models. As for the optical wireless model, three important issues are: the power requirement, the bandwidth requirement, and the achievable BER.

The problem with coding is that the codes designed for a specific communication link usually have a limited variation range, although adaptive coding techniques have been used in the latest communication systems [15].

There is the possibility of employing modulation techniques in conjunction with coding [16]. The system model used in this paper shows the connection to coding patterns. That is, the system model will determine the code design process to accommodate the system requirements. The detailed coding design issues are out of the scope of this paper, so we leave it to another discussion.

Fig. 7 illustrates the possible system states of a tunable M-n-PAPM modulation scheme.

As demonstrated by the figure, the system adopts different states according to the real system BER. There are two points to be clarified:

1. How fast does the system need to respond to the BER change?
2. How frequently does the system need to perform amplitude or slot number changes?

Over-actively changing in a small time scale will result in a fluctuation in data rate, and unstable transmission. This raises another important issue: the quality of service (QoS).

The QoS usually refers to control mechanisms that can provide a different priority to different users or data flows. [17] In communication systems, the BER, data rate, power requirements and bandwidth requirements form a combined priority bank instead of one main priority header in computer networks. The priorities are set according to different circumstances. The BER and data rate in most applications are more certain than other parameters.

According to Fig. 7, the system will benefit from the tuning only when the appropriate selection is present. This is not the same case with fixed mode modulation schemes, where the optimal fit is not applicable.

To summarise, starting from the system requirements, channel reliability depends on correlations between candidate modulation patterns formed by possible system states. An intentionally-designed coding scheme can improve the BER performance, but not necessarily optimize the modulation scheme itself. A properly engineered modulation scheme shows the potential system versatility to cope with uncertain constraints arising from the real channel conditions.

VI. CONCLUSIONS

We have investigated a real system model and proposed a tunable modulation technique for high speed optical wireless communication channels. The resulting tunable M-n-PAPM scheme has excellent potential to combat the BER variation without compromising

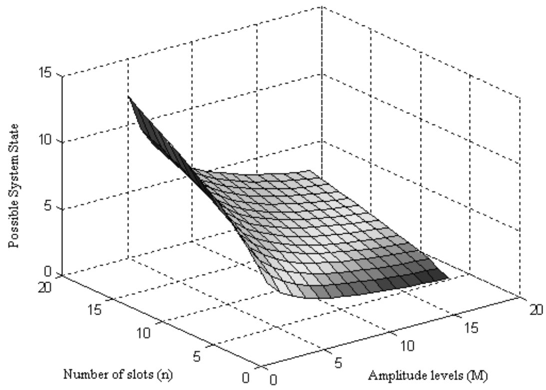

Figure 7. System states versus amplitude (M) and pulse slot number (n)

between power and bandwidth requirements. This is different from other modulation schemes in terms of its tunability. The proposed scheme can provide adaptive functionality for the real time channel at a relatively low cost. This provides the system with the freedom to adapt to changing environments, rather than using same modulation schemes for every application.

When both power and bandwidth efficiency are considered, by moving amongst the matrix of amplitude levels and pulse slot numbers, the proposed modulation scheme can ameliorate system performance degradation. In comparison with coded schemes, the proposed tunable scheme achieves a simple system structure and less calculation redundancy. This work offers the prospect of a practical adaptive modulation scheme for high-speed personal mobile communication applications.

We have applied a specially-designed fuzzy logic control system to the proposed tunable modulation scheme. The test system realized real time pattern selection to minimize the BER variation.

According to the results, the proposed tunable modulation scheme is very promising in providing a reliable optical wireless communication channel.

Nevertheless, the results presented in this paper are by no means a claim to limit the system model to 2-dimension modulation patterns; a multi-dimensional system model can be derived using the model discussed in part IV.

ACKNOWLEDGMENT

The authors would like to thank Dr. Xiaoming Jian from the Warwick Physics Department for thoughtful discussions, and also thanks the anonymous reviewers for their constructive suggestions.

REFERENCES

[1] http://www.irda.org/.
[2] J. R. Barry, *Wireless infrared communications*. Boston, Mass. ; London: Kluwer Academic, 1994.
[3] J. M. Kahn, W. J. Krause, and J. B. Carruthers, "Experimental characterization of non-directed indoor

infrared channels," *Communications, IEEE Transactions on*, vol. 43, pp. 1613-1623, 1995.
[4] S. J. Chapman, *MATLAB programming for engineers*. Pacific Grove, Calif. ; London: Brooks/Cole-Thomson Learning, 2002.
[5] M. D. Audeh, J. M. Kahn, and J. R. Barry, "Performance of pulse-position modulation on measured non-directed indoor infrared channels," *Communications, IEEE Transactions on*, vol. 44, pp. 654-659, 1996.
[6] H. Sugiyama and K. Nosu, "MPPM: a method for improving the band-utilization efficiency in optical PPM," *Lightwave Technology, Journal of*, vol. 7, pp. 465-472, 1989.
[7] D. C. M. K. Lee, J.M. Audeh, M.D. , "Trellis-coded pulse-position modulation for indoor wireless infrared communications," *Communications, IEEE Transactions on* vol. 45, pp. 1080-1087, 1997
[8] A. S. Alahmari, "Turbo Coded Pulse Position Modulation for Optical Communications," PhD Thesis, School of Electrical and Computer Engineering, Georgia Institute of Technology, 2003.
[9] H. Park, "Coded modulation and equalization for wireless infrared communications," School of Electrical and Computer Engineering, Georgia Institute of Technology, 1997, pp. 135.
[10] J. Harris, *An introduction to fuzzy logic applications*. Dordrecht ; London: Kluwer Academic, 2000.
[11] D. Driankov, H. Hellendoorn, and M. Reinfrank, *An introduction to fuzzy control*. Berlin ; New York: Springer-Verlag, 1993.
[12] F. Gfeller and W. Hirt, "A robust wireless infrared system with channel reciprocity," *Communications Magazine, IEEE*, vol. 36, pp. 100-106, 1998.
[13] P. Hyuncheol and J. R. Barry, "Trellis-coded multiple-pulse-position modulation for wireless infrared communications," *Communications, IEEE Transactions on*, vol. 52, pp. 643-651, 2004.
[14] S. Hranilovic and F. R. Kschischang, "Capacity bounds for power- and band-limited optical intensity channels corrupted by Gaussian noise," *Information Theory, IEEE Transactions on*, vol. 50, pp. 784-795, 2004.
[15] G. W. K. Marsh, J.M. , "Channel reuse strategies for indoor infrared wireless communications," *Communications, IEEE Transactions on* vol. 45, pp. 1280-1290, 1997.
[16] J. J. Grubor, V. Langer, K.-D. , "Rate-adaptive multiple sub-carrier-based transmission for broadband infrared wireless communication," *Optical Fiber Communication Conference, 2006 and the 2006 National Fiber Optic Engineers Conference, California, USA*, pp. 10, 5-10 March 2006
[17] QoS : Measurement and evaluation of telecommunications quality of service Wiley, 2001

Yu Zeng received the B.Sc degree in Applied Physics from Beijing Jiaotong University, Beijing, China, in 2001 and M.Sc degree in Advanced Photonic and Communications from University of Warwick, Coventry, UK, in 2003. He is currently working toward the Ph.D degree in electrical and electronic engineering at the University of Warwick. His research interests include adaptive modulation schemes, channel coding and channel optimization for optical wireless.

Mr. Zeng is a Student Member of the IEEE and IET.

Roger J Green received the B.Sc. degree in electronics from UMIST, Manchester, U.K., in 1973 and the Ph.D. degree in communications in 1976. He was a Research Engineer at GEC Avionics, Basildon, U.K., from 1976 to 1978 and took academic posts starting in 1978. He became the Professor of Electronic Communication Systems at Warwick in September 1999, and Head of the Division of Electrical and Electronic Engineering in August 2003, with research interests in photonics, video and imaging.

He has published over 180 papers in the field of optical communications, optoelectronics, video, and imaging, and has several patents. Some 45 Ph.D. research students have worked successfully under his supervision. He leads the Communications and Signal Processing Research Group, which is the largest in the School of Engineering at Warwick. He currently serves on two IEEE committees concerned with communications and signal processing. He is a member of the Smart Optics Faraday Partnership at Warwick, a member of the UK EPSRC grants Peer Review College, and an evaluator for proposals in the EU Framework 6 activities.

Professor Green is a Fellow of the IET, a Chartered Engineer, and a Senior Member of the IEEE.

Shaobo Sun received the B.Eng degree in telecommunication engineering from Beijing University of Posts and Telecommunications, Beijing, China, in 2004 and M.Sc degree in Advanced Photonic and communications from University of Warwick, Coventry, UK, in 2005. In 2006, he worked in the R & D centre of Ericsson in Beijing, China, as an Integration and Verification Engineer carrying out telecom hardware and software testing. He is currently working toward the Ph.D degree in electrical and electronic engineering at the University of Warwick. His research interests include optical communication systems and optical receivers.

Mark S Leeson is an Associate Professor in the Division of Electrical and Electronic Engineering, and a member of the Communications and Signal Processing Research Group. He received the degrees of B.Sc. and B.Eng. (with First Class Honors) in Electrical and Electronic Engineering from the University of Nottingham, UK, in 1986, and the Ph.D. degree in novel optical modulators in the Engineering Department from the University of Cambridge, UK, in 1990. From 1990 to 1992, he worked in the IT Division of a large United Kingdom bank carrying out communication network simulations. He then held several academic appointments prior to joining Warwick in March 2000.

His current research interests are mainly at the systems level in the communications area, particularly the analysis and simulation of both subsystems and networks. He has published over 85 journal and conference papers, and has been a member of the EPSRC peer review college since January 2003. He is currently supervising three PhD students (following seven successfully completions). Dr Leeson is a member of the UK Institute of Physics, a Chartered Physicist, a member of the IEEE and a Fellow of the Higher Education Academy.