RF Subcarrier Beamforming Scheme over IM/DD Optical Syst

Jiang Liu, Wasinee Noonpakdee, Hiroshi Takano and Shigeru Shimamoto

Abstract

An RF over optical (RFoO) relay system where an RF signal is relayed over the optical band based on intensity modulation with direct detection (IM/DD) technology is proposed to eliminate the interference caused by RF mobile terminal in RF sensitive area. The proposed RFoO relay system effectively utilizes the phase information of the RF signals transported earlier and adopts RF band beamforming technology to pre-adjust the phase shifts before modulating into the optical signal. With this kind of processing, relay station selects an optimal optical beam pattern from a pre-defined beam sets according to the appropriate information indicated by the mobile device and creates a power-increased service area for the mobile device, namely "Bright-Spots". Simulation results show that with proper design of radiation patterns, the received power can be increased and therefore significantly improves the bit error rate (BER) performance. By the dynamic beam selection, our system can provide wider optical communication coverage with practicable received optical power levels at the mobile terminal than conventional non beam formed radiation system.

Keywords: beamforming, beam codebook, RFoO, bright-spot, IM/DD

1 Introduction

The use of mobile phones and terminals is rapidly increasing. As a Radio Frequency (RF) transceiver, a mobile phone or terminal has the potential to cause disturbances to the operation of sensitive electronic equipment. A typical example is the cardiac pacemaker. To reduce the chance of such problems many hospitals require that mobile phones to be turned off [1]-[3]. These concerns are not limited to hospitals they also apply to Doctor's offices, small clinics, and ambulances. Neither are the concerns limited to medical equipment, government regulations restrict the use of cellular phones in aircraft to eliminate a possible cause of interference with communication and navigation systems [4].

There is usually a desire, and often a requirement, to maintain mobile communications in RF sensitive environments for providing last few meters' connectivity. To fulfill this, optical wireless communication (OWC) becomes one of strong candidates to replace RF communication due to its non-interactive property to electronic apparatus. As an alternative solution, in this paper, optical wireless communication is taken as a feasible complementary for RF communication in some special area, where RF interference would be a possible danger to other devices such as medical equipment in hospitals, flight control system in aircrafts.

Our proposed solution is using OWC link to relay RF signal, referred to as RF-over-Optical (RFoO). It provides a way of simplifying the architecture of relay station. Shown as Figure 1, in the proposed system an RF relay antenna is set up outside the RF sensitive environment to communicate with a remote base station. The RF antenna is connected by cable to multiple optical transceivers located inside the sensitive area. These optical transceivers communicate with mobile phone/terminals by encoding the original RF signal with intensity modulation (IM) over the optical signal. Mobile phone/terminals receive the RF subcarrier intensity modulated optical signal and extract the RF signal by using direct detection (DD). The extracted RF signal is then demodulated by the mobile terminal.

For the design of an indoor optical wireless system, it faces multiple challenges: At infrared frequencies optical signals can suffer from absorption by atmospheric molecules, resulting in limited transmission range; Optical signals do not propagate through ordinary building materials as RF does; Optical signals do not diffract around corners in usual settings. The result is that optical wireless communication systems mostly use line-of-sight (LoS) scenarios.

In the LoS wireless communication system, there is a trade-off between beam coverage and signal strength at the receiver: A signal can be transmitted in a narrow optical beam to allow higher received signal strength but at the cost of reduced coverage. Therefore, we desire to find a method to use a diffuse optical beam to provide sufficient signal strength over an adequate area. There is a way to improve

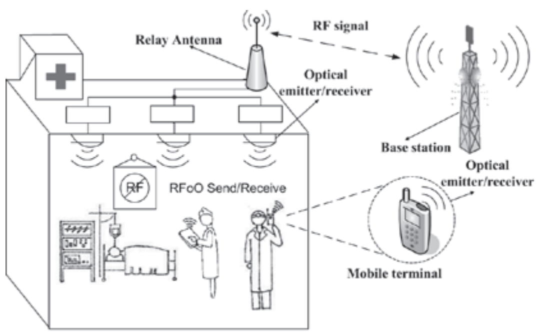

Fig. 1 Application of RFoO in an RF Sensitive Environment

the transmission range and mitigate the background light effects by using optical beamforming. Optical beamforming concentrates the electric power in a limited coverage area, and maximizes power efficiency. However, optically controlled beamforming techniques usually used for optical fiber [5]-[7], are hardly used to setup wireless optical links since it significantly suffers from dis-alignment between transmitter and receiver. Moreover, optical devices used for beamforming are very complex and costly. By reasons of these, optical beamforming is very hard to be implemented in a practical OWC system. An indoor IM/DD OWC system is studied in [8], but it did not mention the modulation method and did not evaluate the BER performance of such kind of system at all. Some systems using subcarrier modulation have been discussed in [9]-[11], but none of them utilized the phase adjustment of the subcarrier. In [12], we proposed to utilize phase adjustment of RF subcarrier in RFoO system, but we did not give numerical results. This paper present a very important extension work in [12].

Radio beamforming technology has been used for directional signal transmission or reception for many years. It can be achieved by controlling the phase of the signal at each transmitter of antenna arrays [13]-[14]. Our idea is to use the radio beamforming technology to adjust the phase of the RF subcarrier signal and ignore the phase of optical signal. It is because that optical signal has very high frequency and the optical receiver cannot distinguish the phase of the optical signal. By using Intensity Modulation / Direct Detection (IM/DD), we can only consider the envelope of the RF signal in the optical medium and can utilize the radio beamforming technology to OWC.

The main difference of our approach from the other relay systems is that we use RF beamforming technology to "pre-adjust" initial phases of the RF signal before it is uploaded onto the optical carrier. We do not have to worry about phase change of the optical orientation as we would with RF waves. With proper phase adjustment to RF subcarriers before modulating them to optical signals and sending them from multiple optical transmitters, a power-increased service area can be created for the mobile device, namely "bright-spots". In this paper, the method using phase adjustment to RF subcarriers over IM/DD optical channel is referred to as RF subcarrier beamforming.

In this study, a simple static "bright-spots" is considered. That is to say in the optical wireless indoor local network, before relay station starts to relay, beam patterns should be decided. We design a codebook to decide the phase shift patterns. Mobile Terminals is capable of selecting which beam pattern ("bright-spots") to join in. The proposed scheme is easy to implement and allows for very quick beam changes. A description of this scheme and the results of our computer simulations are presented in the following sections.

2 RFoO system model

Our proposed relay method is using non-regeneration system for indoor IM/DD OWC. By doing so, only a minimal set of front-end hardware components is needed in the receiver/transmitter functions at the relay station. The relay station is setup inside an RF sensitive environment (refer as to "service area" in the following contexts) to provide optical coverage for mobile terminals, that is, the relay station communicates with the mobile devices via optical, rather than RF, signals. The proposed relay station is comprised of three parts: 1) An RF antenna set up typically on the roof of a building outside the service area; 2) Several electro-optic converters that up-convert RF signal into optical band or down-convert optical signal into RF band; 3) Several optical transceivers installed on the ceiling of the building.

The RF signal is relayed with the following operations: The RF signal from a remote base station received by the RF antenna on the roof is passed by cable to the relay station inside the service area. Then the relayed RF signal is splited to multiple channels and the phase of the RF signal in each channel will be adjusted before modulating into optical intensity. At the mobile terminal, the original RF signal is extracted using direct detection by photo-detection elements. The extracted RF signal is passed to the mobile terminal's RF front end for demodulation. The demodulation method is the same as which is used in radio communication.

We assume each of the optical transmitters generates a diffused optical beam with coverage of the whole service area. The phase of each subcarrier is adjusted before emitted as optical signal by the light emission element. We exploit the phase pre-adjustment to provide RF subcarrier beamforming. The idea behind this design is to keep a large optical coverage, and to generate some special areas with higher signal strength, referred as "bright-spots" inside the optical media by dynamically choosing the optimal phase shift pattern of RF signal. Different set of phase shifts could generate the "brightspot" in different optical beam covering different locations of service area. The intensity of these "bright-spots" is also controlled to provide adequate room coverage with sufficient signal intensity at mobile terminal.

The beam patterns are pre-designed for each system, which is a kind of physical layer design. Besides, we need to consider a suitable Media Access Control (MAC) data communication protocol for the practical communication. Two steps achieve the signal relay process:

1) Beamforming operation:
   Mobile terminal needs to select the best beam pattern which can provide the best signal strength and the relay station needs to use the best beam pattern to relay signal. That is to say, beamformed communication link

needs to be set-up before the relay station starts to relay information signal to mobile terminal. The process that setting up a beamformed communication link is referred as to beamforming operation

2) Relay information signal
After the beamforming operation finished, the beamformed communication link is used to relay information signal.

Proposed system aims to use proper beam to relay information signal at different place. An example is shown in Figure 2, at different place, the optimal beam pattern might be different. When mobile terminal moves from one place to another place, it should choose the best beam pattern for better communication quality.

The time slot procedure of beamforming operation is shown as Figure 3. In every certain period of time, the relay station sends a series of training sequences using each pre-defined beam pattern. For example, if the system has three beam patterns A, B, and C, the relay station will send the same training sequences using beam pattern A, B and C. The mobile terminal receives the training sequences from relay station and estimates the Signal-To-Noise Ratio (SNR) of these training sequences to determine the optimal beam pattern. Many methods have been studied to estimate SNR [15]-[16]. In this paper, we want to focus on the analyses of beam generation and just assume that the SNR can be estimated at the mobile terminal side.

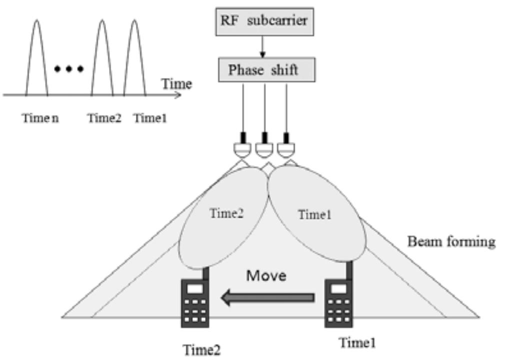

Fig. 2 Configuration of IM/DD Based Relay Scheme

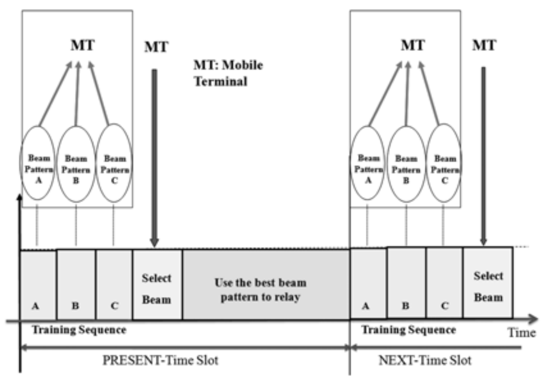

Fig. 3 Time slot procedure of beamforming operation

After estimated the SNR, the mobile terminal indicates the transmitter the index of the best pattern where the mobile terminal is in "bright-spots" coverage with the strongest receive signal. The relay station then uses the corresponding beam pattern to generate a "bright-spot" at the location of the mobile terminal.

The proposed relay system not only improves system transmission performance, but also provides a non-radio propagation environment at the last-few-meters of RF transmission.

3 IM/DD based relay scheme with RF subcarrier beamforming

Let S_{RF} denote the RF signal received by the external antenna, defined as:

$$S_{RF}(t) = A_{RF}(t)e^{j(2\pi f_{RF}(t)+\alpha_0)} \tag{1}$$

where A_{RF}, f_{RF} and α_0 are amplitude, frequency and phase of transmit signal respectively. Based on this RF signal, a transmit optical signal is generated by the optical transceiver by adding a fixed direct current (DC) part, denoted as

$$P_t(t) = P_{opt}\{1+m(S_{RF}(t)+N_{RF}(t))\}, \tag{2}$$

where P_{opt} is the average radiation power of light emission element, $N_{RF}(t)$ is an additive white Gaussian noise (AWGN) with a double-sided power spectral density, m is the modulation index. To simplify the discussion without loss of generality, we use the parameter m to adjust the ratio of information signal part to DC part. The amplitude of RF signal is normalized. The absolute value of $mS_{RF}(t)$ shall be lower than 1 ($|mS_{RF}(t)|<1$) since optical signal shall be nonnegative [17].

According to Lambertian radiation intensity pattern, the wireless optical channel for this system can be expressed as follows:

$$h(t) = \frac{n+1}{2\pi}\cos^n\theta\cos\varphi\,\mathrm{rect}(\theta/FOV)\frac{A_{bg}}{r^2}\delta(t-\tau), \tag{3}$$

where θ is the angle between the maximum direction of the transmission beam and the line connecting the transmitter and receiver. ϕ is the angle between the direction vertical to the aspect of the optical detector and the line connecting the optical transmitter and receiver. r is the distance between the optical transmitter and receiver. A_{bg} is the photosensitive area of the optical detector where the incident radiation is collected and converted to an electronic signal. n is defined as the exponential power of Lambertian. FOV is the angle of field of view. $\delta(t-\tau)$ is the delayed function, $rect(x)$ is the rectangular function defined as:

$$rect(x) = \begin{cases} 1 \ for \ |x| \le 1 \\ 0 \ for \ |x| > 1. \end{cases} \tag{4}$$

We assume there are K transmitters. If we define the transmitted optical intensity over the ith optical transmitter is $P_{ti}(t)$, the ith optical channel is $h_i(t)$, and the optical noise is N_{opti}, the spatial average of received optical intensity over photodetector surface $P_r(t)$ can then be given by

$$P_r(t) = \sum_{i=1}^{K} (P_{ti}(t) \otimes h_i(t) + N_{opti}(t)). \quad (5)$$

Here, $\otimes$ denotes convolution operation.

The noise $N_{opt}(t)$ at the optical receiver namely avalanche photo diode (APD) includes both shot noise and thermal noise, which are modeled as AWGN with a double-sided power spectral density. The expression of the noise variance is given by

$$N_{opt} = \sigma_{shot}^2 + \sigma_{th}^2, \quad (6)$$

$$\sigma_{shot}^2 = 2qrP_aB + 2qrp_{bg}\Delta\lambda_{nb}A_{bg}B, \quad (7)$$

$$\sigma_{th}^2 = \frac{4kTB}{R_L}, \quad (8)$$

where δ^2_{shot} is the variance of the shot noise. The first term of (7) is the variance of the shot noise from signal light and the second term of (7) is the variance of the shot noise from ambient light. δ^2_{th} is the variance of the thermal noise. Pa is the average received optical signal power. The other parameters are described in table 1.

From (6)-(8), it is shown that the shot noise component changes with P_a while the thermal noise is unrelated to it. Therefore, if P_a is very big, the shot noise is the main party of the optical noise; if P_a is very small, the thermal noise and the noise from ambient light are the main part of the optical noise.

In this paper, the same fixed DC component of optical current is used in all transmitters and the received signal can be expressed as:

$$\begin{aligned} Y_o(t) &= P_r(t)R \\ &= R\sum_{i=1}^{K}(P_{ti}(t)\otimes h_i(t) + N_{opti}(t)) \\ &= R\sum_{i=1}^{K}((P_{opti}\{1+m(S_{RF}(t)+N_{RF}(t))\})\otimes h_i(t) + N_{opti}(t)), \end{aligned} \quad (9)$$

where R is photo detector response factor.

Assuming the DC component can be eliminated at the output of the photodetector, the received signal without DC component is:

$$Y(t) = Rm\sum_{i=1}^{K} P_{opti}((S_{RF}(t)+N_{RF})\otimes h_i(t) + N_{opti}(t)), \quad (10)$$

where S_{RF} is the RF signal.

Figure 4 shows the down-link transmission beams with multiple optical transmitters. FOV = 90° is assumed here. We neglect the propagation phase changes of optical signal due to the big difference between RF and optical signal in the receiver elements at both the relay station and the mobile terminals. For an RF device, the antenna size is around the size of an RF wavelength (λ_{RF}) whereas for an optical device the photodetector surface (1cm^2 in this paper) is many times larger than optical wavelength (λ_{Opt}), which results that the photodetector cannot distinguish the phase shift of optical signals. The received optical signal is thus simply the sum of all signals coming from transmitters and it is nothing with optical phase information.

Based on (3), the optical channel from ith transmitter to the receiver, $h_i(t)$, can be expressed as:

$$h_i(t) = \frac{n+1}{2\pi}\cos^n\theta_i\cos\varphi_i\frac{A_{bgi}}{r_i^2}\delta(t - r_i/c), \quad (11)$$

where c is light speed, r_i is the distance between the ith optical transmitter and receiver.

From (10)-(11), the received optical signals Y(t) from K transmitters can be given as

$$\begin{aligned} Y(t) &= Rm\frac{n+1}{2\pi}\sum_{i=1}^{K}P_{opti}[\cos^n\theta_i\cos\varphi_i\frac{A_{bgi}}{r_i^2} \\ &\cdot(A_{RF}(t)e^{j[2\pi f_{RF}(t-r_i/c)+\alpha_0]} + N_{RF}(t)) + N_{opti}(t)] \\ &= Rm\frac{n+1}{2\pi}\sum_{i=1}^{K}P_{opti}[\cos^n\theta_i\cos\varphi_i\frac{A_{bgi}}{r_i^2} \\ &(A_{RF}(t)e^{j(2\pi f_{RF}t+\alpha_0-2\pi r_i/\lambda_{RF})} + N_{RF}(t)) + N_{opti}(t)], \end{aligned} \quad (12)$$

where $e^{j(-2\pi r_i/\lambda_{RF})}$ is the phase shift due to propagation from

Table 1 Parameters of shot noise and thermal noise

Symbol	Quantity	Value
A_{bg}	Detector area	1(cm^2)
$\Delta\lambda_{nb}$	Noise-bandwidth factor	30(nm)
q	Electron charge	1.6 × 10-19(C)
r	Photodetector responsively	0.7 (A/W)
p_{bg}	Background irradiance per unit bandwidth	5.8 μ W/(cm^2·nm)
k	Boltzmann's constant	1.374 × 10-23 (J/K)
T	Temperature	300(K)
R_L	Load resistance	240(Ω)
B	Desired bandwidth	56.2(MHz)
m	Modulation index	0.1

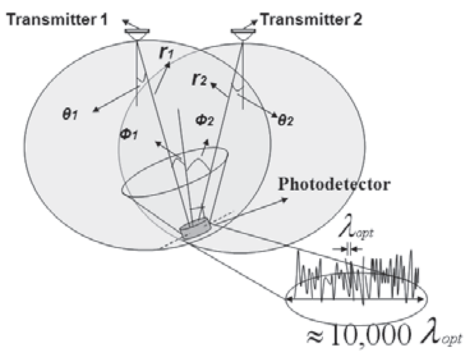

Fig. 4 Multiple optical transmitters' model

different transmission paths. In this paper, we propose to use diffused optical beam and assume $n = 1$.

In the proposed system, the phase shifts of RF signals are adjusted to generate the RF beam pattern inside the optical media, that is, the RF data sequence is multiplied by a complex weight vector $W = [w_1, ..w_i, ..w_k]$ before upconverted into optical band. When we use K optical transmitters to transmit optical signal and use W to multiply the RF subcarrier, the received signal will be:

$$Y(t) = P_{opt} Rm \frac{n+1}{2\pi} \sum_{i=1}^{K} (\cos^n \theta_i \cos\varphi_i \\ \frac{A_{bgi}}{r_i^2} (A_{RF} e^{j(2\pi f_{RF} t + \alpha_0 - 2\pi r_i/\lambda_{RF})} + N_{RF}) w_i + N_{opti}) \tag{13}$$

Here, we define

$$w_i = e^{-j\beta_i} \tag{14}$$

β_i in (13) can be adjusted to control the signal power in different places, it may generate bright-spots inside the optical beam with a highest signal strength. As an example, two optical transmitters are used and signals are pre-adjusted by two phase shifters with three different phase shifts 0, π, $\pi/2$. If four phase patterns $[0, \pi/2]$, $[0, \pi]$, $[\pi/2, 0]$, $[\pi, 0]$ are generated with $[\beta_1\ \beta_2]$ the phase shift set in the two phase shifters, we can get four different "bright spots" each in one of the 4-corners of a room. Mobile Terminals is capable of selecting the best "bright-spots" to use.

At the receiver, each mobile device shall extract its own information signal by passing the extracted RF through a band pass filter over its own sub-band. The output of the band pass filter, that is the RF signal, is fed into the input of the RF front-end of the mobile device, then down-converted into baseband and performs baseband signal processing. An important advantage of the proposed RFoO relay system is that a very little extra electric circuit is required at mobile terminals.

To reduce the overhead and simplify the beamforming operation, in this paper, the weight vector W_i (refer to (14)) will be selected from a beam codebook. The codebook can be well designed and the "bright-spots" can be controlled to increase the received signal strength in desired area. For example, in the case of two optical transmitters with four set of phase patterns as shown in table 2, we can get four different "bright spots" each in different locations. Mobile terminal is thus capable of selecting one of them to join in.

Table 2 Example codebook of two optical emitters

Beam Pattern ID	β_1	B_2
1	0	0
2	0	$\pi/2$
3	$\pi/2$	0
4	0	π

4 Simulation Results

The proposed RFoO relay system is evaluated by computer simulations in Matlab. Firstly, the received optical power is calculated when using different beam patterns; secondly, the beam directivity using our designed beam patterns is given; finally, the BER performance of our system is analyzed. In the simulations, both shot noise and thermal noise are considered, modeled as AWGN with a double-sided power spectral density. The parameters of optical noise are shown in table 1. The optical noise is added at the optical receiver, that is, Avalanche Photo Diode (APD). The level of background irradiance per unit bandwidth at the receiver is 5.8 μ W/cm^2·nm. The SNR of the radio communication at the relay station is assumed to be 12dB.

Better BER performance can be achieved by increasing received optical power. Multiple transmitters have been used to increase the received power in many papers [18]-[19]. In this paper, we also use multiple transmitters. Figure 5 shows one of the example configurations with two optical antennas as transmitters. In this figure, a is the distance of the center point of the ceiling to the wall, d is the distance of the center point to each transmitter. Plane M_H and M_V are measuring planes for the received power evaluation. Plane M_H is parallel to the ceiling in this figure with the distance of b to the ceiling. Plane M_V is vertical to the ceiling and passing though the connecting line of two transmitters. The distance between the two transmitters is $2d$.

Figure 6 shows the received optical power in plan M_H (refer to Figure 6) when a = 2 meters, b = 2 meters, m = 0.1,

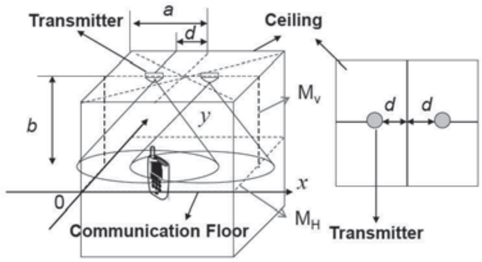

Fig. 5 Optical system model with two transmitters

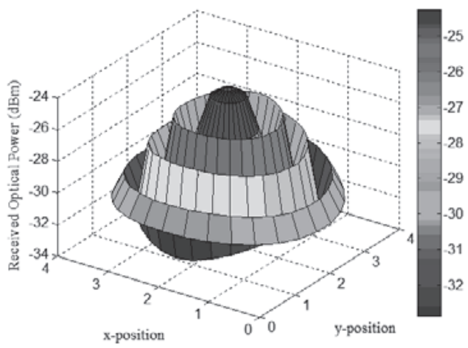

Fig. 6 Received optical power when $\beta_1 = \beta_2 = 0$

f_{RF} = 0.8G, $2d = \lambda_{RF}$ = 37.5 cm (λ_{RF} is the wave length of RF signal), and there is no phase adjustment for the two transmitters. For easy understanding, the received power shown in this figure and following figures does not include the redundant DC part.

The average radiation power of each optical transmitter P_{opt} is assumed to be 32dBm. β_1 is the RF phase shift to transmitter 1, β_2 is the RF phase shift to transmitter 2. In this case the two transmitters transmit the same signal without delay, that is to say $\beta_1 = \beta_2 = 0$. Figure 7 shows the received optical power when $\beta_1 = 0$, $\beta_2 = \pi/2$. Beside β, Figure 6 and Figure 7 use same parameters.

It is found that in Figure 6 the received power pattern has an elliptical symmetry. However in Figure 7, the power strength pattern is not symmetrical - one side is brighter than the other due to they have different value of β (phase adjustment). This demonstrates the basic concept of an important part of our scheme: the use of RFoO phase shifts to create "bright spots".

In order to understand our system more clearly, we design one example of beam patterns on plane M_V (Refer to Figure 5). Figure 8 shows four beam patterns generated at plane M_V inside the optical media. The four beam patterns with beam pattern ID from 1 to 4 are corresponding to four possible beams generated using the phases listed in Table 2, referred it as the beam codebook.

Each pattern represents the normalized effective receive power of signal over plane Mv, RF center frequency f_{RF} = 800MHz, antenna spacing $2d = \lambda_{RF} = 37.5cm$. The maximum effective receive power is 0dB (normalized by the maximum power at the center points) coordinated by the biggest circle in the figure. It is shown that the four beams cover around 60 degree under the transmitters. Whenever the mobile terminal is within this area, it may always find the best beam pattern used for transmission. The more sophisticated beam codebook, which specified more beam pattern, is adopted, the more "bright spot" can be generated for mobile terminals within the optical coverage. Therefore the receive power can be significantly improved by well-designed optical beam patterns.

Figure 10 shows the received optical power with optical antenna distribution as shown in Figure 9 for two optical antenna cases. c is the distance of the receiver to the left wall. We assume that the optical receiver is parallel to the ceilling. Phase adjustment as proposed in this paper is applied when two transmitters are installed. Here we assume $f_{RF} = 800MHz$, $2d = \lambda_{RF} = 37.5cm$, $a = 2m$, $b = 2m$. From this figure, we can see if at each place, the mobile terminal

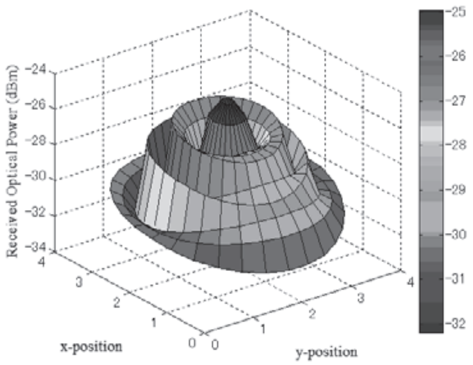

Fig. 7 Received optical power when β_1=0, β_2=π/2

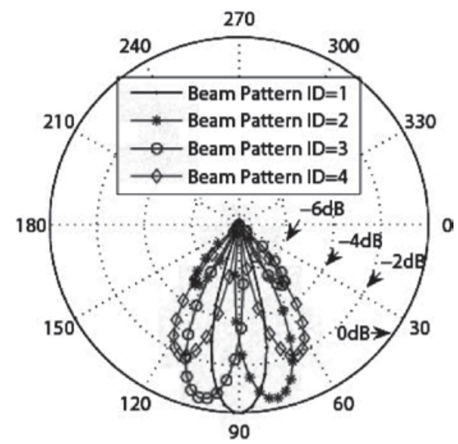

Fig. 8 Different beam patterns are created by two transmitters using different relative phase shifts.

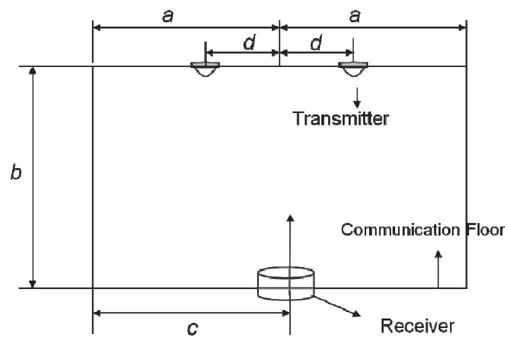

Fig. 9 Views of RF sensitive environments used for results presented in Figures 10, 11, 12. Two transmitters with beamforming (plane Mv of Figure 5)

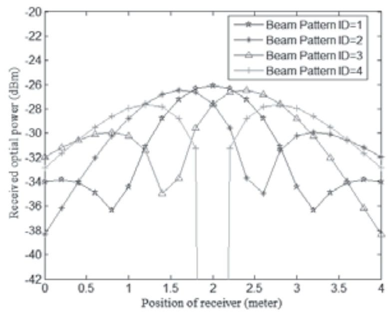

Fig. 10 Received power vs distance along the communication height of plane Mv (Figure 5) for two-transmitters with beamforming

chooses the best beam to transmit, the coverage with the acceptable received power increases. In detail, the beam 1 will be best beam when the mobile terminal is in the range of 1.75m-2.25m, according, beam 2 is the best in the range of 1.25m-1.75m and 3.75m-4m; Beam 3 is the best in the range of 0m-0.35m and 2.25m-2.75m; Beam 4 is the best in the range of 0.35m-1.25m and 2.75-3.75m.

Figure 11 shows the improved receive optical power using proposed scheme compare to non-beam formed scheme. From this figure, we can see, the maximum improved power is about 8dBm by using the proposed RF subcarrier beamforming scheme.

Figure 12 shows the BER performance when the same distribution shown as Figure 10 is used. The simulation parameters are shown as table 1 and the beam codebook is shown as table 2. From this figure, it is found that if the desired BER performance is less than 10^{-4} and if we just use pattern 1, the transmission range is just around 0.5m (from 1.75m to 2.25m). However, if we chose beam pattern in different position, the transmission range will be enlarged to 2.5 m (from 0.75m to 3.25m).

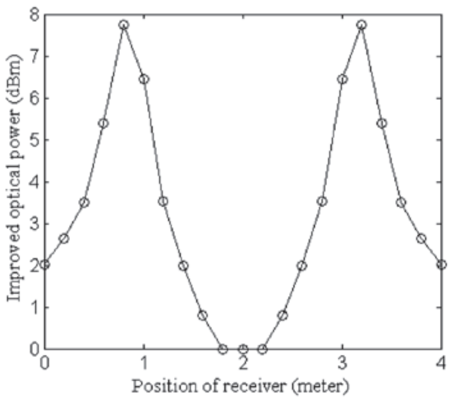

Fig. 11 Improved power vs distance along the communication height of plane Mv (Fig 10) for two-transmitters with beamforming

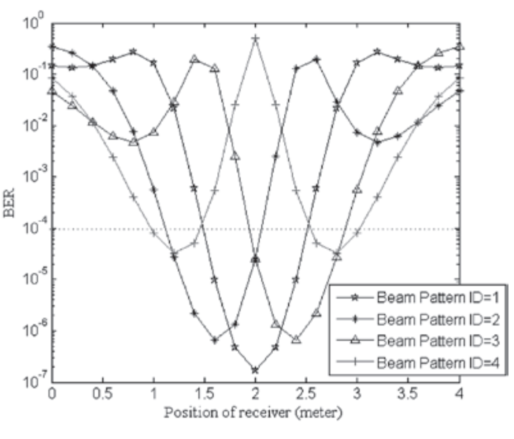

Fig. 12 Bit Error Rate (BER) vs distance along the communication height of plane Mv (Fig 11) for two-transmitters with beamforming

5 Conclusion and future works

In this paper, we propose a relay system where an RF signal is relayed over an optical band based on IM/DD technology, termed as RFoO relay system. The proposed RFoO relay system effectively exploits phase information of RF signals, adopts RF subcarrier beamforming technology to pre-adjust the phase shifts before modulating into the optical signal. The proposed relay station generates an optimal optical beam based on the appropriate phase shifts information indicated by the mobile devices and creates bright-spots in the service area. We design a codebook to decide the phase shift patterns. The proposed scheme is easy to implement and allows for very quick beam changes. Simulation results show that with proper design of radiation patterns of our system, the proposed RFoO relay system enhances the power of receive optical signal, enlarge the coverage area, and improve the system BER performance. We believe it would be a good reference for wireless communication inside an RF sensitive area. The more sophisticated beam pattern designs, the MAC layer design for multiple user case will be studies in the near future.

References

[1] Ministry of Internal Affairs and Communications (MIC), "A Survey of the influence of electromagnetic waves on electro-medical apparatus, Information and Communications Policy Bureau," Japan, 2002.

[2] Ministry of Internal Affairs and Communications (MIC), "A report on the suitability of the electromagnetic waves protection standard to mobile terminal terminals, Information and Communications Policy Bureau," Japan, 2002.

[3] Electromagnetic Compatibility Conference (EMCC), "Regulations for avoiding electromagnetic interference with electro-medical apparatus due to mobile terminal terminals," Japan, 1997.

[4] Strauss, Bill, M.Granger Morgan, Jay Apt and Daniel D. Stancil "Unsafe at any airspeed," IEEE Spectrum http://www.spectrum.ieee.org/mar06/3069

[5] T.Akiyama, K.Inagaki, T.Ohira, and M.Hikita, "Two-Dimensional Optical Signal-Processing Beamformer Using Multilayer Polymeric Optical Waveguide Arrays", IEEE Transactions on Microwave Theory and Techniques, Volume 49, Issue 10, Oct. 2001.

[6] B.Vidal, D.Madrid, J.L.Corral, V.Polo, A.Martinez and etc., "Photonic true-time delay beamformer for broadband wireless access networks at 40 GHz band", IEEE MTT-S International Microwave Symposium Digest, 2002.

[7] M.Volker, "Coherent all-fiber optical beam-steering technique for phased array antennas," Proc. Inst. Elect. Eng., pt. J, vol. 139, pp. 305-308, 1992.

[8] H.Takano, S.Shimamoto, "A proposal of optical wireless communication with RF Subcarrier", IEEE Topical Conference on Wireless Communication Technology, pp.327-328, Oct. 2003.

[9] Wei Huang, Jiro Takayanagi, Tetsuo Sakanaka, Masao Nakagawa, "Atmospheric Optical Communication System Using Subcarrier PSK modulation," IEICE TRANSACTIONS on Communications Vol.E76-B No.9 pp.1169-1177, Sep., 1993.

[10] Y.Tanaka, K.Tomioka, M.Takano, M.Nakagawa, "Wireless

CATV Uplink System with Subcarrier Modulation Using Infrared Communications for Apartment Houses", IEICE Trans. on Commun., vol. E84-B, no.12, pp.3235-3242, Dec., 2001.

Space Method", IEEE Trans. on Information Theory, vol. 48, Issue 2, (Feb. 2002).

[11] Y.Roy and J.M.Kahn, "Upper Bounding the Capacity of Optical IM/DD Channels with Multiple-Subcarrier Modulation and Fixed Bias Using Trigonometric Moment.

[12] Jiang Liu Noonpakdee, W.Takano, H.Shimamoto, S. "A cross layer design for optical relay system employing RF subcarrier beamforming," in Proc. of 2010 IEEE International Conference on Wireless Information Technology and Systems (ICWITS), pp.1-4, Aug.-Sept. 2010.

[13] A Agarwal, Yoo Yang Mo, F.K.Schneider, Gao Changqing; Koh Liang Mong; Kim Yongmin; "New Demodulation Method for Efficient Phase-Rotation-Based Beamforming" IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, pp. 1656-1668, Aug., 2007.

[14] E.Yadin and A.Strupinsky, "Adaptive beamforming on imperfect phase synchronizing source echoes [radar applications]", Radar 92. International Conference, pp. 454-457, 2002.

[15] Barry T.Bosworth, W.Robert Bernecky, James D.Nickila, Berhane Adal, and G.Clifford Carter, "Estimating Signal-to-Noise Ratio (SNR)", IEEE Journal of Oceanic Engineering, pp. 414-418, 2009.

[16] N.J.Bershad, and A.J.Rockmore, "On estimating signal-to-noise ratio using the sample correlation coefficient", pp. 112-113, Jan., 2003.

[17] J.R.Barry, "Wireless infrared communications," Kluwer, Boston, (1994).

[18] A.Sivabalan and J.John, "Improved power distribution in diffuse Indoor Optical Wireless systems employing multiple transmitter configurations", Optical and Quantum Electronics, pp.711–725, 2006.

[19] Y.Alqudah, and M.Kavehrad, "Optical Wireless Multi-Spot Diffusing; a MIMO Configuration", IEEE International Conference on Communications, 2004.