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Bidirectional gigabit ethernet optical wireless communications system for home access networks

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Abstract: The design, simulation and practical implementation for a bidirectional 1.25 Gbit/s indoor optical wireless communications system has been presented. It is a part of the European community funded hOME Gigabit Access project (OMEGA). The line-of-sight (LOS) system uses angle-diversity transceivers enabling discrete beam steering. Each transceiver uses three transmitting and receiving elements giving an overall field of view of $\sim 25 \times 8^\circ$ and a transmission range of 3 m. Measurement shows that the system can operate at a bit error rate below 10^{-9} without channel coding and the handover between cells is <400 ns. Detail of a demonstrator of high-definition (HD) video embedded in gigabit ethernet stream using this system is also reported.

1 Introduction

The demand for very high speed home data networks is driven by the desire to fully utilise the very high speed broadband that will connect most homes in the future. Such a home access network (HAN) should be capable of delivering multiple data services at rates up to gigabits per second. The aim of the OMEGA project [1] is to realise a HAN system utilising various high-speed data transmission techniques including radio-frequency (RF) [2], power line (PLC) [3, 4], visible light (VLC) [5, 6] and infra-red communications (IRC). In the OMEGA HAN, different communication technologies are interconnected and seamlessly controlled by an intelligent media access control (MAC) layer which will select one of these technologies according to the currently offered performance [7].

Fig. 1 shows a typical configuration of the proposed OMEGA network. PLC forms the backbone network in the HAN whereas the radio and optical wireless (OW) links provide wireless connectivity for the home users. Incoming data from external data service provider is distributed to different locations of the house via PLC network and then delivered to the static and mobile users via a number of wireless RF or OW hotspots. Table 1 summarises the communications technologies in the OMEGA HAN and their specifications [1].

Optical wireless communications in the OMEGA HAN consists of broadcast visible light communications and gigabit per second duplex IRCs. These technologies are selected for communications depending on the channel state, the type of service and the data rate required. In this paper we present the IRCs system. High speed line-of-sight (LOS) optical wireless links with narrow fields of view (FOV) are relatively straightforward to implement, and free space optical (FSO) links operating over several hundreds of meters at gigabit rates are available for building-to-building communications. In indoor optical wireless communications achieving wide area coverage and high data rate is challenging because of the constraints on transmit power and limited receiver sensitivity. In addition, the availability of commercial optoelectronic components optimised for gigabit optical wireless is very limited as most of products are dedicated for optical fibre communications.

At low data rates good coverage can be achieved using wide FOV transceivers with only one single transmitting and receiving element. In [8], Wisely has reported such a system running at 155 Mbit/s with the coverage of 40° (full angle) for a range of 2 m. However, high data rates demand for narrow FOV communication links, which makes it much more challenging to provide coverage [9, 10]. This requirement is because of the decreased receiver sensitivity, which drops with increasing the data rate, and the small photodetector areas that are achievable for high-bandwidth receivers.

In [11], links operating at 4×12.5 Gbit/s are presented, showing that very high rates can be achieved. The links shown in [11] have transmitter FOV that give coverage of $\sim$0.8 m at $\sim$2.4 m. However, since the coverage is only provided if the light enters the receiver on-axis, it is required to align the receiver very carefully. (The authors mentioned that the link performance is very sensitive to receiver tilting which reveals immediately that a receiver with a very narrow FOV is used.) This is a consequence of the constant radiance constraint, which limits the product of

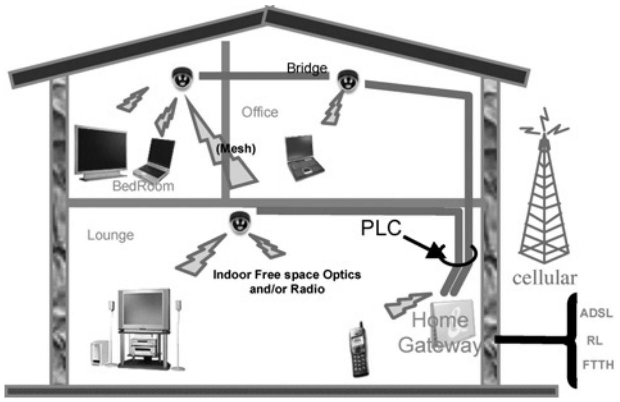


Fig. 1 *Schematic of OMEGA HAN configuration*

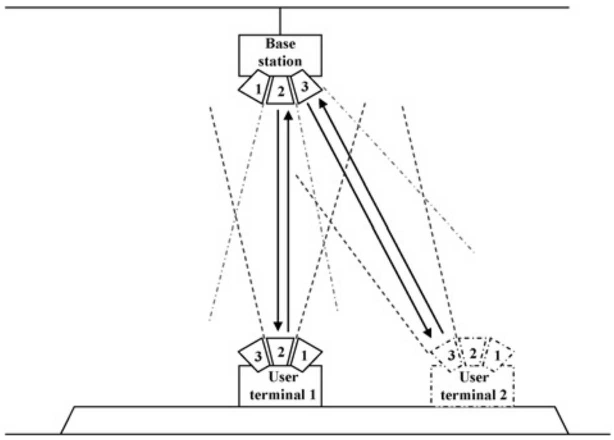


Fig. 2 *Angle diversity system with one-dimensional discrete beam steering*

collection area and receiver FOV. In order to receive sufficient power for high data rate communications, the collection area needs to be increased, but at the cost of a narrow receiver FOV.

The challenge is to enable a large system FOV, even though the actual communication link is based on a narrow FOV receiving and (possibly) transmitting element. Possible solutions are either micro-mechanical tracking configuration, or multi-element designs which base on switched beam concepts, or combinations of both. Beam switching can be implemented both by imaging [12] and angle diversity [13] approaches. The system described here is based on angle diversity transceivers, which use multiple narrow FOV receiving and transmitting elements pointing in different directions (Fig. 2). Each narrow FOV-element covers a different, small fraction of the total solid angle associated with the system FOV. Since LOS transmission is assumed where the light impinges only from one single direction, in the simplest case only one single transmitting and only one single receiving element needs to be activated to establish a link. This link takes advantage of the large directional gains of the narrow FOV-elements [10]. Additionally, the multipath dispersion is dramatically reduced, since non-direct transmission paths barely contribute to the received signal. The 'selection combining' technique described here can easily be implemented and is chosen for the demonstrator, although it will work sub-optimally since the individual narrow FOV (transmitting or receiving) beams overlap to a small extent. This partially overlapping is required to avoid gaps between the corresponding spots in the transceiver planes.

Our aim in this work was to show a complete system demonstration, including continuous coverage with handover between different transceiver elements, and bidirectional operation with real data traffic. In [9] and [14] we reported first results from a 1.25 Gbit/s angle diversity system, and some of the lessons learned in its construction.

Table 1 Summary of communications technology in OMEGA HAN [1]

Technology	Target data rate	Communications type
60-GHz LOS RF	1 Gbit/s	duplex
PLC	100 Mbit/s	duplex
IRC	1 Gbit/s	duplex
VLC	100 Mbit/s	broadcast

Here we report detailed design and aspects of the system. Although much faster link rates have been reported for configurations that require alignment we believe this to be the fastest system demonstration of a switched beam concept.

A typical switched beam angle diversity system which allows one-dimensional tracking (i.e. only on the x- or on the y-coordinate) is shown in Fig. 2. The system consists of a base station (BS) and a number of user mobile terminals (UT) which move within the BS coverage area. Each BS or UT has a number of transceiver elements (three in this figure) that are oriented in different directions and that can be switched on and off individually. Adjacent cells can be partially overlapped to avoid gaps between the spots in the BS- or UT-plane.

Both BS and UT have the same physical layer that is designed to transmit and receive data from and to the media access control (MAC) layer at each end of the link. Each transceiver element consists of an IR module, where the IR-transmitter as the same 'per element' FOV as the IR-receiver. Duplex communications is therefore possible. Communication via a single transceiver element is feasible when the BS and UT can 'see' each other within their element FOV. In Fig. 2 the coverage of the BS is depicted where by both on-axis and edge (off-axis) communications are illustrated.

In our design the transmitters in the BS are all switched on and transmit the same data in order to provide broadcast coverage for multiple users. At the UT end, only one receiving element is activated to establish a data link. In the uplink, only one UT transmitting element and only on BS receiving element is activated to build a link. The mechanism for element selection will be described in the later section.

Support for multiple terminals is being implemented in a MAC layer which is being developed by another OMEGA partner [7] and is not the emphasis of this work. In this paper we focus on system concept, design and fabrication of the physical layer.

The paper consists of five main sections. After the introduction in Section 1, we introduce the design concept and constraints of the system in Section 2. Section 3 presents the design and the fabrication of the transmitter and receiver subsystems. Implementation of element selection nd handover system will be discussed in Section 4. The system demonstration and the overall system performance evaluation are given in Section 5.

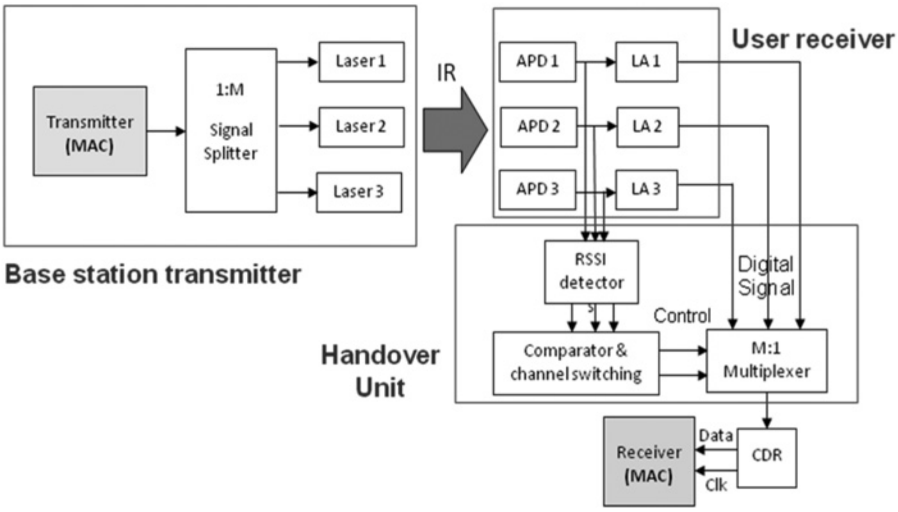


Fig. 3 *Functional block diagram of a BS/UT unit, which includes three transmitters and three receivers*

2 System description

2.1 System overview

Fig. 3 shows the functional block diagram of the physical layer (PHY). Data from the MAC layer input to the PHY is divided by a power splitter whose outputs modulate the IR beams emitted from the transmitter lasers. The receiving subsystem consists of three receiver elements, whose outputs are continuously monitored by the 'received signal strength indicator' (RSSI) signals. These RSSI signals are used to choose one 'good enough' receiving and (with it) transmitting element. 'Good enough' means that the corresponding RSSI signal needs to be greater than a pre-defined threshold [at which the received bit error rate (BER) is $\leq 10^{-9}$]. According to the element selection, the demultiplexer will route that received signal to the clock and data recovery (CDR) module. The detected (binary) data is then forwarded to the MAC, together with the recovered clock. If two RSSI signals exceed the threshold, which may happen in regions with spot overlapping, our sequential RSSI signal polling will choose the first one. The element selection remains unchanged until the next data packet arrives.

2.2 Design constraints

2.2.1 Eye safety: Optical wireless system emitters must be class 1 eye-safe for indoor use (as defined by IEC60825-1) [15]. The limitation on the permitted radiant intensity according to the wavelength of the source and its apparent diameter D is calculated and shown in Fig. 4.

It can be seen that in the near-IR range (800–1400 nm) the radiant intensity can be increased when the source diameter is increased. At wavelength greater than 1400 nm this is not the case. A system using a shorter wavelength with a sufficient source diameter can therefore provide greater radiant intensity headroom.

2.2.2 Wavelength choice: Fig. 4 shows the dependence of the permitted emitted radiant intensity against the wavelength of the laser source. Additionally, the effect of photodetector responsivity and capacitance are important and should be taken account in the choice of wavelength. Receiver sensitivity inversely depends on capacitance and the large capacitance decreases the data transmission rate. Additionally, the photodiode responsivity variation against

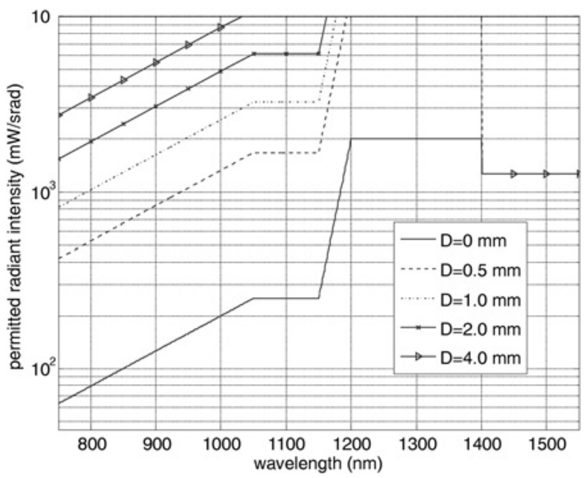


Fig. 4 *Variation in permitted source radiance for class 1 source with wavelength and source size*

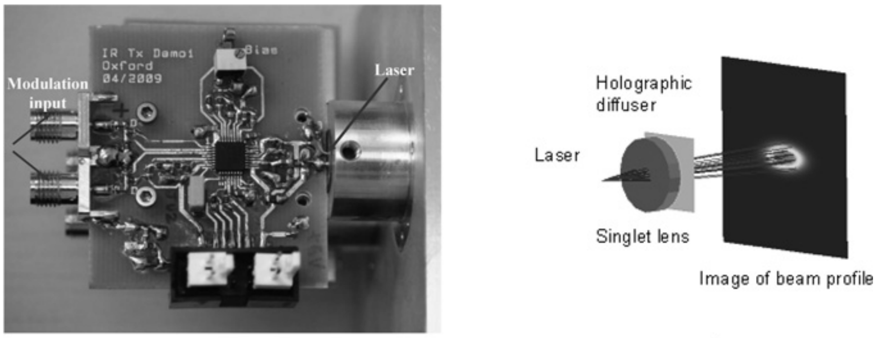
the wavelength will also affect the system performance. Silicon detectors are generally used for applications with wavelength shorter than 1000 nm, and beyond this range InGaAs detectors are usually used. Despite the higher responsivity of these devices, the much higher capacitance (typically a factor of at least five times that of an equivalent silicon device) offsets this gain and makes the link budget for InGaAs detector-based systems substantially worse than the near-IR regime [10].

As can be seen in Fig. 4 systems can use higher transmit power if the source diameter is diffused, which will be further described in the next section. Together with the commercial availability and cost of sources system operation in the near-IR spectrum range is preferred for the demonstration, and a wavelength at 825 nm was chosen for the demonstration reported here. In addition the operating wavelength is outside the operation range of most home appliance remote controllers (870, 930 and 950 nm [16]).

3 System implementation

3.1 Transmitter design

The transmitter is composed of a laser driver, laser and optics system. Fig. 5*a* shows the prototype of the laser driver board.



a b

Fig. 5 *Transmitter design*

a Transmitter laser driver
b Optics subsystem

A commercial (Maxim max3869) laser driver is used to provide up to 70 mA DC bias and 80 mA peak-to-peak modulation currents. The achieved maximum average optical power of the communication signal is 25 mW [i.e. 50 mW peak-to-peak non-return-to-zero (NRZ) signal].

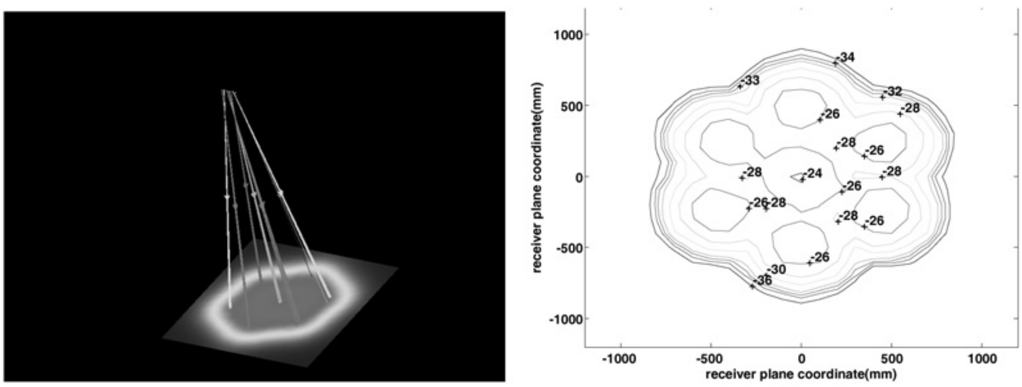
The emitted laser beam is in elliptical shape and a holographic diffuser is used to achieve a round beam footprint on the receiving surface and to meet the eye safe limit. The laser beam is first collimated by a singlet lens and then illuminates a holographic diffuser (Luminit LSD-10°). This creates the desired 10° FOV transmitter beam. The elliptical pattern formed by the beam illuminating the diffuser becomes the new apparent source, thus allowing the source to be eye-safe. This was independently verified to ensure this was the case. Fig. 5*b* illustrates a ray-tracing simulation of the transmitter beam pattern, implemented using a commercial ray-tracing package Zemax.

3.2 Receiver design

Simulation to determine the link margin of seven-element transceiver-based IR links is carried out using Zemax ray-tracing. The available transmitted power of 25 mW and FOV (full angle) of 10° per element is used. Whereas three-element transceivers (as fabricated for demonstration purpose) enable only a one-dimensional tracking capability, seven-element transceivers would provide full coverage. The beam can be steered on both the *x*- as well as on the *y*-coordinate. Fig. 6*a* shows the received power footprint at a vertical distance of 2 m from the seven-cell transmitter. The received power distribution is illustrated in Fig. 6*b*, where the power variation between the middle and edge points is ~4–6 dB. The received power in the on-axis is −24 dBm whereas a 3–4 dB drop (i.e. received power of −27 or −28 dBm) is observed at the overlapping area of two cells. The strong received power will ensure a large link margin in a range 7–11 dB depending on the position of the receiver at the centre or at the edge of the optical cell (Table 2).

The receiver consists of two main elements: an optical concentration system and received-optical sub-assembly (ROSA). The lens system is designed to concentrate the incoming beam onto the collection area of an avalanche photo detector (APD). Fig. 7*a* depicts one optical receiving element. Two plano-convex lenses are used to achieve a 10° per element FOV, which matches that of the transmitter beam profile. In addition a 10 nm optical bandwidth inference filter is used to reduce the ambient light received by the system. The measured FOV profile of the receiver is plotted in Fig. 7*b*. This shows the normalised received powers against the angles of the receiver FOV. It can be seen here there is a sharp cut off outside the 10° FOV (Table 3).

The optoelectronics part of the receiver elements includes a commercial APD having the collection area of 0.19 mm^2 (diameter of 0.5 mm) and an integrated transimpedance amplifier (AD500-1.3G-TO5). The overall optoelectronic bandwidth is ~850 MHz at a measured sensitivity of



a b

Fig. 6 *Receiver design*

a Footprint of received power created by seven transmitting elements
b Corresponding power distribution

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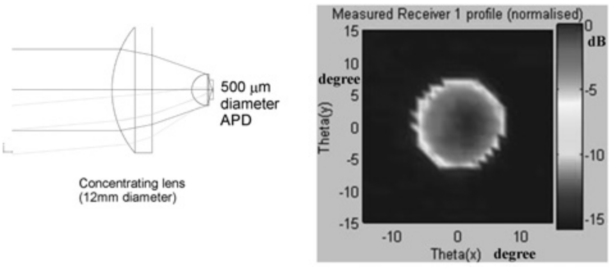
Table 2 Link budget for a 2-m link (vertical distance) assuming seven-element transceivers

	Cell centre	Cell edge (5° half angle)
transmitted average communications power	+14 dBm (25 mW)	+14 dBm
estimated available power	−24 dBm	−28 dBm
available APD received sensitivity (measured)	−35 dBm	−35 dBm
estimated margin	11 dB	7 dB



a b

Fig. 7 *Receiver design*

a Receiver optics ray-tracing design
b Received power against angle of incidence (normalised to maximum value). This plot shows the receiver field of view

Table 3 Measured performance

Parameters	Value
NRZ data rate	1 Gbit/s
line code	8B10B
line rate	1.25 Gbit/s
FOV (full angle) per element	8°
system FOV (full angle)	25°
number of elements	3
range for coverage measurements	3 m
transmitted power (each element)	25 mW
on-axis optics gain	300
cell lens aperture area	1 cm^2
target BER	10^{-9}

−35 dBm at the BER below 10^{-9}. This is measured for NRZ data at a rate of 1.25 Gbit/s.

4 Element selection and fast handover

The receiver of the demonstrator BS or of the UT composes of three receiving elements, each of which points towards a different angle. In each receiver subsystem Rx1, Rx2 and Rx3, the transimpedance amplifier output signal is sent to a post-amplifier, which limits the output signal, creating the PECL logic standard. Each post-amplifier also outputs the RSSI signal which will be used for the element selection as described in Section 2.1.

Fig. 8 depicts the element selection circuit. It includes an analogue comparator (AD8564) followed by a priority 8-to-3 encoder (74LS148). The comparator is used to compare each RSSI-signal with a threshold. For each input signal whose RSSI exceeds the threshold a BER of at least 10^{-9} is ensured. This corresponds to the elements work ‘good enough’ status. The priority encoder checks the comparator outputs sequentially. If it detects a RSSI-signal which exceeds the threshold, the corresponding data signal is mapped through the multiplexer, independently if there are further elements which may work, too. In operation the AD8564 sets the logic level of *D*-output to low if the signal power is sufficiently high. Here the reference level is set (at the point where the system BER is $=\leq 10^{-9}$). The eight logic levels at the outputs of the comparator are mapped to a 3-bit codeword by an encoder and it is used to select the ‘working’ cell. In 74LS148 the first ‘low’ bit detected from eight inputs will immediately enable the coder to output the 3-bit codeword corresponding to the input index of the detected ‘low’ bit regardless of the states of the remaining subsequent inputs.

This implemented ‘select good enough’ mechanism is inferior compared with maximal ratio combining or even to select the best combining. Since no adaptive modulation is used and a BER of 10^{-9} is always assured, select the best

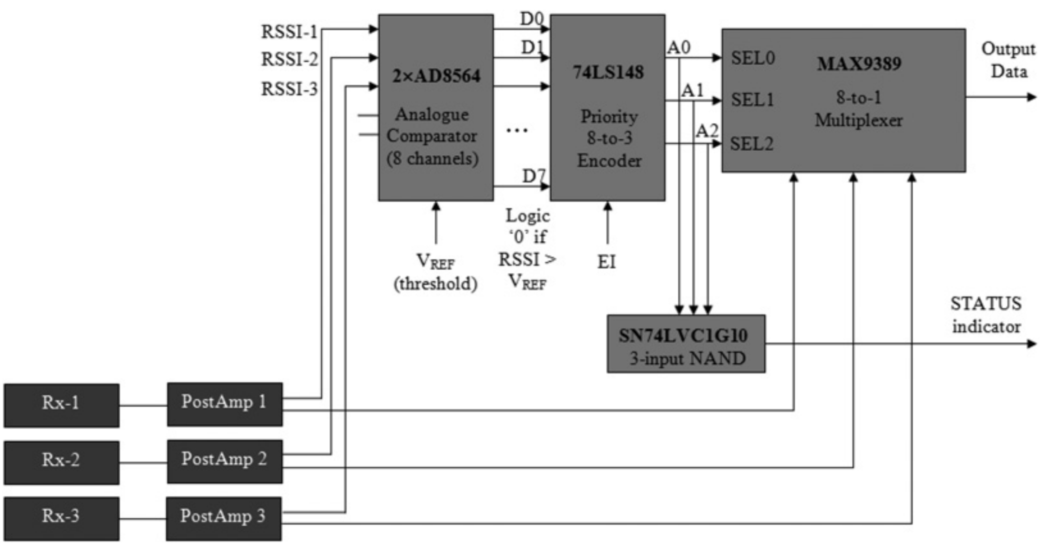
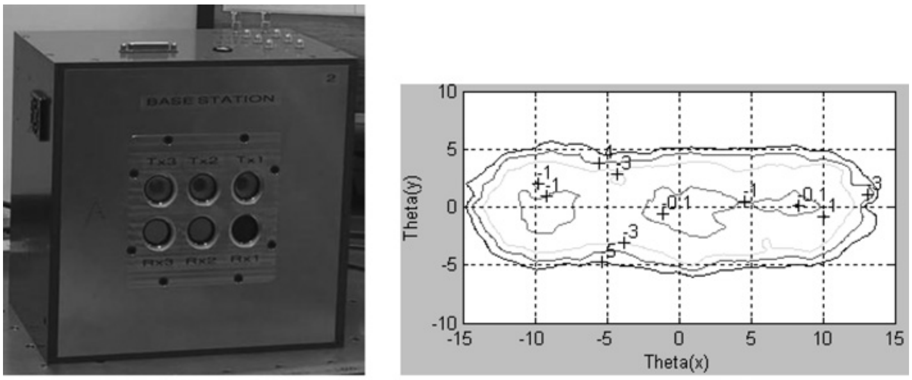


Fig. 8 *Circuit diagram for ‘good enough’ element selection*



a

b

Fig. 9 *Transmitters and receivers*

a Layouts of three element transmitters and receivers at the BS/UT
b Measured received power distribution at the range 3 m (normalised)

combining in this case would not provide a significant advantage. As only a simple priority encoder integrated circuit is needed to implement the 'select good enough' strategy, it is good and sufficient for this demonstration. In the case where two cells (or more) have their reading RSSI values greater than the threshold (which might happen at the overlapped region of two cells or more), the one with the lower given index number (e.g. Rx1 has lower given index number than Rx2) will be selected.

Only one received signal will be selected from the input signals of the multiplexer (Max9389). The binary output signal of the multiplexer is then retimed and regenerated by the CDR module. This 'clean' data signal is forwarded to the MAC layer in together with the extracted clock signal.

Fast handover between the elements could be achieved with the proposed circuit. The overall response of the circuit was measured and a duration of less than 400 ns is required for signal handover between two arbitrary elements. In the demonstrator system, a training sequence (with its length greater than 400 ns) is added to each data packet at the MAC layer. Within the duration of the training sequence, element selection and clock recovery is ensured, which enables the detection of a unique 'start frame delimiter' bit pattern prior to the PHY and MAC header.

5 Experiment and results

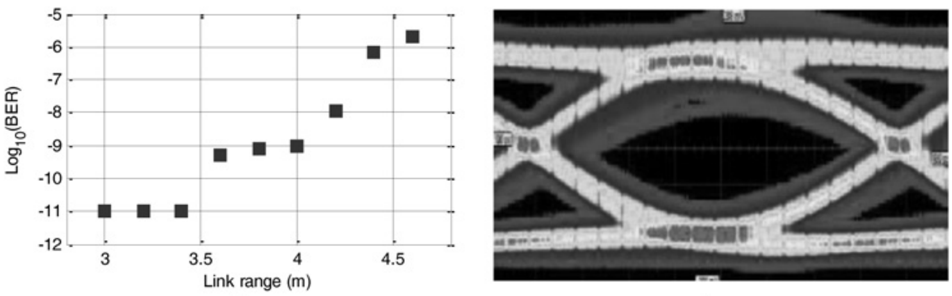
An optical wireless angle diversity system having one BS and one mobile UT is set up. The link configuration is depicted in Figs. 2 and 3 and the data source from MAC layer is a NRZ PRBS 2^{15}-1 stream.

The three transceiver elements of BS/UT were laid out in one-dimension, as shown in Fig. 9*a*. That covers an area of 1.3 m $\times$ 0.45 m at a distance of 3 m, equivalent to a BS FOV of 25° $\times$ 8°. A contour map of the measured received power distribution illustrates the half-power (-3 dB) region against the system FOV, which is shown in Fig. 9*b*.

Fig. 10*a* shows the BER performance against the on-axis link range. The link operates well at the target 3 m range with no error detected. On-axis, the error free link (considered at the BER level below 10^{-9}) can be extended up to 4 m. A difference of 3 dB in received power is measured when the link operates at 3 and 4 m, indicating the practical link margin of approximately 3 dB for a range of 3 m. Referring to Fig. 9*b* where the contour of the received power distribution is plotted, the -3 dB contour boundary indicates the edge of reliable link operation for off-axis angles which matches with the design. The received signal eye diagram is displayed in Fig. 10*b* showing a good eye opening for the on-axis received signal at 1.25 Gbit/s.

Fig. 11*a* shows the BER against power collected by the receiver. This shows a collected power (through the lens aperture, 1 cm^2) of approximately -23.5 dBm is required for a BER of 10^{-9}. Fig. 11*b* shows the equipment power density to achieve different levels of BER. The difference between these figures and the sensitivity of the bare APD receiver is because of the system optical gain (lens) and losses (lens and insertion loss in electrical domain).

The received power per element is measured, which shows that a total power collected through the lens aperture (1 cm^2) is -23.5 dBm, see Fig. 11*a*. The equivalent receiver power



a

b

Fig. 10 *BER performance*

a System BER against link range
b Eye diagram of the 1.25 Gbit/s received signal at 3 m

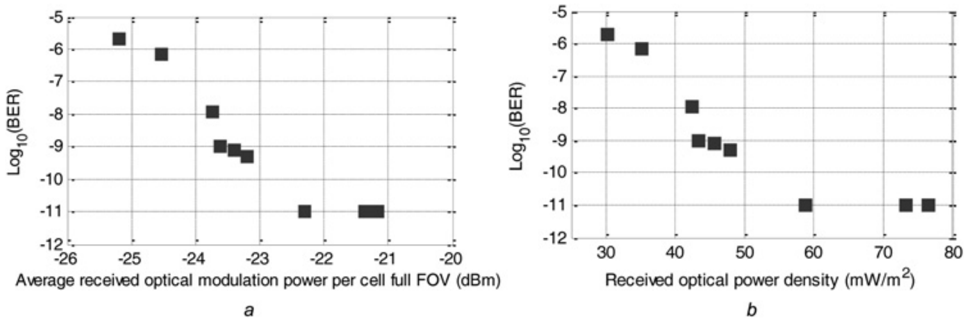


Fig. 11 *Link BER performance (at 1.25 Gbit/s, PRBS: $2^{15}-1$) against*

a Total minimum received power required per cell
b Received power density within BS coverage

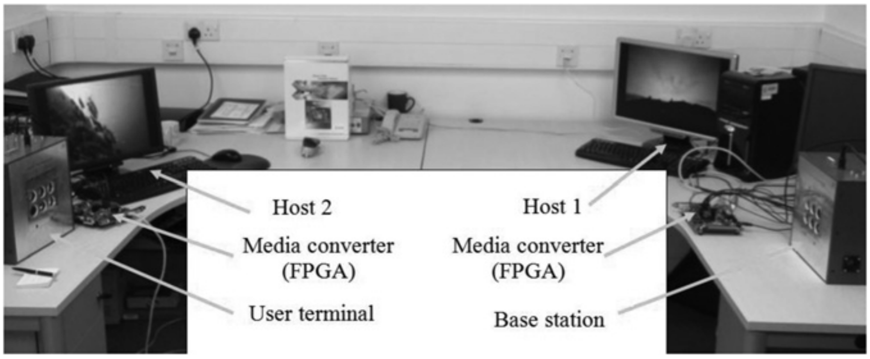


Fig. 12 *Setup for video streaming over the link, at 3.4 m*

density on the receiving plane at the link distance of 3 m is depicted in Fig. 11*b*. Note that in both plots the BER counter records any BER whose level is below 10^{-11} at the level.

Bi-directional data transmission using user data protocol (UDP) was also demonstrated. The transmission setup using the optical wireless BS and one UT is shown in Fig. 12. BS and UT are connected to two FPGA boards acting as the media converters. These convert 1000BASE-TX Ethernet data streams received from the host computers into 1000BASE-SX NRZ streams to transmit over the link (and vice versa). Wireshark software was used to generate and receive the data as well as monitor the Ethernet packet traffic across the link. For a loop back test, error free operation was obtained. We also successfully demonstrate high-definition video streaming over these links in both directions.

6 Conclusion

We have reported the design and implementation for an IR angle diversity communications systems operating at 1.25 Gbit/s for HAN, the fastest system demonstration of its type to the best of our knowledge. Error-free link operation under various tests and data transfer conditions were achieved, showing Gbit/s operation with reasonable coverage is feasible. The challenge for higher data rate systems is to combine coverage and capacity. Custom components and integration approaches such as imaging diversity offer one possibility to combine these competing requirements, as do tracking-based systems. In both cases further research and development are required.

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