COL 10(Suppl.), S22502(2012) CHINESE OPTICS LETTERS December 30, 2012

Research on infrared optical wireless network for automotive application

Xiaoqing Song (宋小庆)[1*], Roger. J. Green[2], Zhiguo Wong (王治国)[1], Kewei Chen (陈克伟)[1], and Yunzhao Zhu (朱昀炤)[1]

[1]*Department of control engineering, Academy of Armored Force Engineering, Beijing 100072, China*
[2]*School of Engineering, Warwick University, CV47AL, UK*
[*]*Corresponding author: swxq@vip.sina.com*

Received May 24, 2012; accepted June 25, 2012; posted online December 28, 2012

Wired local network is used widely in a vehicle. It brings the benefits of sharing information and controlling automatically as well as causes negative reaction and a troublesome problem to vehicle such as weight, cost, electromagnetism and space and so on. Infrared optical wireless communications are an alternative way to break through these limitations for increasing safety, decreasing fuel consumption and high bandwidth. In this letter, we address the issue of design a wireless network in a vehicle with an infrared link and ring topology. We discuss the performance requirement of the network, and analyz its bandwidth, power, link distance choice and message schedule. At last, we simulate the preferred parameters of an optical link system.

OCIS codes: 250.0250, 200.0200, 130.0130, 350.0350.
doi: 10.3788/COL201210.S22502.

Since the 1970 s, electronic system has been being replaced the pure mechanical or hydraulic gradually. Various data are produced and applied in vehicle in order to communicate information efficiently. For example, in the middle of 1980, Robert Bosch GmbH developed controller area network (CAN) which was the first integrated in Mercedes production cars in the early 1990 s[1]. Currently, vehicle is tending to become smaller and smarter as fuel prices increase, the space available in vehicle for installing communicate in line is becoming smaller. Furthermore, the electronic devices in vehicle are increasing. It is estimated that more than 80% of all innovations within vehicle are derived from electronic systems. That means more and more information should be transmitted in vehicle. In today's luxury cars, up to 2500 signals (i.e., elementary information such as the speed of the vehicle) are exchanged by up to 70 electronic control units (ECUs)[2]. Today distributed vehicle control systems are running on communication architectures consisting of different types of communication buses providing different functionality, from advanced control to entertainment. So hybrid-network with different Date-Bus (such as local intercon nect network (LIN), CAN, FlexRay and so on) are applied widely in vehicle[3]. Now, the problem is that so many different wired networks in-vehicles are causing difficulty harness not only the different networks software but also hardware. Eventually, the wiring harness became the single most expensive and complicated component in vehicle electrical systems. At the same time, it also increases the electromagnetism and the fuel cost of the vehicle[4].

As an emergency technology, wireless optical communication technologies are beginning to be useful in areas of automotive in which its particular advantages include versatility, ability to operate in confined spaces, immunity to electromagnetic interference, and low power[5−9]. Recently, a diffuse wireless optical intra-cabin network has been reported by Ke *et al.*[10] and infrared wireless communication is used in indoor.

We propose an in-vehicle network plan designed in a hybrid topology with infrared optical wireless channel. The hybrid topology includes ring topology and star topology. In this letter, we only discuss the channel characteristic and simulate the performance of infrared wireless communication systems in ring topology. We calculate the preferred bandwidth based on the numbers of the nodes, the power requirements according to the data speed and error ratio.

As a modern vehicle, its functionality is not limited to the end-user functions, but also includes function to support for production and service. So not only high motility, flexibility, safety comfort are expected, but also connectivity, entertainment and survivability are attracting the people's attention. Some literatures classify the vehicle function into five domains.

The communication messages are based on the requirement of the function. According to Table 1, we classify the messages into four types as Table 2.

Optical wireless network can offer high bandwidth than wired network. Basic links for indoor infrared communication are the directed line-of-sight (LOS) and the diffuse link. In directed LOS way, with careful Tx-Rx alignment transmission, speeds far beyond 100 Mb/s can be achieved.

We can divide message into two types simple: short size message and long size message. Long size message, such as audio and video, can be transmitted in a diffuse way with star topology, while short size refers to the information of body, powertrain and chassis domain which collected by sensors and transmitted in ring topology.

Figure 1 shows the topology of infrared optical network. It is composed of two parts. Part one is the star topology. Driver terminal and other passages seat terminals communicate information with internet through base station (BS) which fixed on the top floor. Part two with ring topology is used in communicating information

Table 1. Domains of Vehicle Function

Domain	Function	Context
Powertrain	Motility	The Control of Engine and Transmission and the Diagnostics
Chassis	Flexibility Safety	Control Suspension, Steering and Braking and the Diagnostics
Body	Basis Usage	Control the Vehicle Body's Simple Devices Such as Lights, Doors, Windows and So On, and the Diagnostics
Infotainment	Entertainment Comfort	Includes Internet Connection, Audio and Video Consoles
Telematics	Survivability Connectivity	Communication Network Outside Vehicle to Finish Some Task, Such as Fleet Management, Anti-theft and Remote Repair and Maintance.

Table 2. Characteristics Requirement for In-vehicle Message

Type	Size Bytes	Real-time (ms)	Rate (Mb/s)	Reliability	Priority	Latency
Short Crisis Periodical	2−32	highest (2−10)	$\geqslant 1$	High	Highest	Lowest
Short No-Crisis Periodical	2−32	Low (10−50)	$\geqslant 0.25$	Average	Medium	Average
Short, Crisis No-periodical	2−32	higher	$\geqslant 1$	High	High	Lower
Long, No-crisis No-periodical	200−500	Medium (5−20)	$\geqslant 10$	Medium	Average	Medium

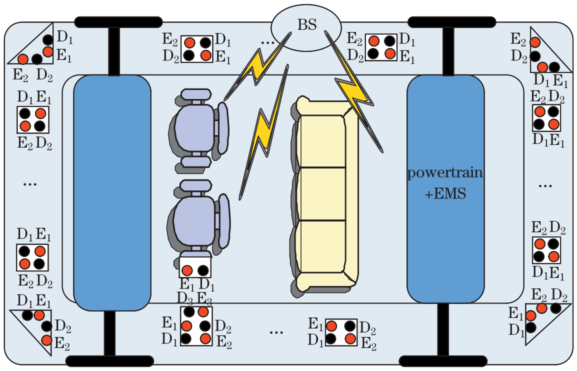

Fig. 1. Structure of network in-vehicle.

between driver terminal and subsystems nodes with infrared optical link through the pipes of the vehicle.

As driver terminal, it needs to monitor the real-time of condition of the vehicle including body information, chassis information and power-train information and so on. At the same time, it should send control messages to subsystem node controller in real time.

In this letter, we only study the network of ring topology. The reminder part of star topology about diffuse link channel will be discussed in the later letter.

Assume the number of nodes in ring network is N and these nodes are named node $i(0 \leqslant i \leqslant N)$. There are three types about message transmission:

1) Nodes need to report message to driver terminal controller in periodically or non- periodically;

2) Messages are shared between two nodes;

3) Driver terminal issues control message to other nodes.

The message array is shown in Table 3. The mutative of the scheduling strategy is to escape transmission conflict and reduce the latency time.

It is easy to understand, from Table 1, each node is possible to receive message from the two or three directions at the same time. So message which is sent from this node should wait for a moment while the other message is in the queue. In order to escape this conflict event and reduce the waiting time, we induce message scheduling strategy as follows.

1) Message was classified into two types: periodical message and no-periodical message. Periodical message is submitted with fixed period with different initial phase.

2) Control messages, as for transmitted from driver terminal to nodes, are transmitted from two sides of the driver terminal according to the positions of the nodes. $(n/2)$ nodes are arranged in the right side of driver terminal. These nodes are coded form node1 to node $[(n/2)]$; in the left side, there are n-$(n/2)$ nodes which coded from node $[n-(n/2)]$ to node n. Control message will be transmitted from the right side if the address of the received node is no more than $(n/2)$. Otherwise, it will be transmitted from the left side.

3) In order to transmit message reliably, shake-hand is important before the data message is transmitted. Data can be transmitted immediately following the handshake signal if transmit task is run only between nodes. However, in ring network with many nodes, assuming

Table 3. Transmission Message Array

Emitter Receiver	Driver Terminal	Node 1	Node 2	···	Node	Node 9
Driver Terminal		Status Message	Status Message	Status Message	Status Message	Status Message
Node 1	Control Message		Shared Message	Shared Message	Shared Message	Shared Message
Node 2	Control Message	Shared Message		Shared Message	Shared Message	Shared Message
···	Control Message	Shared Message	Shared Message		Shared Message	Shared Message
Node n-1	Control Message	Shared Message	Shared Message	Shared Message		Shared Message
Node n	Control Message	Shared Message	Shared Message	Shared Message	Shared Message	

transmit task is run among k nodes ($2< k \leqslant N$), it will increase waiting time if the data message only can be transmitted until the whole link is built. Waiting time can be reduced if the transmission link process accompany the data transmission process one node by one node method as Fig. 2.

Enough Bandwidth is the basement for message which could be transmitted in time. Table 2 shows the shortest time for latency is no more than 2 ms. According to the process of traffic scheduling above, the latency has several components as

$$\text{Latency} = T_{\text{hand shake signal}} + T_{\text{data}} + T_{\text{waiting}}, \tag{1}$$

$$T_{\text{hand shake}} = \sum_{i=n+1}^{m} 4\times(t_{\text{hsend for ward}} + t_{\text{hpropagation}}), \tag{2}$$

$$T_{\text{data}} = \sum_{i=n+1}^{m} t_{\text{dsend for ward}} + t_{\text{dprop agation}}, \tag{3}$$

$$T_{\text{waiting}} = \sum_{j=0}^{k} (t_{j\_\text{send forward}}), \tag{4}$$

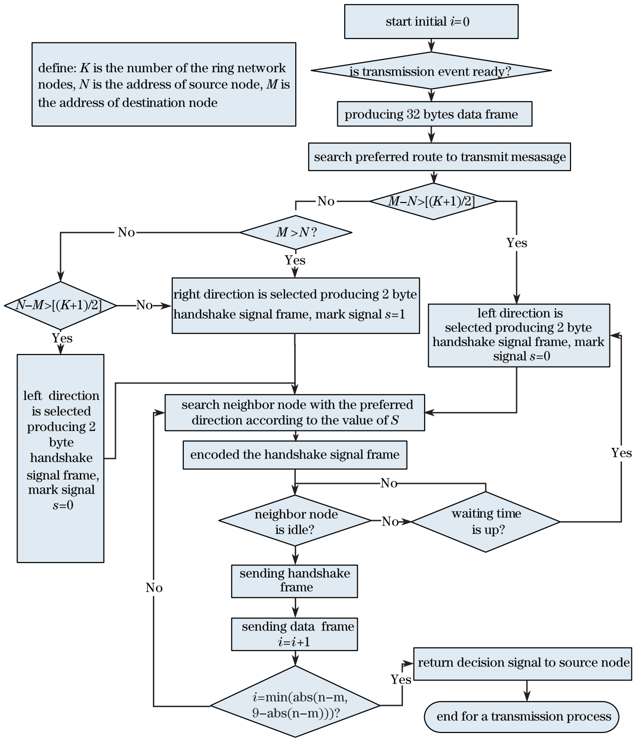

Fig. 2. Process of message transmission.

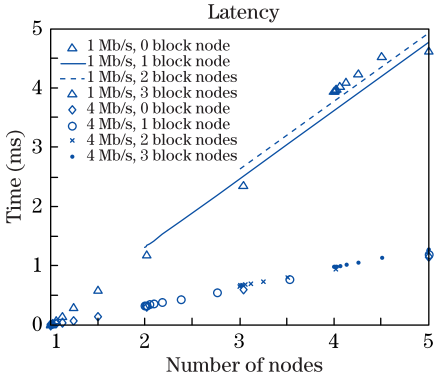

Fig. 3. Simulation results of latency with different bandwidth.

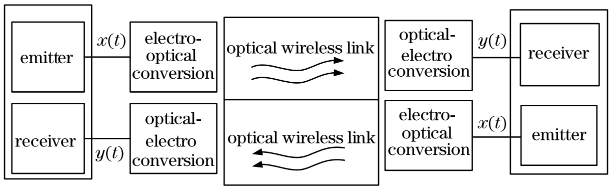

Fig. 4. Basic elements of point to point optical link.

where, $t_{\text{hsend for ward}}$ and $t_{\text{dsend for ward}}$ are the transmit time through the link. $t_{\text{hprop agtion}}$ and $t_{\text{dprop agation}}$ are the propagation delay through the link. Assume handshake frame is x bytes and data frame is y bytes, K is the times of waiting, R_{b} is the bandwidth, and d is the distance between two neighbour nodes. Then,

$$\begin{aligned}\text{Latency} &= T_{\text{hand shake signal}} + T_{\text{data}} + T_{\text{waiting}} \\ &= \sum_{i=n+1}^{m} 4\times(t_{\text{hsend for ward}} + t_{\text{hprop agation}}) \\ &+ \sum_{i=n+1}^{m} (t_{\text{dsend for ward}} + t_{\text{dprop agation}}) + \sum_{j=0}^{k} (t_{j\_\text{send for ward}}) \\ &= \sum_{i=n+1}^{m} \left[4\times\left(\frac{16x}{R_{\text{b}}} + \frac{d_{\text{i}}}{c}\right) + \frac{16y}{R_{\text{b}}} + \frac{d_{\text{i}}}{c}\right] + \sum_{j=0}^{k} \frac{16y_z}{R_{\text{b}}}.\end{aligned} \tag{5}$$

Figure 3 shows the latency is increased with the number of blocked nodes (when message A needs to be transmitted to a node B and node B is transmitting another message or task, we say message A is blocked by node B, and node B called one block node) and reduced with the bandwidth. Obviously, with the bandwidth of 1 Mb/s, latency is not able to be assured when the message transmission meet other nodes more than 3 which are carrying their transmission task. However, with the bandwidth of 4 Mb/s, the latency is under 1.5 ms even in the worse case (message transmission meet nodes more than 5 which are carrying their transmission task). That also shows we should improve bandwidth to 10 Mb/s if the transmitting nodes are more than 10 nodes.

In ring topology network, a transmission process can be divided into many small two-neighbour-optical-transmit nodes processes. This section will discuss the design analysis of optical link between two neighbours. The basic elements of point-to-point optical link are given as Fig. 4.

The transmitted waveform $x(t)$ is the instantaneous optical power of the infrared emitter. The received waveform $y(t)$ is the instantaneous current in the receiving photo detector. Typical detector areas are millions of square wavelengths, leading to spatial diversity that prevents multipath fading. So, channel can be modeled as a baseband linear system with $x(t)(x(t) \geqslant 0)$, $y(t)$, $h(t)$. $h(t)$ is an impulse response. Then baseband channel model[11] is summarized by

$$y(t) = Rx(t) \otimes h(t) + n(t), \tag{6}$$

where R is the detector responsivity.

The average transmitted optical power

$$P_{\text{t}} = \lim_{T\to\infty} \int_{-T}^{T} x(t)\mathrm{d}t. \tag{7}$$

The average received optical power is given by

$$P = H(0)P_{\mathrm{t}}, \tag{8}$$

where the channel direct current (DC) gain is $H(0) = \int_{-\infty}^{+\infty} h(t)\mathrm{d}t$.

The performance electrical signal-to-noise ratio (SNR) link at bit rate R_{b} is related to the receiver electrical SNR as

$$\mathrm{SNR} = \frac{R^2 P^2}{R_{\mathrm{b}} N_0} = \frac{R^2 H(0)^2 P_t^2}{R_{\mathrm{b}} N_0}. \tag{9}$$

In direct LOS links, the DC gain can be computed fairly accurately by considering only the LOS propagation path. This approximation is particularly accurate in directed-LOS links.

Suppose transmitter emits an axially symmetric radiation pattern described by the radiant intensity (W/sr) $P_t R_0(\varphi)$.

$$R_0(\varphi) = \frac{n+1}{2\pi}\cos^n(\varphi), \tag{10}$$

where $n = -\ln 2/\ln(\cos\phi_{1/2})$.

$$H(0)_{\mathrm{LOS}} = \begin{cases} \frac{(n+1)A}{2\pi d^2}\cos^n T_{\mathrm{s}}(\varphi) g(\varphi)\cos(\varphi) & 0 \leqslant \varphi \leqslant \varphi_{\mathrm{c}} \\ 0 & \text{else} \end{cases}, \tag{11}$$

where $T_{\mathrm{s}}(\varphi)$ is the signal transmission of the filter, $g(\varphi)$ is the concentrator gain and φ_{c} is the concentrator FOV (semiangle). Path loss is defined as the inverse value of the DC gain of the frequency response of the channel.

When it receivers an instantaneous optical power $p(t)$, a PIN photodiode produces an instantaneous photocurrent $i(t) = Rp(t)$. The total input-referred noise power-spectral density (PSD) of preamplifier is

$$s_{\mathrm{total}}(f) = S_{\mathrm{shot}}(f) + s_{\mathrm{thermal}}(f), \tag{12}$$

$$S_{\mathrm{shot}}(f) = 2qRP_{\mathrm{n}}, \tag{13}$$

where q is the electronic charge, and P_n is the ambient light received with average optical power.

$$\sigma_{\mathrm{shot}}^2 = I_2 R_{\mathrm{b}} 2qrP_{\mathrm{bg}}, \tag{14}$$

where $s_{\mathrm{thermal}}(f)$ is the noise caused by a field-effect transistor.

$$\begin{aligned} s_{\mathrm{thermal}}(f) = {} & \frac{4kT}{R_{\mathrm{F}}} + \frac{16\pi^2 kT}{g_{\mathrm{m}}} \\ & \cdot \left(\Gamma + \frac{1}{g_{\mathrm{m}} R_{\mathrm{D}}}\right) C_{\mathrm{T}}^2 f^2 + \frac{4n^2 K I_{\mathrm{D}}^a C_{\mathrm{T}}^2 f}{g_{\mathrm{m}}^2}, \end{aligned} \tag{15}$$

$$\begin{aligned} \sigma_{\mathrm{thermal}}(f) = {} & \frac{4kT}{R_{\mathrm{F}}} I_2 R_{\mathrm{b}} + \frac{16\pi^2 kT}{g_{\mathrm{m}}} \\ & \cdot \left(\Gamma + \frac{1}{g_{\mathrm{m}} R_{\mathrm{D}}}\right) C_{\mathrm{T}}^2 I_3 R_{\mathrm{B}}^3 + \frac{4n^2 K I_{\mathrm{D}}^a C_{\mathrm{T}}^2}{g_{\mathrm{m}}^2} I_{\mathrm{f}} R_{\mathrm{B}}^2. \end{aligned} \tag{16}$$

The BER between two directed LOS nodes (node i, node i+1) is decided by SNR as

$$\mathrm{BER}_{i,j+1} = Q\sqrt{\mathrm{SNR}} = \frac{1}{2}\,\mathrm{erfc}\left\{\sqrt{\frac{\mathrm{SNR}}{2}}\right\}, \tag{17}$$

$$\mathrm{SNR} = (RP)^2/\sigma^2. \tag{18}$$

Assume a message is needed to pass through k nodes in order to accomplish the transmission from node n to node m, in this network, and nodes alignment in ring topology. We express the whole BER from the source to destination as $\mathrm{BER}_{\mathrm{total}}$. According to the probability theory, it is easy to get the following equation:

$$\mathrm{BER}_{\mathrm{total}} = 1 - \Pi_{i=m}^{n}(1 - \mathrm{BER}_{i,i+1}). \tag{19}$$

Typical, BER of vehicle network is no more than 10^{-6}. Figure 5 shows the BER is increasing with the number of nodes. The BER is nearby 10 times while the number of nodes is 10. So, the BER of the channel between two directed LOS nodes should be no less than 10^{-7}.

Assuming a bandwidth of 4 Mb/s. SNR should be no more than 13.07 dB corresponding a BER of 10^{-7} while there are more than 10 cascade nodes in ring network.

According to the above analysis, too short distance will cause the increasing of BER while too long will increases the path loss. The relationship between distance with SNR is shown as

$$d = \sqrt{\frac{R(m+1)P(t)A\cos^m(\theta)}{4\pi\sqrt{\left(2qRR_{\mathrm{b}}I_2P_{\mathrm{bg}} + \frac{4KT}{R_{\mathrm{F}}}I_2R_{\mathrm{b}} + \frac{16\pi^2KT}{g_{\mathrm{m}}}\left(\Gamma + \frac{1}{g_{\mathrm{m}}R_{\mathrm{D}}}\right)C_T^2I_3R_{\mathrm{B}}^3 + \frac{4\pi^2KI_{\mathrm{D}}^aC_{\mathrm{T}}^2}{g_{\mathrm{m}}^2}I_{\mathrm{f}}R_{\mathrm{b}}^2\right)}\mathrm{SNR}}}. \tag{20}$$

Combined with Eqs. (11), (18), and (19), we can get the relationship among distance, the number of nodes and bit error rate (BER). Figure 6 gives the differential of BER change with two methods (the first method: a number of nodes are inserted into distance d; the second method: during a detail distance d, only two nodes).

Figure 6 shows that while the link distance is longer than 3 m obviously, the BER of the first method is larger than the second one. Otherwise, the BER is smaller than the first one. The figure shows the border of it.

Figure 7 also shows that the differential BEN changes in curve. The absolute value of the differential is increased quickly while the value of link distance is nearby below 3 m and over some special value, however it is decreased quickly when the link distance is less than this value. The red curve is the border of it.

According to Fig. 8, the adopted link distance is inversely proportional to the nodes of network while the number is less than 4. The adopted link distance is basically stable at 1.4 m while the number of nodes is more than 4.

Considering the directed LOS and the detail environment of the vehicle, according to the above analysis, we fixed nine nodes in this system. The preferred distance

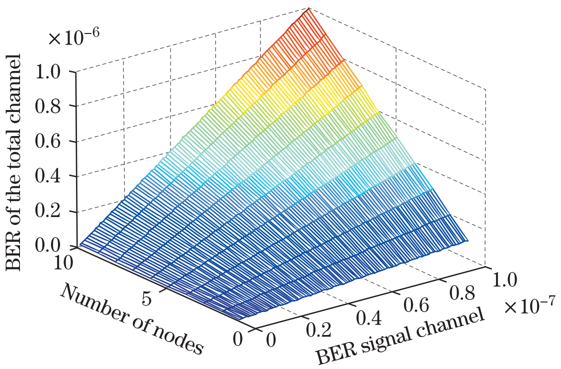

Fig. 5. BER of channel against the number of nodes.

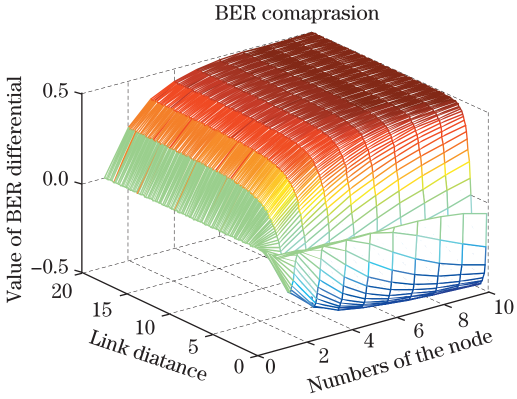

Fig. 6. Differential BER with different distances.

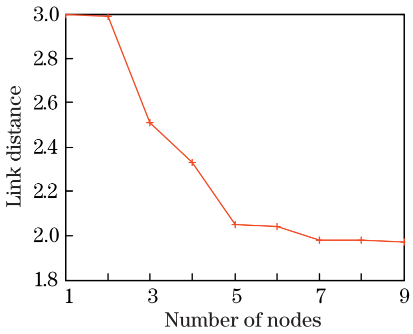

Fig. 7. Zero border of differential BER about two methods.

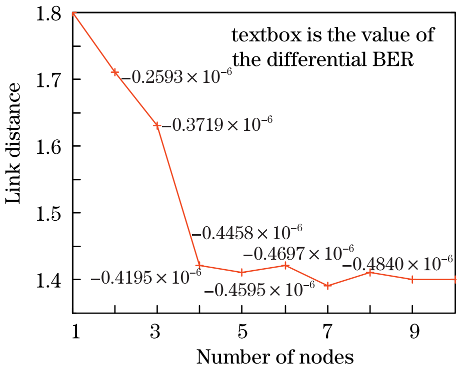

Fig. 8. The biggest differential border of BER about two methods.

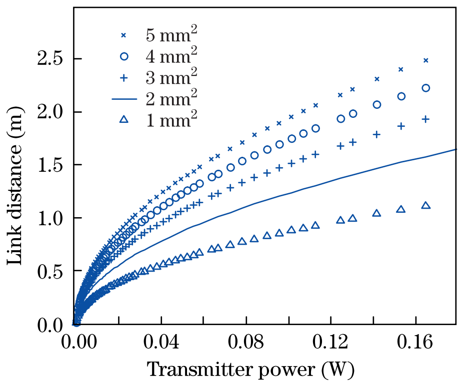

Fig. 9. Link distance against the transmitter power.

is about 1.4 m. The distance between two directed LOS nodes are plotted against the LED power with the different size of receiver area as Fig. 9; Here, we assume that BER between any nodes are almost equal. Figure 9 shows the biggest distance with 1 mm^2 area size with 180 mW is 1 m. Infrared wireless network in ring topology is analyzed and designed in vehicle.

In conclusion, we analyze the requirement of function and information requirement. The message is dynamic scheduled in ring topology in order to improve the real-time performance of network. On the base of the reliability and timeliness of transmission message, we analyze the performance parameter including the BER and latency. Through the simulation, we get the reasonable bandwidth budget, preferred link distance and power requirement.

References

1. N. Navet, Y. Song, F. Simonot-Lion, and C. Wilwert, Proceedings of the IEEE **93,** 1204 (2005).
2. G. Leen and D. Heffernan, Computer **35,** 88 (2002).
3. U. Keskin, “In-vehicle communication networks: a literature survey,” (Technische Universiteit Eindhoven, 2009).
4. “Electromagnetic compatibility and functional safety: Annexe G-Road Transport,” (The Institution of Engineering and Technology, 2008).
5. T. Nolte, H. Hansson, and L. L. Bello, in *Proceedings of* 10th *IEEE Conference on Emerging Technologies and Factory Automation* (ETFA 2005) 8 (2005).
6. N. Schmitt, T. Pistner, C. Vassilopoulos, D. Marinos, A. Boucouvalas, M. Nikolitsa, C. Aidinis, and G. Metaxas, in *Proceedings of* 5th *International Symposium on Communication Systems, Networks and Digital Signal Processing* (CSNDSP 2006) (2006).
7. R. J. Green, in *Proceedings of 12th International Conference on Transparent Optical Networks* (ICTON 2010), 1 (2010).
8. D. O’Brien, Proc. SPIE **7464,** 74640B (2009).
9. D. C. O’Brien, G. E. Faulkner, S. Zikic, and N. P. Schmitt, in *Proceedings of 6th International Symposium on Communication Systems, Networks and Digital Signal Processing* (CNSDSP 2008) 68 (2008).
10. W. Ke, A. Nirmalathas, C. Lim, and E. Skafidas, Photonics Technology Letters, IEEE **23,** 519 (2011).
11. J. M. Kahn and J. R. Barry, Proceedings of the IEEE **85,** 265 (1997).