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Evaluation of Subjective Communication Quality of Optical Mobile Communication Systems by Mean Opinion Score

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SUMMARY Since mobile communication systems using optical rays (optical mobile communication systems) do not radiate radio waves from the mobile terminals, they are expected to be used in environments containing sensitive electronic equipment. However, the placement and direction of the optical receivers must be suitably determined for mobile communication because light has high directivity. In optical mobile communication systems, the communication quality varies with the direction of the mobile terminal. Therefore, we examined the angle over which communication is possible at various measurement points and defined it as the communication angle. The mean opinion score (MOS) was obtained to assess the communication quality using the communication angle as a parameter. In this paper, the two situations, walking and sitting down, was considered the way optical mobile communication systems actually used. We found that for walking, when the communication angle was over 180 degrees, the MOS was over 3 and over 50% of users could communicate usefully. When used sitting down, the communication quality did not depend on the communication angle, but only on whether or not the user could communicate in the direction he/she was facing. Thus, if the communication angle in the service area is over 180 degrees, it is possible to communicate in practical situations, even while walking.

key words: *mobile communication system, optical wireless communication, communication quality, MOS*

1. Introduction

As mobile communication systems spread and are used in more and more types of places, the interference between radio waves and electrical equipment is increasing. Their use is prohibited in places such as intensive care units and operating rooms in hospitals and in airplanes [1]. Optical mobile communication systems, on the other hand, do not radiate radio waves from their mobile terminals, so they should be useful in particular electromagnetic environments that contain sensitive electrical equipment [2].

An optical wireless communication system has been developed for use in a local area network (LAN) [3], [4], because optical wireless communication is suitable for high-speed communication in a small area. However, the receiver and transmitter must be mounted on a fixed object such as a desk or bookshelf, because it is difficult to maintain a communication link if they move since optical communication rays are highly directional. We need a method of determining the placement and direction of the optical receivers to obtain the desired communication areas where mobile communications using optical waves enable.

These parameters are affected by many conditions such as the type of the transmission systems and the noise level of the surrounding environment. One of the important conditions is the communication angel over which communication is possible. The many optical receivers and very wide directivity are needed to achieve the area where communication is possible over any angle. Therefore, it is important to determine the minimum communication angel for mobile communication, because this contributes to reduce the cost of the system. Some simulation method for determining the placement of fixed terminal using radio waves have been reported [5], [6], but they do not consider the communication angle because they calculate the communication area from the electric field strength.

In this paper, we propose a method of using the communication angle to evaluate the service area of optical mobile communication systems. The relationship between the communication angle and the communication quality is experimentally investigated using the mean opinion score (MOS). Section 2 presents the definition of the communication angle and its calculation method. Section 3 presents the relationship between the communication angle and MOS to evaluate the communication quality.

2. Calculation of Communication Angle

2.1 Communication Angle

Figure 1 shows the basic configuration of an optical mobile communication system. In a radio mobile communication system, the speech quality does not depend on the direction of the mobile terminals because this system is non-directional. On the other hand, in an optical mobile communication system, the speech quality does depend on the directivity of the mobile terminal because this system has strong directivity. Therefore, it is difficult to apply service area evaluation methods used for radio mobile communication systems to optical mobile communication systems.

The communication angle is defined in Fig. 2 to aid our discussion of service area evaluation for optical mobile communication systems. It is the sum of the angles over which communication is possible when a mobile terminal is rotated horizontally by 360 degrees. For a radio mobile communication system, the communication angle is 360 degrees in the service area and 0 degrees outside it except for a border of the service area. For an optical mobile communication sys-

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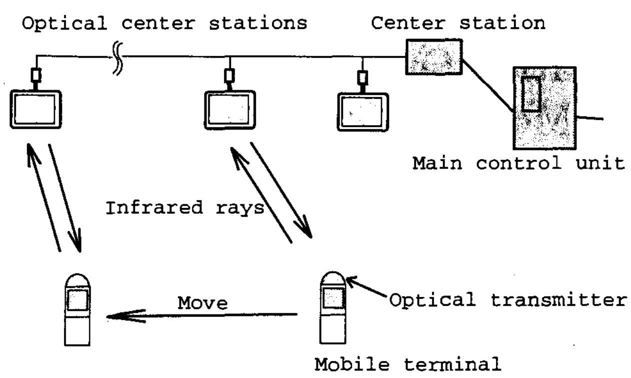

Fig. 1 Basic configuration of optical mobile communication system.

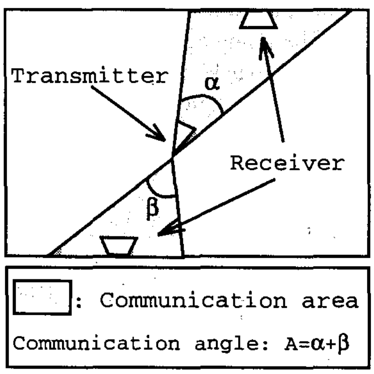

Fig. 2 Definition of communication angle.

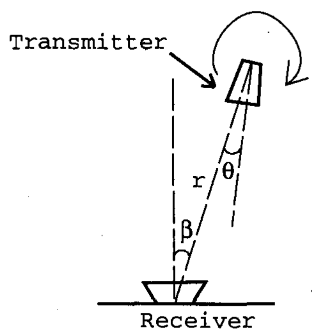

Fig. 3 Model of propagation.

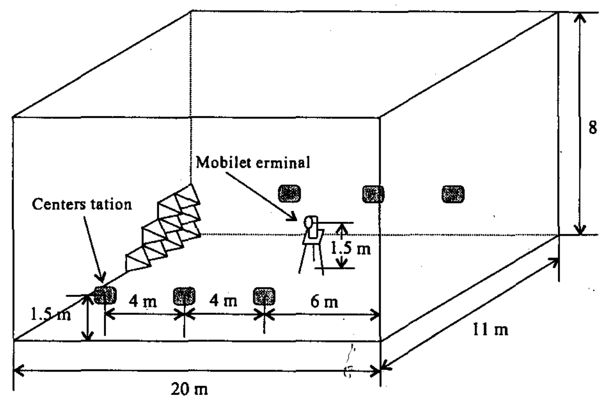

Fig. 4 Experimental setup for measuring communication angle.

tem , on the other hand, it ranges between 0 and 360 degrees in all area. Thus, this evaluation method is an extension of the previous methods.

2.2 Calculation

Figure 3 shows a general model of propagation from an optical transmitter to an optical receiver. Here, the mobile terminal is an optical transmitter, and the optical center station is an optical receiver. The same calculation method can be used in the reverse situation. The light power can be calculated using the ray-tracing method in any position [3], [4]. And the radiation from the transmitter can expressed by a generalized Lambertian model [5]. Thus, the total power received by the optical receiver is given by

$$P = \frac{n_t + 1}{2\pi r^2} P_t \cos^{n_t}\theta \cos^{n_r}\beta, \tag{1}$$

where P_t is the total power emitted by the transmitter, r is the distance between the transmitter and receiver, θ is the angle subtended between the normal to the transmitter and the radiation emission direction, β is the angle of incidence on the receiver, and nt and nr are defined by

$$n_t = \frac{\log(1/4)}{\log(\cos\theta_{ht})}, \tag{2}$$

$$n_r = \frac{\log(1/4)}{\log(\cos\theta_{hr})}, \tag{3}$$

where θ_{ht} is the half-power angle of the transmitter, i.e., the angle at which the communication distance becomes half, and θ_{hr} is the half-power angle of the receiver.

When we assume that the noise from ambient light is sufficiently small, then communication is possible if the total received power of the optical receiver P is bigger than the sensitivity of the optical receiver R_s. That is, if

$$P \geq R_s, \tag{4}$$

We calculated the total received power for each angle while the transmitter was rotated horizontally by 360 degrees and judged whether or not Eq. (4) was satisfied. From this information, we could calculate the communication angle.

2.3 Measurement

To verify the validity of the calculation method, we compared the calculated results with measured ones. Figure 4 shows the experimental setup. The room used for the experiment was 20.0 m long, 11.0 m wide, and 8.0 m high. Radio wave absorbers were attached to the walls and ceiling, so reflectivity was almost zero. Therefore, the height of receiver and transmitter hardly influenced by the directivity of the optical receiver and transmitter. The optical receivers were fixed 1.5 m above the floor. The optical transmitter was placed 1.5 m above the floor and rotated from 0 to 360 degrees. The tilt angle of the transmitter was set so that the maximum radiation angle agreed with the horizontal reference plane. Since the directivity of the optical receiver and transmitter are sufmunication quality for communication angles of 15, 30, 45, 60, and 75 degrees. Figure 9 shows the placement of optical center station.

Each desk had papers on it containing many images and their names. One trial involved two speakers. A was seated in front of a telephone in a small room away from the test area and B was seated in the chair in the test area. A had copies of the papers on the two desks in the test area. The trial began when A called B, selected a picture from among his/her papers, and described it to B, who tried to find it among the papers on the two desks. If B could not find this picture, he/she asked A for a clue. The maximum time allowed for one trial was two minutes.

After each trial, we asked both subjects to evaluate the communication quality, using the same evaluation method as for the walking test.

3.2 Results of Walking Test

Figure 10 shows the relationship between the average communication angle and the MOS in the walking tests, which was evaluated using the five grades of the listening-effort-scale. The larger the MOS, the better the communication quality. This figure reveals that:

(i) The communication qualities reported by speakers A and B were almost the same, at the 95% confidence interval.

(ii) When the communication angle was over 180 degrees, the MOS was over 3.0. When it was 60 or 120 degrees, the MOS was almost 2.0.

(iii) A communication angle of 240 degrees gave the best communication quality while 60 degrees was the worst.

The MOS is statistical value. Therefore, the validity of the value should be evaluated. Any significant difference between the MOSs for each angle is evaluated using Eq. (7). This shows a two-sided T-test [8] at the significance level of 5%.

$$T = \frac{MOS_1 - MOS_2}{\sqrt{\frac{\sigma_1^2 - \sigma_2^2}{n}}} < 2.064 \quad , \qquad (7)$$

where MOS_1 and MOS_2 are values of MOS in the different communication angle, σ_1^2 and σ_2^2 are the variances and n is the number of degrees of freedom (Here, n=24).

There was a significant difference between MOS_1 and MOS_2 when T was less then 2.064. Table 2 shows the results. It indicates that there was no significant difference between 60 and 120 degrees or 240 and 300 degrees. However, there was a significant difference between less than 120 degrees and over 180 degrees. There was a significant difference both A and B in meshed area of Table 2. Thus, when communication angles were over 180 degrees, these communication qualities were almost the same.

Figure 11 shows the relationship between the average communication angle and the acceptability in the walking

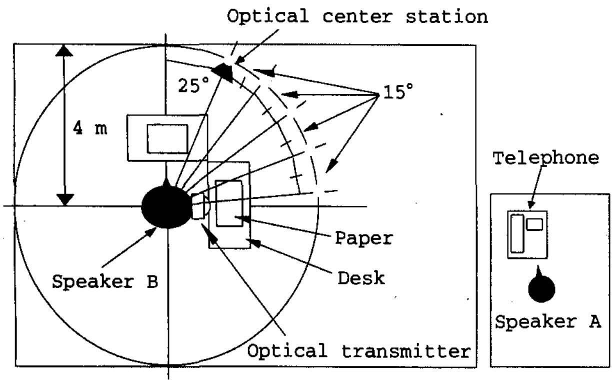

Fig. 9 Experimental setup for sitting-down test.

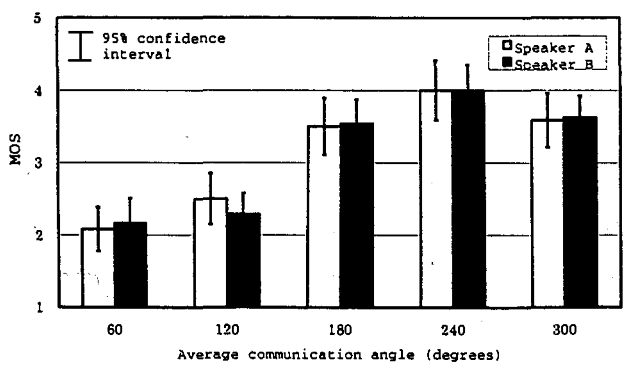

Fig. 10 Relationship between MOS and average communication angle for walking test.

Table 2 Results of T-test for walking test.
(Y: significant difference, N: not significant difference)

Evaluated Person	communication angle[degrees]	60	120	180	240	300
Speaker A	60	-	N	Y	Y	Y
	120	N	-	Y	Y	Y
	180	Y	Y	-	N	N
	240	Y	Y	N	-	N
	300	Y	Y	N	N	-
Speaker B	60	-	N	Y	Y	Y
	120	N	-	Y	Y	Y
	180	Y	Y	-	Y	N
	240	Y	Y	Y	-	N
	300	Y	Y	N	N	-

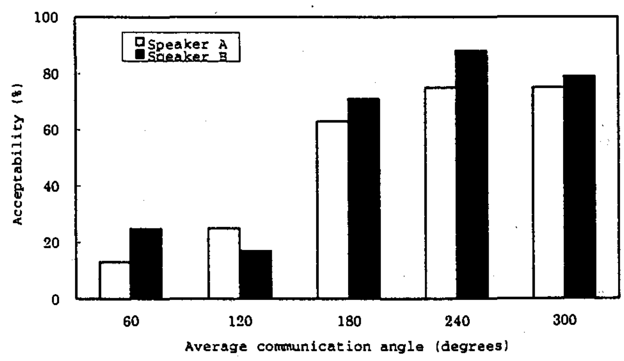

Fig. 11 Relationship between acceptability and average communication angle for walking test.

test. The acceptability indicates the ratio of people would considere the speech quality acceptable. It was over 50% when the average communication angle was over 180 degrees and over 70% for 240 and 300 degrees, but less than 20% for 60 and 120 degrees.

Table 3 shows the average time taken until the end of the test. The shortest time was for an average communication angle of 240 degrees and longest for 60 degrees. Thus, the working efficiency corresponds to the MOS.

3.3 Results of Sitting-Down Test

Figure 12 shows the relationship between the communication angle and the MOS in the sitting-down test. This figure reveals that:

(i) The communication qualities reported by speakers A and B were almost the same, at the 95% confidence interval.

(ii) A communication angle of 75 degrees gave the best MOS, which was about 3.0.

(iii) The communication quality gradually worsened as the communication angle became smaller, but these difference was very small.

We did a two-sided T-test, the same as for the walking test. Table 4 shows the results. It indicates that for A, there was no significant difference among 30, 45, 60, and 75 degrees, but there was a significant difference between 15 and 75 degrees only, with 75 degrees giving better quality than 15 degrees. For B, there was no significant difference between 60 and 75 degrees, but there was a significant difference between less than 45 degrees and 75 degrees. There was a significant difference both A and B in meshed area of Table 4. Considering these results, the communication qualities were almost the same, except for the difference between 15 and 75 degrees.

Table 3 Relationship between task time and average communication angle.

Communication angle (degrees)	task time (min)	standard deviation	confidence interval (%)
60	>3.00	-	-
120	2.90	0.36	14
180	2.65	0.53	21
240	2.39	0.65	26
300	2.43	0.66	26

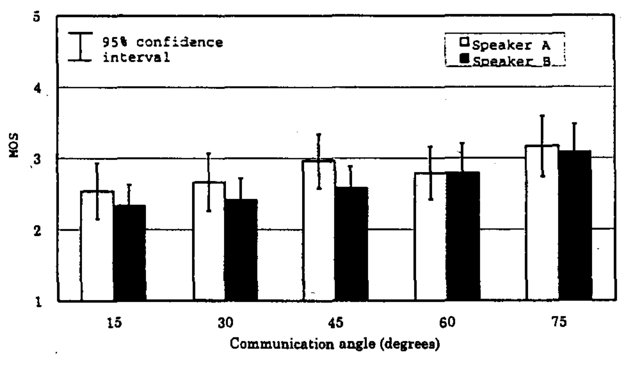

Fig. 12 Relationship between MOS and average communication angle for sitting-down test.

Figure 13 shows the relationship between the communication angle and the acceptability in the sitting-down test. The acceptability was less than 50%, except in the case of 75 degrees for A.

Thus, the results of the sitting-down test varied slightly with the communication angle and the evaluated quality was worse than in the walking test. This is because there were fewer degrees of freedom in the sitting-down test. Therefore, it is more effective to be able to communicate in the direction in which the speaker is facing than in all directions.

3.4 MOS and Acceptability

Figure 14 shows the relationship between the MOS and the acceptability, which is a cumulative normal distribution. The MOS was about 3.0 when the acceptability was 50%. For comparison, the MOS of speech quality for a normal telephone is about 2.0 when the acceptability is 50% [9]. The unacceptability in [9] was changed to the acceptability in Fig 14 using the following rerations

$$Y\ (\%) = 100 - X\ (\%) \tag{8}$$

where Y is the acceptability in Fig. 14 and X is unacceptability in [9]. Thus, the subjects evaluated the communication qual-

Table 4 Results of T-test for sitting-down test.
(Y: significant difference, N: not significant difference)

Evaluated Person	communication angle [degrees]	15	30	45	60	75
Speaker A	15	-	N	N	N	Y
	30	N	-	N	N	N
	45	N	N	-	N	N
	60	N	N	N	-	N
	75	Y	N	N	N	-
Speaker B	15	-	N	N	N	Y
	30	N	-	N	N	Y
	45	N	N	-	N	Y
	60	N	N	N	-	N
	75	Y	Y	Y	N	-

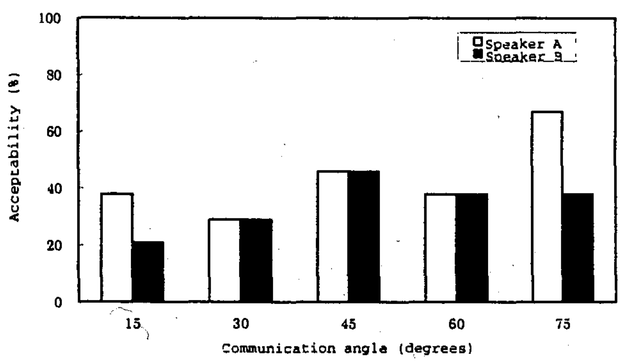

Fig. 13 Relationship between acceptability and communication angle for sitting-down test.