Evaluation of Signal Quality Improvement With Rake Reception Using an Ultrawideband Indoor Area Propagation Measurement

Katsuyuki Haneda, Member, IEEE, Jun-ichi Takada, Member, IEEE, and Ken-ichi Takizawa, Member, IEEE

Abstract—Achievable improvement of signal quality using rake reception was evaluated for ultrawideband impulse-radio and spread-spectrum systems. The evaluation was based on extensive area propagation measurement in a line-of-sight office environment. Influence of large- and small-scale propagation behavior on improvement of receiving signal-to-noise ratio (SNR) was analyzed. The analyses revealed that having eight fingers could achieve sufficient improvement of receiving SNR under practical conditions. It was also demonstrated that eight-finger rake reception could extend service coverage and reduce outage probability.

Index Terms—Area propagation measurement, rake reception, ultrawideband (UWB).

I. INTRODUCTION

ULTRAWIDEBAND (UWB) technology has been considered as a promising technology to realize both high and low data-rate applications ranging from video streaming to sensor networks. In impulse-based and spread spectrum transmission techniques [1], rake reception is an important method to collect energy spread over wide ranges of delay time due to multipath propagation. This method increases the receiving signal-to-noise ratio (SNR), leading to the improvement of bit error rate (BER) of data transmission. In general, however, there is a tradeoff between the achievable SNR improvement and the number of time instants where energy is collected, namely rake fingers, due to increasing hardware complexity and signal processing load to realize the full performance [2], [3]. There have been a few measurement-based evaluation of rake reception in improving receiving SNR and BER, such as papers [3]–[6]. These papers mainly evaluated the small-scale effect of radio wave propagation in different scenarios and frequency bands. Following their important insights, this letter attempts to analyze the effective number of rake fingers and their achievable performances based on extensive propagation measurements. The relationship between achievable performance and large- and small-scale propagation phenomena was discussed. Analysis on BER demonstrated that the rake reception could extend service coverage and reduce outage probability.

II. AREA PROPAGATION MEASUREMENT

Area propagation measurement is an important method in predicting the service coverage of specific systems or equipment. The measurement covers wide areas inside an environment to look at both large- and small-scale effects of propagation channels and its influence on the data transmission performance. Our area propagation measurements were conducted in an office room. There were several desks, chairs, television displays, and metal-furnished shelves. Walls were made of metal, and the ceiling was composed of plaster board. The floor plan of the room is depicted in Fig. 1. The receiving antenna (Rx) was fixed at the corner of the room, while the transmitting antenna (Tx) could be positioned at almost any place in the room.
by the aid of a large spatial scanner covering the whole areas of the room. The location of Tx antenna can be categorized as follows: a small $5 \times 5$ array was formed on the horizontal plane to probe the small-scale effects of channels, which is simply referred to as an “array” in later descriptions; while the array measurement was performed in 168 positions in the room to capture large-scale effects. In total, 4200 spatial samples were measured on the Tx side. Interarray distance was 500 mm, and interelevation spacing in the array was 25 mm. The channel transfer function of a single Tx-Rx combination was measured by a vector network analyzer (VNA). Other details of measurement specifications are summarized in Table I.

The maximum detectable delay time without ambiguity is the inverse of a frequency sampling interval of the measurement, and in our case, 200 ns. This value was sufficient to capture dominant propagation paths which could be used for energy collection in the rake reception. Line-of-sight (LOS) was assured in most Tx positions except for two arrays where LOS was obstructed due to television displays. The whole measurement took about 6 h, but there was no moving object during the measurement so that the time-invariance of the angular-delay channel characteristics was ensured. Phase drift of the VNA was carefully compensated during the measurement by performing an internal calibration procedure of the VNA once in 2 h.

### III. ANALYSIS OF RAKE RECEIPTION

Several different rake reception methods have been proposed depending on the selection criterion of rake fingers: all-rake, partial-rake, and selective-rake [2]. As it is reported that the selective-rake reception performs better and more practical than others under the limited number of rake fingers and computational resources available, the selective-rake reception is considered in the following.

The rake reception can be expressed by a simple tapped delay line model [2], [4]. The use of the model allows us to evaluate the ideal performance without considering influences of imperfections in practical implementation, such as the design of template waveform in correlation receivers and hardware impairment. In the model, the delay interval between successive taps (or bins) was set to the inverse of the measurement bandwidth, 0.13 ns in our case, which was equivalent to the delay resolution of the system. Amplitude of a channel impulse response (CIR) was calculated for each delay tap. The selective-rake reception chooses the strongest $L_3$ amplitudes for energy collection, and then amplitude synthesis is performed based on the maximum-ratio combining. In deriving the amplitude of CIR, values were padded with zeros if it was below the measurement noise level. Dynamic range of signal components over the noise level was 15 to 30 dB depending on Tx-Rx antenna separation.

#### A. Signal Quality Improvement

Influences of the large-scale propagation effect on the improvement of receiving SNR were first investigated. In Fig. 2(a), a cumulative distribution function (CDF) of the improvement of receiving SNR is shown for various number of rake fingers. Receiving SNR was calculated for each number of rake fingers, and its improvement was identified by comparing it with the SNR in a single rake finger case. In drawing the CDF, first a median value of improved SNR was identified in each array, and then CDF was calculated using the values from all the arrays. Fig. 2(a) revealed that having the first three rake fingers improved SNR more than 3 dB on average compared to the single rake finger case. However, the effect of additional rake fingers became gradually less afterwards. After eight fingers, adding a new finger contributed only the 0.3 dB improvement at the most. Hence, eight-finger rake reception was set to be the reasonable number of fingers under practical tradeoffs. With eight-finger rake reception, 6-dB improvement of receiving SNR can be expected, with its variation within ±2 dB. The variation was due to the large-scale effect, where larger Tx-Rx separation tended to show better SNR improvement. This was attributed to greater number of multipaths in larger Tx-Rx separation.

Fig. 2(b) shows a small-scale variation of the SNR improvement. The CDF was derived from each array, with the normalization performed relative to its median value. It was found that the small-scale variation was within ±3 dB. The largest and smallest variations in the positive and negative sides were observed at random locations, meaning that small-scale performance was independent with large-scale effects.

Finally, improvement of link budget was analyzed. Link budget here is equivalent to the path loss during wave propagation. The lowest link budget was identified in each array, both for 8-finger and for single-finger rake reception. The results are plotted against Tx-Rx separation as shown in Fig. 3. It was found that the improvement of the lowest link budget was about 6 dB, which did not change much on Tx-Rx separation. The improvement is advantageous in realizing better transmission performance without increasing transmitting power, or in reducing the transmitting power for energy saving while keeping the same transmission performance.

#### B. BER Characteristics

The BER characteristics are, under intersymbol interference (ISI) free situations, dominated by the lowest receiving power occurring in small-scale fading effects. Thus improvement of the lowest link budget discussed in the previous subsection can lead

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SPECIFICATIONS OF THE AREA PROPAGATION MEASUREMENT</th>
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<tbody>
<tr>
<td>Bandwidth</td>
<td>3.1 – 10.6 GHz</td>
</tr>
<tr>
<td>Measurement equipment</td>
<td>Vector network analyzer, Room-wide spatial scanner, Low-noise amplifier (30 dB)</td>
</tr>
<tr>
<td>Frequency sweeping points</td>
<td>1501</td>
</tr>
<tr>
<td>Antennas</td>
<td>UWB monopole antennas</td>
</tr>
<tr>
<td>Transmitted power</td>
<td>–17 dBm (CW)</td>
</tr>
<tr>
<td>Measured area</td>
<td>5.1 × 7.6 m²</td>
</tr>
<tr>
<td>Tx-Rx antenna separation</td>
<td>0.6 to 9.3 m</td>
</tr>
<tr>
<td>Tx and Rx antenna height</td>
<td>1.3 m above the floor</td>
</tr>
</tbody>
</table>
Fig. 2. Improvement of the receiving SNR compared to the single rake finger case. (a) Large-scale effect. Results for the number of rake fingers from 2 to 20 are shown. Median values from each array were used for the figure. (b) Small-scale effect. Eight-finger rake reception was considered. The values were normalized by the corresponding median values in each array.

Fig. 3. Improvement of the lowest link budget in each array. Results from eight-finger rake reception were compared with the single rake finger case.

As a result demonstrated that introducing the selective-rake reception can enhance the service coverage and reduce the outage probability. Furthermore, it was found that the area distribution of BER in Fig. 4(b) was similar to that derived from the transmitted SNR of 71 dB without rake reception. It means that introducing eight-finger rake reception allows about 6–7 dB reduction of transmitted power to achieve similar BER characteristics. This observation is also supported by the insight obtained in the previous subsection that the improvement of the lowest link budget was 6 dB on average when using eight-finger rake reception.

C. Energy Captured

Finally, the composition of energy captured relative to the total receiving power was analyzed. The total receiving power was calculated by summing the amplitude from all the fingers, which is called all rake reception. BER derivation was performed for eight-finger and single-finger rake reception. The area distributions of the BER are shown in Fig. 4. Transmitting SNR was 65 dB in both results, where the transmitting spectral density was assumed to be uniform over the frequency domain. According to the result, most of the far Tx antenna positions comprising 60% of the room suffered from high BER above $10^{-2}$ in the single rake finger case. Reliable data transmission was possible only in a few points near the Rx antenna located at the upper-left of the figure. Whereas all the areas with BER above $10^{-2}$ disappeared when eight-finger rake reception was introduced. Areas with BER less than $10^{-6}$ became 12 times larger, and it comprised 30% of the room. The result demonstrated that introducing the selective-rake reception can enhance the service coverage and reduce the outage probability. Furthermore, it was found that the area distribution of BER in Fig. 4(b) was similar to that derived from the transmitted SNR of 71 dB without rake reception. It means that introducing eight-finger rake reception allows about 6–7 dB reduction of transmitted power to achieve similar BER characteristics. This observation is also supported by the insight obtained in the previous subsection that the improvement of the lowest link budget was 6 dB on average when using eight-finger rake reception.

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Fig. 5 shows an energy capture performance of eight-finger rake reception against Tx-Rx separation. There was clear dependency of the energy captured on Tx-Rx separation. In Tx-Rx separation less than 300 mm, eight-finger rake reception could capture more than 40% of the total receiving power. Energy captured was monotonically decreasing with increasing Tx-Rx separation. In the shortest Tx-Rx separation of 570 mm, the energy captured accounted for the highest value, 68%. This is because most of the dominant multipaths including a LOS path reached Rx antenna so closely with each other in the delay domain that the paths fell only in several delay taps. In contrast, the energy capture performance with Tx-Rx separation larger than 7000 mm was as low as 25% due to large number of multipaths spread over wide delay ranges. This suggests that 8 fingers are too small to catch majority of the available signal components. In fact, however, it is often necessary to have more than 100 fingers to collect half of the total receiving power, which is not a
Fig. 4. Area distribution of BER with the constant transmitting SNR of 65 dB. (a) Single finger. (b) Eight-finger rake reception.

Fig. 5. Dependence of energy captured on Tx-Rx separation when eight-finger rake reception was used. Median values in each array were considered.

practical solution. The energy capture performance of the Tx-Rx separation from 3000 to 7000 mm took a wide range of values from 20 to 45% even with the same Tx-Rx separation. Area distribution of the energy captured revealed that a small value was found when Tx was near the wall. Further analysis revealed that the small-scale variation of energy capture characteristics was also dependent on Tx-Rx separation. For large separation of Tx and Rx, the variation was always less than 20%. In contrast, variations as large as 40% were found in short Tx-Rx separations. This is attributed to a high signal dynamic range and varying shape of CIR in short Tx-Rx separations.

IV. CONCLUSION

Signal quality improvement using selective rake reception was analyzed based on UWB area propagation measurements. The practical number of rake fingers was identified as 8, and 6–dB improvement of receiving SNR was expected compared to the single rake finger case. Large- and small-scale variations were found to be within ±2 and ±3 dB. Larger Tx-Rx separation resulted in better SNR improvement, while its small-scale variation was almost independent on antenna separation distances. The SNR improvement can lead to the extension of service coverage, reduction of outage probability, and saving transmit power. Analysis of energy captured revealed that it could vary depending on Tx-Rx separation as well as antenna locations. The longer the antenna separation, the lower energy captured and less small-scale variation could be expected.

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REFERENCES