

Evaluation of Relay Transmission in Outdoor-to-Indoor Propagation Channels

Katsuyuki Haneda*, Veli-Matti Kolmonen*, Taneli Riihonen*,
Risto Wichman*, Pertti Vainikainen*, and Jun-ichi Takada†

* SMARAD Centre of Excellence, Helsinki University of Technology (TKK), Finland

Email: katsuyuki.haneda@tkk.fi

† Department of International Development Engineering, Tokyo Institute of Technology, Japan

Abstract—This paper investigates the performance of relay transmission against real-world propagation channels. The investigation focuses on outdoor-to-indoor communication links where a relay terminal provides enhanced data transmission capability for indoor receivers (Rx) by forwarding signals from outdoor base station. Real-time channel sounder was used to measure three links constituting the relay transmission: source-relay, source-destination, and relay-destination links. Amplify-and-forward (AF) and decode-and-forward (DF) methods were considered for signal relay schemes. Evaluation of end-to-end channel capacity revealed the following conclusions: 1) introducing relay in outdoor-to-indoor radio link extends the BS coverage around the relay terminal; 2) relay improves outage capacity better than mean capacity; 3) DF achieves twice the capacity improvement of AF on average when destination terminals are around the relay terminal; and finally, 4) power adaptation enhances the system performance, but the effect is minor.

I. INTRODUCTION

Deployment of future mobile communication systems in higher frequency bands is always important to consider, given the scarcity of available frequency bands at lower frequencies below 5 GHz. It is required that the future mobile communication systems achieve data rates as high as 100 Mb/s. The wireless metropolitan area networks, also known as WiMAX, is considered as one of the standards that achieve high data rate mobile communications covering outdoor urban scenarios [1], [2]. Several frequency bands are planned to be used in the WiMAX system, among which the 5 GHz band is regarded as one of the candidates. The higher frequency bands inevitably suffer from higher pathloss in propagation, resulting in smaller area coverage. However, WiMAX considers relay transmission as a key technology which can reinforce the high pathloss. Relay terminals extend the service coverage by forwarding a signal from a base station (BS) to an area which the BS cannot cover. The relay transmission also improves the quality of links by realizing multiple transmission routes between the transmitters and receivers, leading to diversity effects. One of the particular installation scenarios of the WiMAX is that an outdoor BS covers indoor users. Insertion loss of buildings is normally so high that there is a high probability of dead spots inside, and therefore, introduction of signal forwarding schemes is crucial in many cases.

Relay system performance has been analyzed by many researchers mainly in theoretical fields, showing the inherent potential of the relay (e.g., the work by Laneman et al. [3]).

Effect of radio channel conditions on the system performance have also been discussed by several researchers: for example, Pabst et al. [4] reported that the relay improves throughput near the relay station, provided that the antennas equipped in the relay station have high directional gain. Boyer et al. [5] analyzed the amplify-and-forward (AF) and decode-and-forward (DF) schemes, suggesting that positions of relay nodes determine the performance of relay systems. Li et al. [6] showed that the relay transmission gain benefits from increasing signal-to-noise ratio by power adaptation for the relay nodes. The theoretical performance estimates by Laneman et al. have recently been examined against measured channel data by Kyritsi et al. [7], [8], showing the feasibility and practicality of relay transmission in real indoor channels. The concepts and insights reported in those papers are informative in supporting the effectiveness of relay transmission. On top of these, this work is dedicated to provide more detailed view of relay systems for its achievable performance under real outdoor-to-indoor channel conditions.

The purpose of this work consists of the following three items: 1) to assess the performance of relay transmission under realistic deployment scenarios; 2) to investigate the effect of propagation conditions on relaying; and ultimately, 3) to provide deployment guidelines for relay systems.

II. CHANNEL MEASUREMENT CAMPAIGNS

Relay analysis in this paper is based on measured channel data in outdoor-to-indoor scenarios. In this section, measurement environment and apparatus of the channel sounding are described.

A. Measurement Environment

The channel sounding for relay analysis consists of two separate measurements, which were performed on different days. Each measurement was done with a fixed position of the transmitter (Tx) and a set of continuous routes by moving the receiver (Rx). Figure 1 is a map of the measurement site, showing the Tx positions and the Rx measurement routes. The locations of Tx's were different for the two measurements while the Rx measurement routes were common, leading to a virtual dual-link measurement. One Tx was located outdoor on the rooftop of a building, resembling a BS forming micro-cell or small macro-cell coverage. Another Tx was placed inside

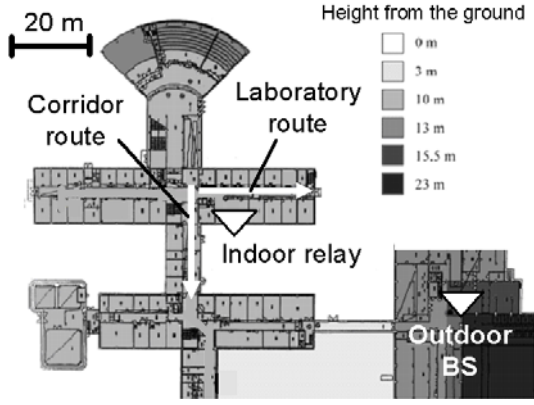


Fig. 1. Map of the measurement location.

a building to represent an indoor relay. The link between the outdoor BS and the indoor relay was also measured. The Rx measurement routes consisted of two corridors as shown in Fig. 1. One route faces many office rooms in a laboratory, while another route is a common corridor having large windows. Those routes are called laboratory and corridor routes for clarity hereinafter. The laboratory route is 32 m long, and is mostly non-line-of-sight (NLOS) to the outdoor Tx except for the end of the route. There is LOS to the indoor Tx at the beginning of the laboratory route. The corridor route is 26 m long, and is LOS to the outdoor Tx in the middle of the route through window glasses. LOS to the indoor Tx is blocked and shadowed in most positions of the corridor route due to brick walls and pillars. The link between outdoor Tx and indoor Tx has LOS through the window, but is slightly shadowed due to branches of trees in the middle of the link. The Rx routes as well as indoor Tx are on the third floor of the building, while the outdoor Tx is placed 2.5 m higher than the third floor level of the building.

B. Measurement Apparatus

The channel sounding was performed using a real-time multiple-input multiple-output (MIMO) sounder [9]. The sounder equips antenna arrays on both sides of the link. Planar and semi-spherical arrays were used at the outdoor and indoor Tx, respectively. Each antenna array comprises 16 dual-polarized patch antennas, leading to 32 feeds in total. A semi-spherical dual-polarized antenna array was also used for the Rx. Antenna arrays used in the measurement are summarized in Table I. It must be noted that the antenna arrays at Rx and indoor Tx were different due to availability reasons, which necessitated a special consideration on antenna arrays at the relay later. The height of the antenna arrays was 1.7 m above the floor. The Rx array was mounted on the receiver attached to a trolley. The trolley was manually moved to measure continuous routes. The channel sounder is capable of wideband measurement using a pseudo-noise sequence with a 60 MHz chip rate. The carrier frequency of the sounder is 5.3 GHz. The input power to the feeds of Tx antennas was approximately

TABLE I
ANTENNA ARRAY SPECIFICATIONS IN THE MIMO CHANNEL SOUNDING.

Measurements (Corresponding scenarios)	Antenna arrays
Outdoor Tx to indoor Rx (Source to relay/destination)	Tx: Planar dual-polarized array (45 deg slanted polarization) Rx: Semi-spherical dual-polarized array
Indoor Tx to indoor Rx (Relay to destination)	Tx, Rx: Semi-spherical dual-polarized array

37 dBm, which was high enough to ensure sufficient signal-to-noise ratio at the Rx routes.

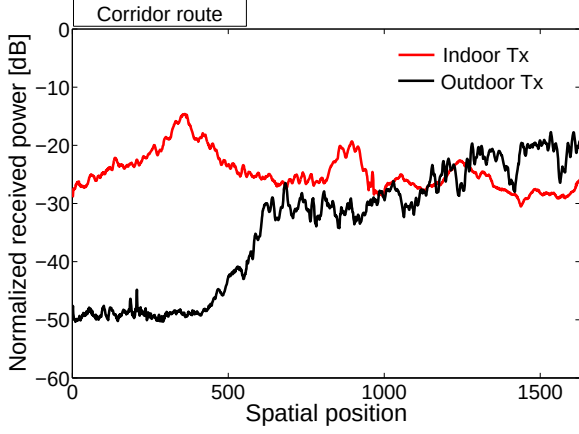
C. Application of Measurement Data for System Evaluation

It is always necessary to apply a set of data processing to utilize the measurement data for system analysis. Elimination of measurement noise is one of the most important procedures. Noise level was first estimated using a power delay profile (PDP) of links. PDP was calculated by an incoherent sum of single-input single-output (SISO) channel impulse responses comprising MIMO channels. Noise level estimation was done for each Rx position, since it can vary depending on Rx locations. A threshold level was then determined based on the estimated noise level. Amplitudes of the channel impulse responses were padded with zeros if the level was below the threshold level. The inverse Fourier transform was applied to the remaining signal components to derive the corresponding frequency transfer functions, followed by the deconvolution of the transmitted signal spectrum. Since the spectrum of the transmitted signal reveals a sinc function, signal strength is weak at band edges. Therefore, only 10 MHz in the middle of the band was used for the simulation out of 60 MHz total bandwidth. Samples of the transfer functions in 10 MHz are used to increase the number of independent data samples in fading statistics. Hence the following system evaluation is a narrowband analysis.

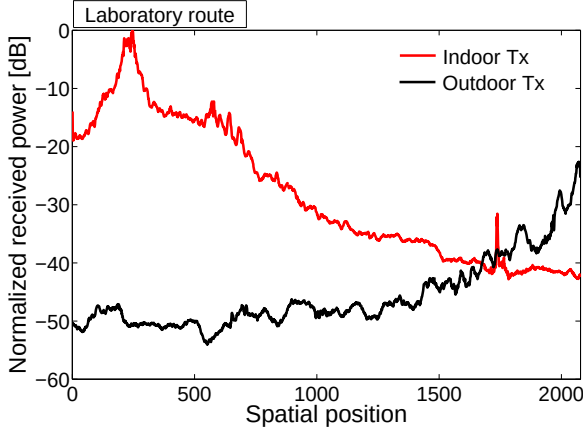
Another important aspect to consider is the relay antenna configuration in the channel sounding. As described in the previous subsection, the antenna configuration was different for the reception and transmission of signals at the relay. This means that antenna structure at the relay cannot be specified in our analysis. Therefore, it is decided that the antenna information is not exploited, but only the statistical distribution of transfer functions is derived from all the antennas, and then they are used for system evaluation. This means that MIMO antenna solutions are not possible at the relay, and hence all the terminal antennas are supposed to equip a single antenna or diversity antennas on either side of the link. 114300 samples of transfer functions were used to constitute the fading statistics for each Rx location.

D. Basic Propagation Parameters

Finally, key propagation parameters are shown as a reference for further discussions on system evaluation results.



(a)



(b)

Fig. 2. Normalized received power of the corridor and laboratory routes with outdoor and indoor Tx.

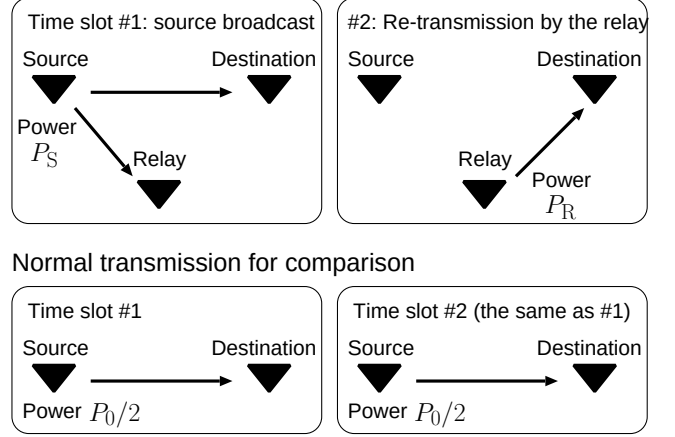
Figure 2 shows normalized wideband received power characteristics in the corridor and laboratory routes. The result revealed that the indoor Tx provided 30 dB higher power than the outdoor Tx if the Rx was near the indoor Tx. It is expected that signal forwarding via the indoor relay enhances link quality between outdoor BS and indoor Rx in these areas. The normalized wideband received power of the link between outdoor BS to indoor relay was -21 dB.

III. RELAY SYSTEM MODEL

A. Time Domain Half-Duplex

The time domain duplex was considered as a data transmission protocol in this analysis. A schematic representation of the protocol is illustrated in Fig. 3. The protocol consists of two consecutive time slots to deliver one data frame from the source to the destination. The source broadcasts signals to the relay and destination nodes in the first frame, followed by signal forwarding from the relay to the destination in the

Relay



* In the normal transmission, different data are sent in two time slots.

Fig. 3. Data transmission protocol with/without relay.

second frame. The source, relay, and destination correspond to the outdoor Tx, indoor Tx, and Rx in the measurement. The same frequency band is used for the two time frames, so they are orthogonal with each other in the time domain. The protocol is called a half-duplex transmission, since it needs twice the time resources to complete the data transmission when compared to the direct transmission. The transmitted power of the source and relay is defined as P_S and P_R , respectively. As a baseline for the comparison, a protocol of direct data transmission is also defined. It uses the first and second time slot for sending different data with the transmitted power of $P_0/2$. Total transmitted power for the consecutive two time slots are set such that $P_0 = P_S + P_R$ is fulfilled. Two types of signal forwarding schemes are considered at the relay: DF and AF relaying.

B. AF Relaying

The AF relaying transfers the received signal from the source to the destination after signal amplification. Let the transmitted signal from the source be s , and the k -th sample of the transfer function in the source-relay link be $a_{sr}(k)$. The received signal at the relay, $y_r(k)$, is then expressed as

$$y_r(k) = a_{sr}(k)s + n_r(k), \quad (1)$$

where $n_r(k)$ denotes complex additive white gaussian noise at the relay. $E[|s|^2] = P_S$, and $E[\cdot]$ denotes an operation of the ensemble average. The signal is amplified by a factor of β and transmitted to the destination. The received signal at the destination $y_d^{AF}(k)$ is

$$\begin{aligned} y_d^{AF}(k) &= \beta \left(a_{sr}(k)s + \sqrt{F}n_r(k) \right) a_{rd}(k) + n_d(k) \quad (2) \\ &\triangleq x_d^{AF}(k) + n_d^{AF}(k), \quad (3) \end{aligned}$$

where

$$x_d^{AF}(k) = \beta a_{sr}(k)a_{rd}(k)s \quad (4)$$

$$n_d^{AF}(k) = \beta \sqrt{F}a_{rd}(k)n_r(k) + n_d(k) \quad (5)$$

and furthermore, $a_{sr}(k)$, F , and $n_d(k)$ correspond to the k -th sample of the transfer functions in the relay-destination link, noise figure of an amplifier at the relay, and noise at the destination, respectively. The noise figure was set to 6 dB in this analysis. The amplification factor β is chosen such that the mean transmitted power from the relay is equivalent to P_R , namely,

$$P_R = \frac{1}{K} \sum_{k=1}^K \beta^2 |a_{sr}(k)|^2 P_S + F \sigma^2 \quad (6)$$

is fulfilled. K and σ^2 denote the number of data samples of transfer functions and noise power at the relay. Assuming the noise power at the relay and destination is the same as σ^2 , signal-to-noise ratio (SNR) $\gamma_d^{AF}(k)$ at the destination becomes

$$\gamma_d^{AF}(k) = \frac{\beta^2 |a_{sr}(k) a_{rd}(k)|^2}{\beta^2 F |a_{rd}(k)|^2 + 1} \cdot \frac{P_S}{\sigma^2}. \quad (7)$$

Hence the mean and outage end-to-end channel capacity, $\bar{C}$ and $\hat{C}$ are calculated in each location of Rx as¹

$$\bar{C}_d^{AF} = \frac{1}{2} \cdot \frac{1}{K} \sum_{k=1}^K C_k, \quad (8)$$

$$\hat{C}_d^{AF} = \frac{1}{2} \left(\arg \max_{\rho} \{ \Pr(\{C_k\}_{k=1}^K \leq \rho) \leq 0.1 \} \right), \quad (9)$$

$$C_k = \log_2 (1 + \gamma_d^{AF}(k)). \quad (10)$$

The outage capacity here is defined as lower 10% value in the fading statistics. The factor 1/2 in the channel capacity formula is due to the half-duplex transmission.

C. DF Relaying

The DF relaying transmits re-modulated and re-coded signals at the relay after detecting, decoding, and demodulating signals from the source. The end-to-end system performance of DF is mainly determined by the characteristics of a link with worse performance, and hence the channel capacity is expressed as

$$C_d^{DF} = \min \{ C_{sr}^{DF}, C_{rd}^{DF} \}, \quad (11)$$

where C_{sr}^{DF} and C_{rd}^{DF} are obtained by substituting SNR terms, $\gamma_{sr}^{DF}(k)$ and $\gamma_{rd}^{DF}(k)$, into equations (8) – (10). The SNR terms are given as

$$\gamma_{sr}^{DF}(k) = |a_{sr}(k)|^2 \frac{P_S}{\sigma^2}, \quad (12)$$

$$\gamma_{rd}^{DF}(k) = |a_{rd}(k)|^2 \frac{P_R}{\sigma^2}. \quad (13)$$

The channel capacity of the DF scheme is also halved due to the half-duplex transmission.

¹As mentioned in Section II-C, $K = 114300$ samples of the transfer function are available for each location of Rx.

D. Combining the Direct and Relay Links at the Destination

It is often the case that the direct link between the source and destination is available when they are not far apart from each other. Hence utilizing both direct and relay links at the destination increases the channel capacity. At the destination, signals arriving directly from the source in the first time slot are stored, and then signal combining for the direct and relay links are performed after the signal arrival from the relay node in the second time slot. Maximum-ratio combining (MRC) of direct and relay links is considered as the signal combining method. In the AF scheme, the received SNR at the destination after MRC is

$$\gamma_{MRC}^{AF}(k) = \frac{|a_{sd}(k)|^2 + \beta^2 |a_{sr}(k) a_{rd}(k)|^2}{\beta^2 F |a_{rd}(k)|^2 + 1} \cdot \frac{P_S}{\sigma^2}, \quad (14)$$

where $a_{sd}(k)$ denotes the transfer function of the source-destination link. The channel capacity is calculated using equations (8) – (10) with $\gamma_{MRC}^{AF}(k)$ substituted into the SNR term in Eq. (10).

In the DF relaying, diversity combining is performed for the source-destination and relay-destination links. The SNR at the destination is expressed as²

$$\gamma_{MRC}^{DF}(k) = \frac{|a_{sd}(k)|^2 P_S + |a_{rd}(k)|^2 P_R}{\sigma^2}. \quad (15)$$

Here the end-to-end system performance is dominated by the poorer quality of the source-relay and combined links,

$$C_d^{DF} = \min \{ C_{sr}^{DF}, C_{MRC}^{DF} \}, \quad (16)$$

where C_{MRC}^{DF} is obtained from equations (8) – (10) with the SNR term, $\gamma_{MRC}^{DF}(k)$.

E. Power Adaptation

As the channel capacity is dependent on the transmitting power at the source and relay, power allocation for them can be optimized under the total power constraint $P_0 = P_S + P_R$. Power allocation procedure was performed in a brute force manner: many combinations of P_S and P_R were tested, and a combination that maximized channel capacity was identified. P_R was set within a range of $(P_0 - 30)$ and $(P_0 - 1)$ dB with a 1 dB interval. Improvement of system performance was analyzed by comparing with equal power allocation, meaning that $P_S = P_R = P_0/2$ holds.

IV. RESULTS AND DISCUSSIONS

A. Channel Capacity of Relay Links

Figure 4 compares the channel capacity of the direct and relay links for the corridor and laboratory routes. The results are based on the equal power allocation for the BS and relay terminal. The results clearly show the following findings:

²This expression holds only if the relay re-encodes and re-modulates information from the source the same way as the source does.

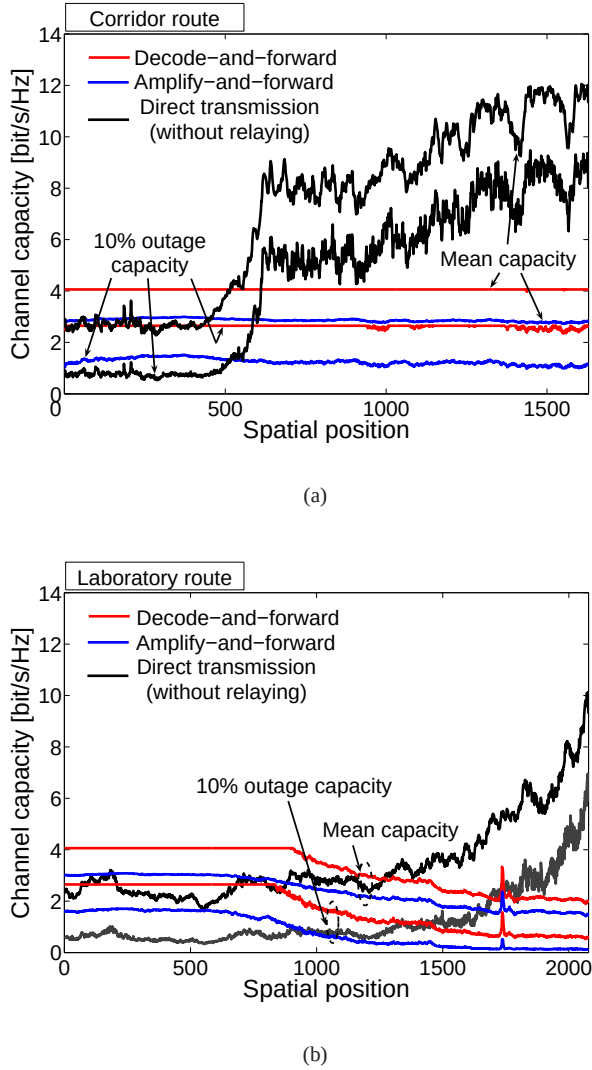


Fig. 4. Comparison of channel capacity for relay and direct links. Power adaptation is not considered. (a) corridor and (b) laboratory routes.

1) *The capacity values of relay links were higher than those of direct transmission when direct links were weak:* The relay link outperformed the direct link when the destination positions were near to the relay, and the direct link was weak. Spatial positions 0 to 1000 in the corridor route and 0 to 800 in the laboratory route are categorized as that area. The mean improvement of the mean channel capacity with the DF scheme was 1.3 and 0.6 bit/s/Hz for the corridor and laboratory routes, respectively. BS coverage extension was accomplished in those areas using the relay. In contrast, the capacity of direct transmission outperformed the relaying at destination positions 600 to 1600 in the corridor and 1800 to 2000 in the laboratory routes. According to the floor plan of the measurement site (Figure 1) and pathloss results (Figure 2), the direct link had slightly obstructed LOS for those destination positions, leading to comparable or stronger received power of the direct link than that of the relay-destination link. When

both direct and relay-destination links were weak such as in spatial positions 1000 to 1500 of the laboratory route, direct and relay links revealed comparable channel capacity values. The main reason that the relay did not improve the channel capacity relative to the direct transmission in those areas was the penalty of the half-duplex transmission. It halves the end-to-end throughput, but the relay transmission could recover the penalty by improving signal quality by diversity effects. It was found from the analysis that the improvement of link quality was not enough to compensate for the half-duplex transmission.

2) *Greater improvement was observed in the outage capacity rather than in the mean capacity:* It was found that the improvement of channel capacity was more visible in the 10% outage than in the mean capacity. In the corridor route with the DF scheme, the mean improvement of the outage and mean capacity was 1.8 and 1.3 bit/s/Hz. Furthermore, the number of spatial positions where the capacity improved relative to the direct link was larger in the outage than in the mean capacity. The improvement of the outage capacity is due to the inherent diversity effects of the relay transmission. It is less probable that the source-relay and relay-destination links suffer from fading dips simultaneously.

3) *DF outperformed AF in most destination positions when only relay link is considered:* Comparison of DF and AF performance revealed that the mean and outage capacity of DF were better than those of AF transmission. The worse performance in AF is due to the noise enhancement during the signal amplification at the relay. The mean performance differences between DF and AF were 1.3 and 0.9 bit/s/Hz for the corridor and laboratory routes, respectively. The difference was almost the same for the mean and outage capacity. As a result, AF revealed comparable or lower values of capacity relative to the direct link in most destination positions. It was also found that both DF and AF showed saturation of channel capacity when the destination was around the relay node. This is due to poor quality of the source-relay link, affecting as a bottleneck for the end-to-end system performance.

B. Channel Capacity of Combined Direct and Relay Links

Figure 5 illustrates the end-to-end channel capacity when the direct and relay links were combined at the destination. Power adaptation for the source and relay nodes was introduced, and the result was compared with the case where the equal power allocation was exploited. Results of the mean capacity are not shown in the figure, given the previous finding that they are less affected by the relay transmission than the 10% outage capacity. Capacity values of the direct link are overlaid in the figure as a reference. Results from the corridor and laboratory routes revealed the following findings:

1) *AF could outperform DF when the signal combining between the direct and relay links was considered:* In contrast to the previous observation, the performance of AF was better than DF in some spatial positions. The result is attributed to less signal attenuation in the source-destination link, leading to the increase of SNR at the destination. The observation is supported by the fact that the channel was almost LOS to

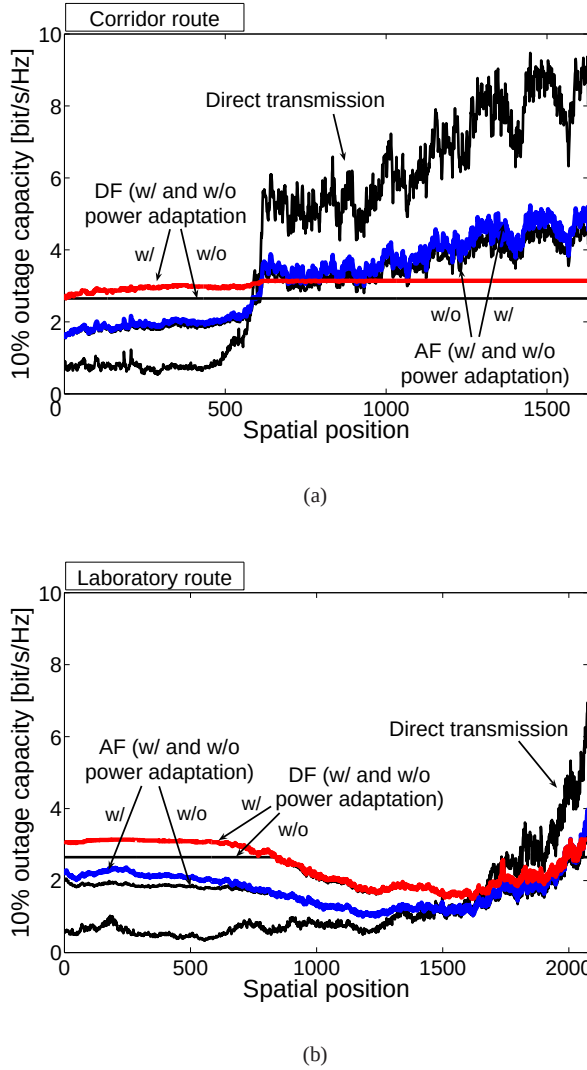


Fig. 5. Variation of 10% outage channel capacity with the signal combining of direct and relay links at the destination. Characteristics with and without power adaptation are compared. (a) corridor and (b) laboratory routes.

the outdoor BS in spatial positions between 600 and 1600 of the corridor route. The spatial positions between 1800 and 2000 of the laboratory route also revealed relatively large received power. The SNR improvement at the destination was also the case in the DF scheme. However, as the quality of the source-relay link was worse than that of combined source-destination and relay-destination links, the end-to-end capacity was mostly determined by the quality of source-relay link. Under this condition, improvement of the source-relay link is more important than ensuring better signal quality at the destination in order to enhance the end-to-end system performance.

2) *Power adaptation enhanced the system transmission capability:* Comparison of the channel capacity with and without power adaptation revealed that the power adaptation improved the channel capacity. Particularly, the effect of power

adaptation was visible in improving the saturation of channel capacity. In the DF scheme, the mean improvement of the outage capacity value was 0.4 bit/s/Hz for the corridor route. The power adaptation allocates more power to the source in order to improve the source-relay link, which was a bottleneck in the end-to-end channel capacity.

V. CONCLUDING REMARKS

Through the findings from measurement-based analyses of relay transmission, the following insights have been obtained: 1) introducing signal forwarding schemes in outdoor-to-indoor radio link extends the BS coverage around the relay terminal. Improvement by 1.5 bit/s/Hz is expected on average; 2) relay improves outage capacity better than mean capacity. About 1.5 times greater improvement is expected on average for the outage capacity relative to the mean capacity. This is due to the inherent diversity functionality of the relay transmission; 3) DF achieves twice the capacity improvement of AF on average when destination terminals are around relay nodes. On the other hand AF outperforms DF when the pathloss of direct links is not severe. It is essential in both signal forwarding schemes to improve the quality of source-relay link in order to avoid saturation of capacity; and finally, 4) power adaptation enhances the system performance, but the effect is minor. The power adaptation is useful in compensating the pathloss conditions, but even the equal power allocation can achieve moderate performance; their difference is 0.4 bit/s/Hz at most.

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