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Implementation and Evaluation of Reactive Base Station Selection for Human Blockage in mmWave Communications

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***Abstract*—This paper presents implementation of a reactive base station selection scheme for millimeter-wave (mmWave) communications. In mmWave communications, the frame loss rate increases and the throughput sharply decreases when a pedestrian blocks a line-of-sight (LOS) path. To alleviate this human blockage problem, base stations can be selected so as to maintain LOS paths on the basis of communication quality. In this paper, we build a testbed using off the shelf IEEE 802.11ad based wireless local area network (WLAN) devices, and implement a reactive base station selection scheme on the testbed. To the best of our knowledge, there is no existing work which experimentally evaluates human blockage detection system using actual IEEE 802.11ad devices. Our prototype system monitors the throughput measured at each base station and detects human blockage when the throughput decreases below a threshold. The human blockage detection triggers the base station switching. Our experimental results show that the reactive base station selection scheme decreases the duration in which human blockage degrades throughput performance, and the total amount of received data increases by 21%.**

I. INTRODUCTION

The bandwidth shortage caused by rapid increase of mobile data growth and the use of smartphones becomes increasingly prominent. To overcome the bandwidth shortage problem is a key issue of the next generation (5G) cellular networks and wireless local area networks (WLANs). Millimater wave (mmWave) communications using bands from 30 GHz to 300 GHz is expected to be a key enabler for solving the bandwidth shortage in 5G wireless networks [1], [2]. Fig. 1 shows a usage model of mmWave communications in cellular networks. Moreover, the highly directional antennas used in mmWave communication systems emit signal power on a certain direction, which can eliminate interference from other directions and thus provide for efficient use of frequency.

Attenation of received signal strength (RSS) caused when a human blocks a line of sight (LOS) path, called human blockage, is an open issue in mmWave communications. Human blockage averagely decreases RSS by 20 dB [3], [4]. In non-line-of-sight (NLOS) path situations, mmWave communication systems rely on the reception of multipath signals such as diffracted and reflected waves. However, because a diffraction loss of mmWave signals is more than 10 dB compared to direct waves [5] and the reflectance of a wooden or concrete wall is only 16% [6], the received signal power in NLOS communication is much lower than that of LOS in places with a large number of people passing through. Note that such serious blockages do not occur in microwave communications, which is extensively used by wireless access networks.

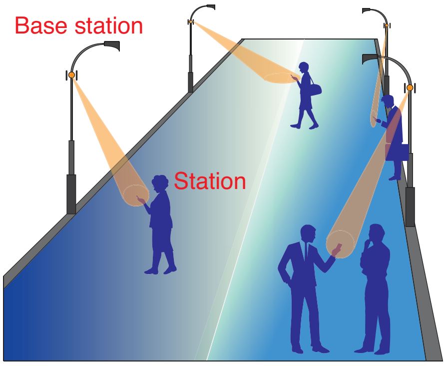


Fig. 1. Usage model of mmWave communications.

To alleviate the human blockage problem, many studies have assessed reactive communication control schemes based on monitoring quality factors such as the received signal strength indicator and the frame loss rate [7]–[10]. The reactive control scheme recovers the attenuation caused by human blockage through the use of a beamforming (BF) technology [6] and by activating a multihop relay system [7], [8] when a degradation of communication quality is detected. In [10], the author discussed and compared handoff algorithms to select suitable base stations intended for WLANs and cellular networks, and showed their usability in 60 GHz networks.

However, these studies were evaluated only through simulations and not tested in the actual environment. For example, in the IEEE 802.11ad technical standard [11] that uses a 60 GHz band, a pair of a base station and a station (STA) achieves the necessary directional multi-gigabit (DMG) link budget for subsequent communication by using a beamforming mechanism. The data transmission rate under IEEE 802.11ad is determined through the selection of the modulation and coding schemes (MCSs) adaptively on the basis of the physical channel state information. These mechanisms could affect the performance of reactive communication control schemes. Moreover, the reflection loss for the actual surface of the

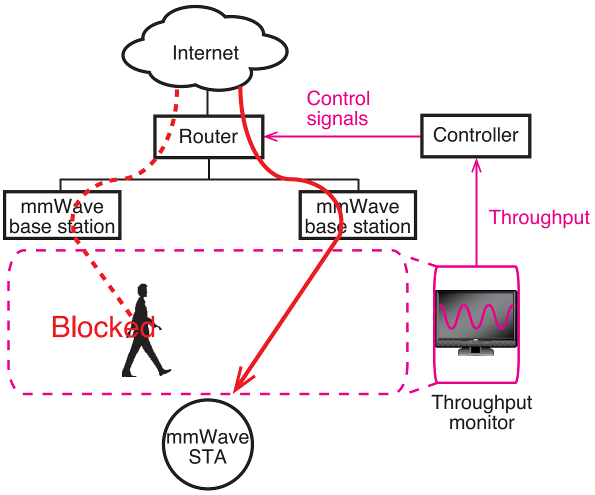


Fig. 2. System model of reactive base station selection.

building is larger than that of the ideal plain surface, because surfaces of a building are considered as an irregular surface at a wave length of the mmWave [12].

In this paper, we presents implementation of a reactive base station selection scheme. To demonstrate the feasibility of the proposed system, we built a testbed using IEEE 802.11ad-based WLAN devices for implementing the system. The experimental system measures throughput and detects a degradation of throughput when a pedestrian blocks a LOS path. On the basis of these information, the reactive base station scheme can switch base stations and thus reduce the duration in which human blockage degrades throughput performance. The experiments were conducted in an office and Transmission Control Protocol (TCP) was used for traffic transmission, which were similar to actual usage of mmWave access networks.

This paper is organized as follows. Section II proposes the reactive base station selection scheme based on the monitoring throughput system. Section III describes the setup of our experiments and the base station selection algorithm implemented in the experimental system. Section IV shows the experimental results and discusses the advantages of the proposed scheme. Concluding remarks are provided in Section V.

II. System Model

Fig. 2 shows system model. The system consists of five modules: a router, mmWave base stations, mmWave STAs, a throughput monitor, and a controller. The throughput monitor measures the throughputs of STAs and thus the controller instructs routers to change routes in order to switch base stations when human blockage is detected from the throughput information.

When a pedestrian blocks LOS path, the throughput sharply decreases. The throughput monitor detects this throughput degradation by measuring the throughput of each base station which is currently used. When human blockage is detected, the controller updates routing table and switches base stations, so that the duration where throughput is degraded by human blockage is reduced.

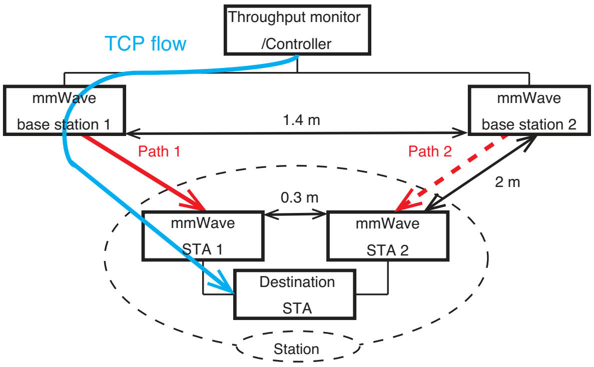


Fig. 3. TCP flow in prototype system.

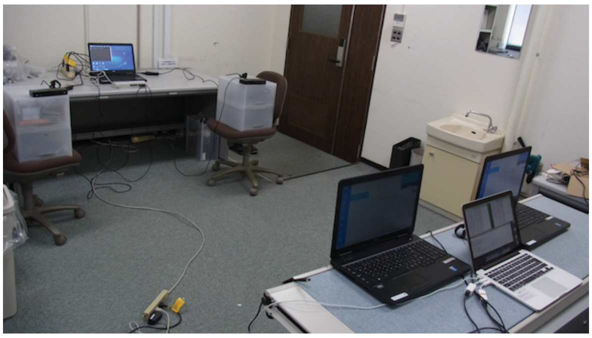


Fig. 4. Prototype system.

III. Prototype Implementation

In this section, we describe the setup of our experimental equipment and the implemented selection algorithm. In this paper, we implemented a simple base station selection scheme in order to confirm the feasibility of the reactive communication control experimentally.

A. Setup

Our prototype system is shown in Figs. 3 and 4. The functions of the throughput monitor and controller in Fig. 2 are implemented on a laptop (Dell Latitude E5540). The laptop, termed as throughput monitor/controller (T/C) node, measures throughputs and selects a base station on the basis of this measurement. Two Dell Latitude E5540 laptops are also used as mmWave STAs 1 and 2. Dell Wireless Dock D5000s serve as mmWave base stations 1 and 2, which are associated with mmWave STAs 1 and 2, respectively; put differently, there exist two paths, 1 and 2. An Apple MacBook Pro Retina acts as a destination STA. We send traffic data from the T/C node to the destination STA via mmWave base station 1 or 2. Specifications of the experimental equipment are shown in Table I.

In our experiment, the destination STA and mmWave STA 1 and 2 serve as one virtual STA, enabling the T/C node to

TABLE I
EXPERIMENTAL EQUIPMENT.

mmWave base station	Dell Wireless Dock D5000
Throughout monitor / Controller & mmWave STA	Dell Latitude E5540 (CPU: Intel Core i5, Memory: 4.00 GB)
Destination STA	Apple MacBook Pro Retina (CPU: Intel Core i7, Memory: 8.00 GB)
Wired Network	1000BASE-T Gigabit Ethernet
WLAN/Channel	IEEE 802.11ad/60.48 & 62.64 GHz

virtually select base stations by changing the destination IP address. The destination STA has two IP addresses, which are allocated respectively to LOS paths 1 and 2. The Latitude E5540 laptop used as a mmWave STA associates with only one wireless Dock D5000 mmWave base station at the same time and requires a few tens of seconds to disassociate with one base station and associate with another. To avoid the delay time caused by reassociation, the T/C node simply changes destination IP addresses to switch base stations used for the communications between the T/C node and the destination STA, allowing the mmWave base stations to be continuously associated with the mmWave STAs.

Gigabit Ethernet is used for the wired network, because the base station has only a 1000BASE-T Gigabit Ethernet port; thus, 1 Gbit/s is an upper limit of the throughput. The IEEE 802.11ad technical standard [11] is used for the WLANs. In the IEEE 802.11ad standard, a pair of a base station and a STA uses a BF mechanism to achieve the necessary DMG link budget for subsequent communication. A beamformed link is established through the successful completion of BF training; a bidirectional sequence of BF training frame transmissions that uses sector sweeping in order to provide the signal necessary to allow each STA to determine appropriate antenna system settings for both transmission and reception. The data transmission rate under IEEE 802.11ad is determined through the use of a set of MCSs that are selected automatically in accordance with the signal-to-interference plus noise ratio (SINR) and the frame loss rate. In our system, the data transmission rate varies from 385 to 4620 Mbit/s.

Downlink traffic is generated by Iperf [13] 2.0.52 at the T/C node. The destination STA measures received traffic using Wireshark [14] version 1.12.1. The throughput which is used for selecting base stations is measured within a given one second interval at the T/C node using Iperf.

B. Implemented Algorithm of Reactive Base Station Selection

Here, we implement a simple base station selection algorithm that switches base stations on the basis of measured throughput and a threshold. We assume that the locations of the base stations and an STA are known, that the LOS paths between them are also known, that at least one LOS path is always available, and that one of the destination IP addresses corresponds to a LOS path.

Fig. 5 shows a flowchart of the base station selection algorithm implemented on the T/C node. In the algorithm, the base stations are switched by changing destination IP address in accordance with throughput θ measured at the currently used base station, and if the throughput is smaller than a threshold θ_{T}, the base stations are changed. In the algorithm, first, the T/C node selects the IP address of a LOS path 1 and starts transmitting data to it. The node updates the value of measured throughput every update interval. As long as this exceeds the threshold θ_{T}, the node continues transmission via the current IP address; otherwise, the T/C node ceases transmission to the IP address and switches to another transmission address.

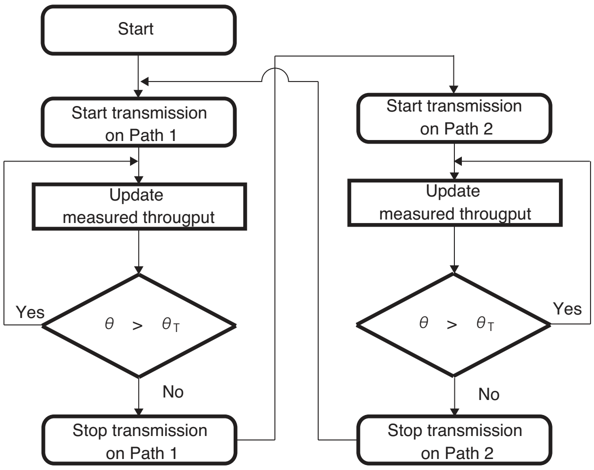


Fig. 5. Flow chart of reactive base station selection.

IV. EXPERIMENTATION

A. Scenario of Experiments

In our experiment, the T/C node transmits a TCP flow to the destination STA via path 1 or path 2. The direct distance between base station i and STA i is 2 m. Physical layer (PHY) rates of 2310, 3080, or 3850 Mbit/s were used for LOS communications, with the most-used PHY rate being 3080 Mbit/s. The distance between base stations 1 and 2 is 1.4 m and that between STAs 1 and 2 is 0.3 m. In order to avoid WLAN interference, 60.48 and 62.64 GHz channels are used, respectively, for paths 1 and 2.

In the experiment, the T/C node generates TCP data traffic, using Iperf to achieve a maximum throughput of 500 Mbit/s. Note that, although the system can achieve throughput higher than 900 Mbit/s, throughput can be decreased owing to increases in the traffic load and CPU load of the base stations and STAs, respectively. Therefore, we limit the throughput to 500 Mbit/s, where it is more stable than at the maximum throughput level.

Measurements are made over 50 s, during which a pedestrian blocks both paths twice. At time 0 s, the T/C node begins generating TCP traffic and base station 1 starts transmission on path 1. After that, during the period from 5 s to 15 s, a pedestrian blocks path 1. During the period from 15 s to 25 s, the pedestrian blocks path 2. During the periods 30 s to 40 s

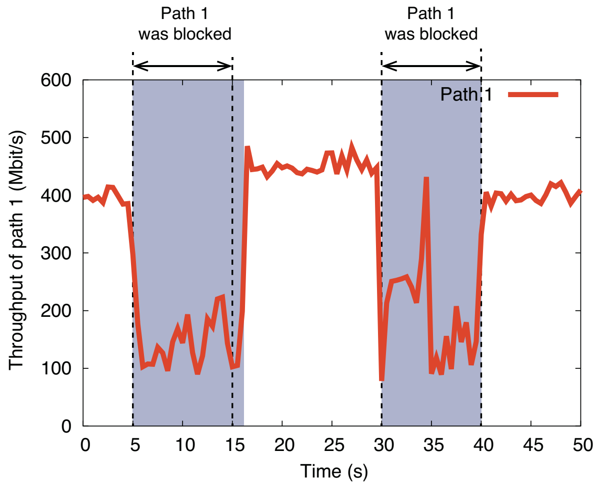


Fig. 6. Experimental results without base station selection.

and 40 s to 50 s, the pedestrian blocks LOS paths 1 and 2, respectively.

In the proposed algorithm, the threshold θ_T used for comparison with the decision index when switching base stations is set to 300 Mbit/s, as this is midway between the system throughput of 200 Mbit/s when the LOS path is blocked by a pedestrian and 400 Mbit/s when it is unblocked.

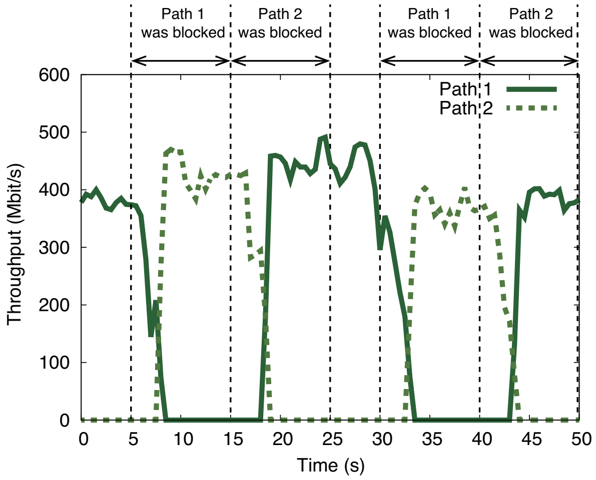
We also implement the experiment without the base station selection scheme and compare our proposed scheme with it; in this experiment, the T/C node transmits a TCP flow to the destination STA only via mmWave base station 1.

B. Experimental Results

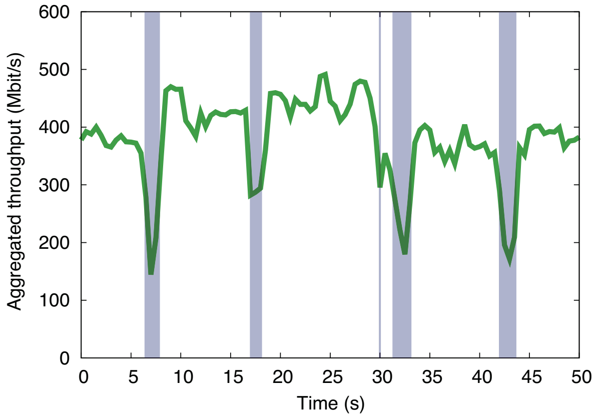
Fig. 6 shows the throughput of path 1 when the base station selection was disabled. The throughput was measured at 0.5 s intervals at the destination STA. When the path was not blocked, the throughput achieved more than 400 Mbit/s; when it was blocked by the pedestrian, the throughput decreased sharply. The shaded area represents periods when throughput was less than 300 Mbit/s.

Fig. 7(a) shows the throughput of each path when the reactive base station selection scheme was used. As seen in the figure, base station selecting was activated after the T/C node detected that the throughput had decreased to less than 300 Mbit/s owing to human blockage. Fig. 7(b) shows the aggregated throughput of the paths. Throughput degradation occurred four times, however, the length of time during which the throughput was degraded to less than 300 Mbit/s was much shorter than the corresponding time when without base station selection. These results indicate that the proposed scheme successfully reduces the duration of throughput degradation caused by human blockage.

Fig. 8 shows the cumulative distribution function of the aggregated throughputs. When without the base station selection scheme, throughput of less than 300 Mbit/s occurred about 42% of the time; on the other hand, when with the reactive base station scheme it accounted for only 15%. Compared



(a) Throughput of each path.



(b) Aggregated throughput of two paths.

Fig. 7. Experimental results with reactive base station selection.

with when the base station selection scheme was not used, our proposed scheme reduced the duration of time during which human blockage degraded throughput performance.

Fig. 9 shows the total amount of received data at the destination STA during the experiments. When without the base station selection scheme, the received data was decreased during the period from 5 s to 15 s and from 30 s to 40 s in which a pedestrian blocked path 1. On the other hand, since the reactive base station system reduced the duration of throughput degradation, the total amount of received data increased 21% compared to the system without base station selection.

V. CONCLUSION

This paper presented implementation of the reactive base station selection scheme based on throughput measurement for reducing the duration of throughput degradation caused by human blockage in mmWave communications. The proposed scheme detected the human blockage from measuring throughput degradation and selected suitable base stations. To implement the proposed scheme, we built a testbed using IEEE 802.11ad-based WLAN devices. Our experimental re-

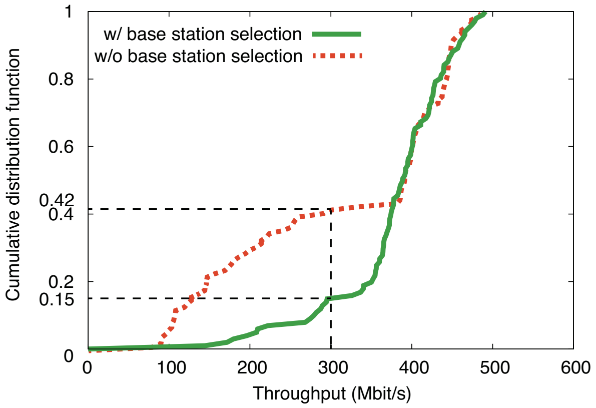


Fig. 8. Cumulative distribution function of aggregated throughput.

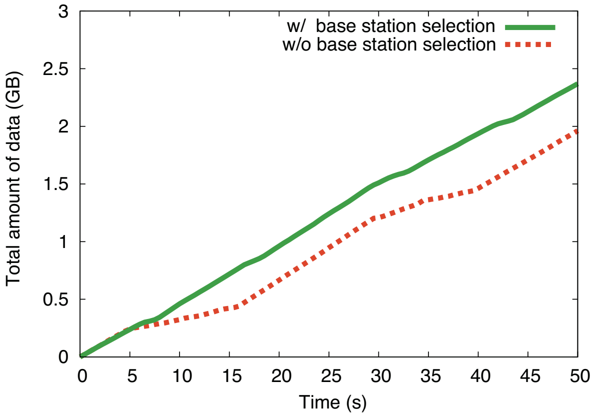


Fig. 9. Total amount of received data.

sults confirmed that our proposed scheme significantly reduced the length of time during which human blockage degraded throughput performance, and the total amount of received data increased by 21% compared to the case where the base station selection was disabled.

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