A Cross-Layer Design for a Software-Defined Millimeter-Wave Mobile Broadband System

Yong Niu, Yong Li, Min Chen, Depeng Jin, and Sheng Chen

Aiming to overcome the challenging problems in mmWave networks, such as interference management, spatial reuse, anti-blockage, QoS guarantee, and load balancing, we architecturally borrow the ideas of heterogeneous cloud radio access networks and software-defined networking to propose a software-defined mmWave mobile broadband system via a cross-layer design approach.

Abstract

Heterogeneous networks, which deploy small cells in the mmWave band underlying the macrocell network, have attracted intense interest from both academia and industry. Different from the communication systems using lower carrier frequencies, mmWave communications have unique features, such as high propagation loss, directional communications, and sensitivity to blockage. Aiming to overcome the challenging problems in mmWave networks, such as interference management, spatial reuse, anti-blockage, QoS guarantee, and load balancing, we architecturally borrow the ideas of heterogeneous cloud radio access networks and software-defined networking to propose a software-defined mmWave mobile broadband system via a cross-layer design approach. In this architecture, a centralized controller is introduced by abstracting the control functions from the network layer to the physical layer. Through quantitative simulations in a realistic indoor scenario, we demonstrate the performance advantages of our system in terms of network throughput and flow throughput. This work is the first cross-layer and software-defined design for mmWave communications, which opens up an opportunity for mmWave communications to make a significant impact on future 5G networks.

Introduction

With explosive growth of mobile traffic, heterogeneous networks (HetNets) with small cells deployed underlying the conventional homogeneous macrocell network have attracted intense interest from both academia and industry [1]. Since the spatial reuse gain of deploying small cells in the carrier frequencies employed in today's cellular systems is fundamentally limited by interference constraints [2], there is increasing interest in deploying small cells in higher frequency bands, such as the millimeter-wave (mmWave) bands, to significantly boost the network capacity of HetNets. With huge bandwidth, small cells in the mmWave band are able to provide multiple gigabits per second transmission rate for a large number of wireless multimedia services such as uncompressed high definition television (HDTV), high-speed data transfer between devices, wireless gigabit Ethernet, and wireless gaming. Moreover, recent developments in transceiver components design have paved the way to practically and economically utilizing the mmWave band, and several standards on mmWave networks have been or are being defined to achieve multi-gigabit rates, for example, IEEE 802.15.3c [3] and IEEE 802.11ad [4].

There are some fundamental differences between mmWave communications and existing communication systems using lower carrier frequencies (e.g., from 900 MHz to 5 GHz). Due to the huge propagation loss, mmWave communications are range-limited and only suitable for local-range communications [5]. Consequently, the most likely scenarios for deploying mm Wave wireless personal area networks (WPANs) are conference rooms, living rooms, and enterprise cubicles [4]. On one hand, in order to overcome huge attenuation, beamforming (BF) has been adopted as an essential technique, and mmWave links are inherently directional [6]. With directional listening and transmitting, third party nodes cannot hear current transmissions, and carrier sensing is disabled, which is referred to as the famous deafness problem. On the other hand, mmWave links are vulnerable to blockage due to their weak ability to diffract around obstacles such as furniture and human bodies. Blockage by a human body penalizes the link budget by about 20 to 30 dB [5].

Due to the rapid growth of mobile data demands as well as to overcome the limited range of mmWave communications, in a practical mmWave mobile broadband system, the number of access points (APs) deployed over both public and private areas increases tremendously. For example, APs must be deployed densely in scenarios such as enterprise cubicles and conference rooms to provide seamless coverage. With APs densely deployed in indoor environments, interference among neighboring basic service sets (BSSs) cannot be neglected, and should be managed efficiently to maximize concurrent transmissions (spatial reuse) [7]. On the other hand, with multiple APs deployed, multi-AP diversity can also be utilized to overcome the blockage problem [8]. With the small coverage area of each AP, user mobility will cause significant load fluctuations in each BSS. Consequently, handover, user association, and resource allocation have to be managed efficiently at each AP in concert

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with other neighboring APs in order to achieve the desired goals such as mobility management and load balancing.

Clearly, coordination among APs must be explicitly considered in the design of mmWave mobile broadband systems. In traditional wireless networks, distributed coordination is usually exploited. Distributed coordination among APs, however, does not scale well [9], and the latency will increase significantly with the number of APs, which is unsuitable for mmWave communication systems where a time slot only lasts for a few microseconds. Moreover, with distributed coordination it is difficult to achieve the intelligent control mechanisms required for complex operational environments that involve dynamic behavior of accessing users and temporal variations of the communication links. Thus, the traditional distributed network control mechanism may not be suitable for mmWave mobile broadband systems, and it is important and urgent to design a new paradigm at the architecture and system level for mmWave communication systems.

Heterogeneous cloud radio access networks (H-CRANs), as a new paradigm for improving both spectral efficiency and energy efficiency, suppress inter-tier interference and enhance the cooperative processing capabilities through combination with cloud computing [10, 11]. On the other hand, software-defined networking (SDN) advocates separating the control plane and data plane, and abstracting the control functions of the network into a logically centralized controller [9].

In this article, we architecturally borrow the ideas of H-CRANs and SDN to propose a software-defined mmWave mobile broadband system via a cross-layer design approach. In this architecture, we extend the original concept of SDN control by taking the functions of the physical layer into consideration as well, not just those of the network layer. Specifically, by abstracting the control functions of both layers, a logically centralized programmable control plane oriented toward both the network and physical layers is introduced, through which we achieve the fine-grained control and flexible programmability of the system. The interfaces between the control plane and data plane are also defined to facilitate cross-layer control of the control plane. With the characteristics of mmWave communications considered, we overcome the challenging problems in the system such as interference management, spatial reuse, anti-blockage, QoS guarantee, and load balancing, by centralized and cross-layer control. To the best of our knowledge, we are the first to propose a software-defined mobile broadband system for mmWave communications via a cross-layer design approach. This software-defined and cross-layer design opens up an opportunity for mmWave communications to make a significant impact on fifth generation (5G) networks.

The article is structured as follows. We first present a typical indoor scenario of the mmWave mobile broadband system. After offering the system design goal and principle, we present the proposed cross-layer software defined mmWave mobile broadband system, and analyze its open problems and challenges. Then we show the advantages of the centralized control and cross-layer design through a typical application scenario for anti-blockage. Finally, we analyze how much gain we can achieve by leveraging such a cross-layer software-defined design by quantitative simulations.

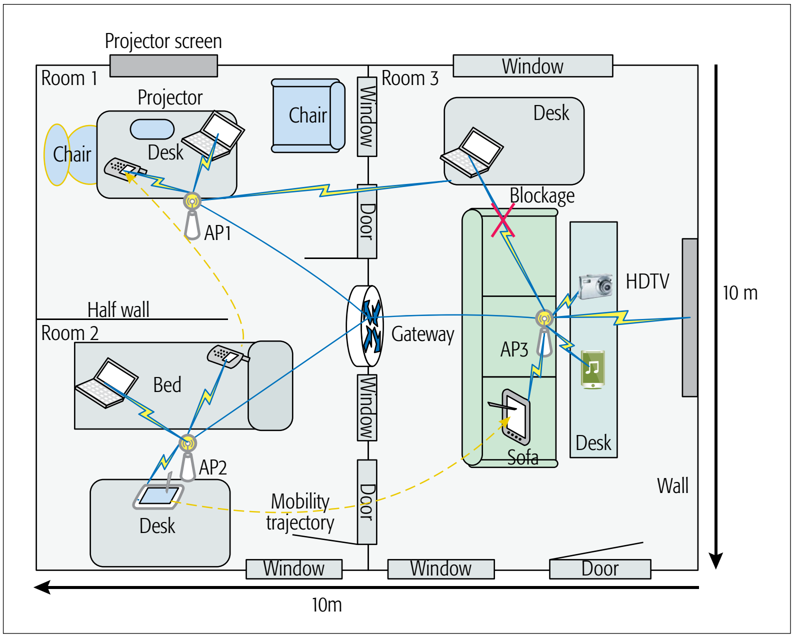

Figure 1. A typical indoor application scenario of the software-defined mmWave mobile broadband system.

System Overview

Typical Indoor Scenarios

As stated in the introduction, the most foreseeable applications for mmWave communications are in the indoor environment. Figure 1 depicts a typical indoor scenario of an mmWave mobile broadband system, where three APs are deployed in the rooms, and they are connected to the gateway via fiber. In this environment, the accessing devices are naturally mobile, the movement trajectories of which are illustrated as yellow dashed lines. In room 3, the line of sight (LOS) path between AP3 and the laptop is blocked by the sofa.

Design Goals

Before presenting the proposed system, we first summarize the design goals for the envisaged software-defined mmWave mobile broadband system.

Interference Management and Spatial Reuse: In mmWave WPANs, directional transmissions enable less interference between links. However, due to the limited communication range, the interference between links cannot be neglected. The interference in an mmWave broadband system can be divided into two portions: interference within each BSS and interference among different BSSs. To enhance network capacity, the interference should be efficiently managed, and concurrent transmissions should be supported among different BSSs as well as within each BSS by global effective interference management and efficient concurrent transmission scheduling.

Robust Network Connectivity: To overcome

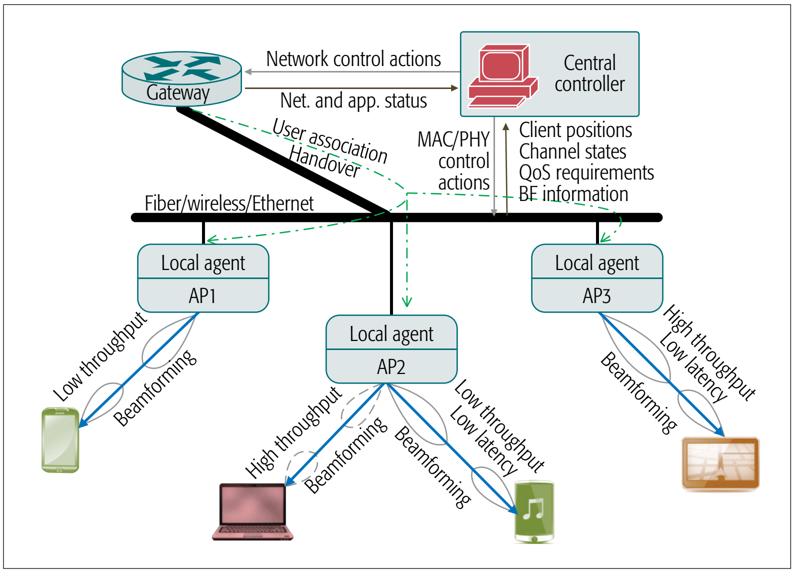

Figure 2. Overview of our proposed architecture for the software-defined mmWave mobile broadband system.

the blockage problem, robust network connectivity should be provided in a cross-layer manner to ensure good user experience. Beam switching to exploit non-LOS (NLOS) transmissions can be applied in the physical layer. Besides, relaying and multihop transmissions in the medium access control (MAC) layer can also be applied. With multiple APs deployed, for devices in the overlapping regions of BSSs, performing handovers in the network layer is also an effective way to overcome blockage through cooperation between APs.

Optimized Load Balance: With a small coverage area, user mobility will cause significant load fluctuations within each BSS. Thus, user association and handovers between APs should be carried out to achieve an optimized load balance through global and intelligent control of all APs in the system.

Flexible QoS Guarantee: The software-defined mmWave broadband system should provide cross-layer QoS guarantees for different kinds of traffic in terms of latency, throughput, and connection reliability. In the physical layer, selection of modulation and coding schemes (MCSs) should be applied to meet different throughput requirements. In the MAC layer, scheduling of flows should be applied to meet the QoS requirement of each flow. In the network layer, handovers between APs should also be performed to ensure the QoS of each flow.

System Architecture

Architecture Overview

In order to achieve the above design goals, we propose a cross-layer software-defined architecture for the mmWave mobile broadband system, as illustrated in Fig. 2. In this architecture, the control functionalities from the physical layer to the network layer are incorporated in a centralized controller. The controller in our architecture encapsulates all the control logic functionality of the network, while the data plane consists of forwarding and wireless communication devices, such as APs and gateway. The controller has two components: the central controller and local agents. The central controller usually resides on the gateway, makes the rules, and controls the behavior of the gateway and APs from a global perspective. Due to the inherent delay between the central controller and each AP [10], there is a local agent residing on each AP to adapt to the rapidly varying network states. The central controller and APs can be connected via wireless, fiber, Ethernet, or any form of backhaul links, which should have short delay to ensure the real-time control of the central controller. To achieve efficient control from the network layer to the physical layer, the measurement interface and control interface between the controller and each data plane device are defined in our architecture. Through the measurement interface, network and application statuses, client positions, channel states, and other state parameters are reported to the controller periodically. On the other hand, through the control interface, control flows in the network layer, MAC layer, and physical layer are resolved and translated to the actions of APs and the gateway.

Interface

The interface between the controller and data plane devices consists of:
- The measurement interface from the data plane devices to the controller
- The control interface from the controller to the data plane devices

Measurement Interface: Through the measurement interface, the controller obtains the local and global network states and application information from each AP and the gateway. Typical state parameters include client positions, channel states of links, BF information of clients, QoS requirements of flows, the number of clients under each AP, and so on. The data plane devices periodically report the state parameters to the controller, which then dynamically updates its local and global network views.

Control Interface: The control interface for the data plane devices resolves the control flows from the controller and translates the control decisions to the actions of each AP or the gateway in the network layer, MAC layer, and physical layer. The control interface adopts the "match-action" strategy, and the control strategies for the network layer and physical layer are quite different.

Network Layer Interface: Handovers, user association, and resource allocation are performed through the control interface in the network layer. For example, forwarding packets from the gateway to the APs is controlled through this interface. Concurrent transmission schedules are also pushed to each AP through this control interface. The control interface operates on a table indexed by "Flow ID". Flow ID is identified based on the function fields in the packet header, such as IP address and MAC address. Specifically, when the gateway receives a packet, it first checks whether this flow matches its control rules. If so, the gateway will execute the corresponding actions. For example, **if** dest IP = xx.xx.xx.xx, **then** forward to AP1.

Physical Layer Interface: The selection of

MCSs according to the channel conditions and traffic patterns, transmission power control, and BF between paired devices are completed through the control interface in the physical layer. Although the physical layer control interface also operates on a table, the match fields, rules, and actions are quite different from those of the network layer control interface. Specifically, when an AP transmits a packet to a client, it first checks whether this flow matches its control rules. If so, the AP executes the corresponding actions. For example, **if** slot = xx and dest IP = xx.xx.xx.xx, **then** direct the beam toward client 2 and transmit at 2 Gb/s.

Controller

Centralized Controller: The central controller controls the data plane devices from the global perspective based on the up-to-date network states obtained via the measurement interface. Given the network states, the controller maintains and updates a global network state database, to which we refer as the "mmWave information center" (MIC). The MIC consists of the following elements.

- **Interference Graph:** A weighted and directional graph where each vertex represents one link, and the weight of each arc is the interference level between the two links. The interference level may be the interference power or other parameters to indicate the interference strength, such as the distance between the transmitter of one link and the receiver of another link, and a binary variable to indicate whether the transmitter of one link is inside the exclusive region (ER) of the receiver of another link [12]. The interference graph can be obtained according to the network state parameters from the measurement interface, such as client positions, BF information of clients, and other physical layer parameters, for example, transmission power, path loss exponent, and the cross-correlation between two links.
- **QoS Graph:** A weighted and directional graph where each vertex represents a client or an AP in the network. The weight of each arc is the QoS requirements of each flow, such as throughput, latency, and connection reliability. The QoS graph can be obtained directly through the measurement interface.
- **Link Quality Graph:** A weighted and directional graph where each vertex represents a client or an AP in the network. The weight of each arc indicates the link quality, which may be the received signal strength at the receiver, the transmission rate that the link can support, or the frequency of the link outage. The link quality graph can be obtained from the transmission rate measurements of the links directly, or inferred from the network state parameters such as client positions and the number of link outages.
- **Flow Statistics:** These are the statistics of the ongoing flows, for example, the number of transmitted packets, the number of queued packets, and the number of flows under each AP.

Based on the MIC, the central controller can achieve effective and efficient radio resource allocation. For example, based on the interference graph, QoS graph, and link quality graph, efficient concurrent scheduling algorithms can be implemented in the central controller to maximize spatial reuse, while effective interference management can be achieved based on the interference graph. Based on the link quality graph and the flow statistics, smoother handovers, and reduced dropped connections and ping-pong can be accomplished. The central controller can also achieve efficient load balancing based on the link quality graph and the flow statistics.

With more APs and users in the system, the workload of the central controller is getting heavy. To address this issue, the central controller in our system can be implemented via a vertical approach with multiple controllers incorporated [14]. The central controller consists of multiple local controllers and one root controller. Each local controller is responsible for managing some APs and users, and the root controller is responsible for coordinating multiple local controllers for global management and control. In this way, more APs and users can be managed by the central controller, and more complete and optimized control functions can be encapsulated in the central controller.

Local Agent: To alleviate the inherent delay from the central controller to each AP, a local agent is deployed at each AP to adapt rapidly to the varying channel conditions and traffic patterns. Since the central controller makes control decisions based on the delayed state information compared to the local agent, the control decisions from the local agent are more timely. When the control decisions from the central controller conflict with those from the local agent, the control decisions from the local agent will be adopted by the control interface. Due to lower complexity of the local agent, the local agent is mainly in charge of delay-sensitive control functions. For example, beam switching to exploit NLOS transmissions in case of sudden blockage is handled at the local agent. The local agent also selects the appropriate MCSs according to the fast varying channel conditions.

Control Overhead

The control overhead in the system mainly consists of three parts: the network state information measurement through the measurement interface, the control decision computation of the control plane, and the control flow forwarding from the control plane to the data plane.

Initially, complete network state information measurements are performed to establish the MIC. With relatively low user mobility, the network states do not change all the time, and remain unchanged for a period. Thus, each kind of measurement is performed periodically to track the variations in the network state. The network state measurements within each BSS are managed by each AP, and the measurements among BSSs are performed via the cooperation of APs under the control of the central controller. Then the network state information is sent to the central controller from the APs via the backhaul links. With the gigabit-per-second transmission rate, this process can be completed quickly. At the same time, to limit the complexity and avoid excessive overhead, some state information cannot be obtained in practice. In this case, some compensation information can be obtained

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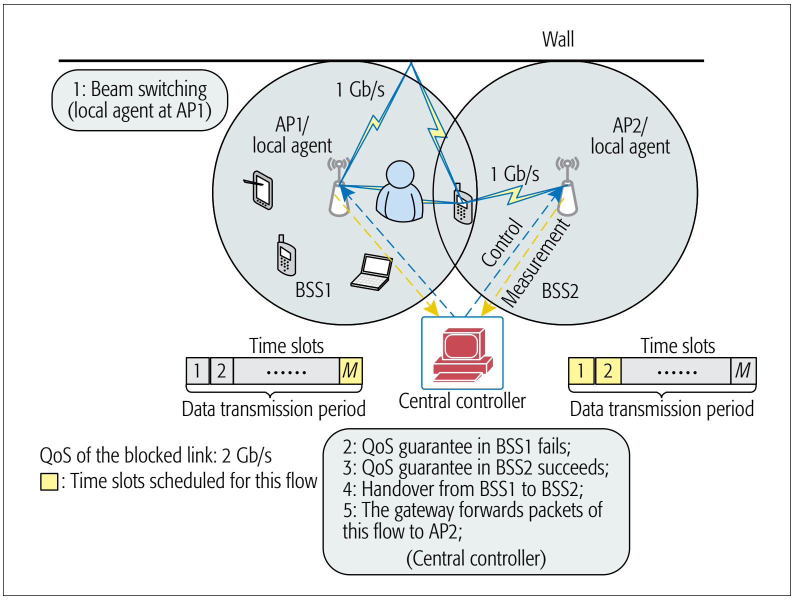

Figure 3. An example of overcoming blockage in the software-defined mmWave mobile broadband system.

instead to estimate the required information. The overhead in the control decision computation of the control plane depends on the efficiency of the algorithms employed in the central controller. Therefore, efficient and effective control algorithms are needed to reduce the control overhead and also achieve good performance. After the control decisions are obtained, the control flows are forwarded from the central controller to the APs via the backhaul links. Then the control flows are distributed by the APs to users within the BSSs. With the gigabit-per-second transmission rate, this process can also be completed in a short time.

Open Problems and Challenges

Measurements

In order for the central controller to obtain an accurate and comprehensive global view of the network, efficient measurement mechanisms are needed. There is already some work addressing this critical issue. For example, a bootstrapping scheme can be executed to obtain up-to-date network topology and node location information [14], while a BF information table that records all the beamforming training results among clients can be established at the AP [15]. However, most of the current work focuses on the network state measurement within a BSS. For clients in the overlapped region of two BSSs, the link quality information and BF information between the clients and the neighboring APs are also required for tasks such as handover and interference management. Since concurrent transmissions should be enabled among different BSSs as well as within each BSS, the interference caused by concurrent transmissions, especially among different BSSs, must be estimated as accurate as possible. On the other hand, with the dynamics due to user mobility considered, the measurement algorithms should be able to track the variations in the network states in as little time as possible to reduce overhead. Therefore, efficient measurement algorithms are open problems that need to be extensively investigated to facilitate the deployment of such an mmWave mobile broadband system.

Algorithms Employed in the Centralized Controller

To achieve the design goals, effective and efficient algorithms for transmission scheduling, load balancing, BF, anti-blockage, and power control are needed. Although there are many works on MAC protocols or scheduling algorithms for mmWave WPANs, most works focus on the scenario of a BSS [7] and do not consider the interference among different BSSs. Also, there are several approaches to overcome blockage, such as beam switching from an LOS path to an NLOS path, relaying [5], and multi-AP diversity [8]. In [8], multiple APs are deployed, and when the link between a client and an AP is blocked, another AP is selected to complete the remaining transmission task. For transmissions between clients, beam switching to an NLOS path is usually a good choice. In some cases, however, the NLOS path is difficult to find, or for high-rate applications, the transmission rate supported by the NLOS path cannot meet the throughput requirement. In this case, relaying is an effective way to overcome blockage and even to improve the throughput [5]. Therefore, every approach has its advantages and shortcomings, and is only efficient in certain circumstances. With global and cross-layer control over the data plane devices, how to combine these approaches and apply them appropriately to ensure robust network connectivity and improve network performance remains an open problem that warrants further investigation.

Dealing with Erroneous State Information

Due to the complexity of the indoor environment and the inherent delay between the central controller and APs, there may be deviation and error in the obtained network state information. In this case, control decisions based on erroneous state information also have deviation and error. Therefore, for some error-sensitive decisions, there should be mechanisms in the centralized algorithms for the central controller to correct errors in the control decisions. After a control decision is made based on some state information, the related network states should be monitored. When the network states do not match the control decision, the central controller should adjust the control decision accordingly, and also re-measure the previous network states the control decision on which was based. Besides, the algorithms in the central controller should be tolerant of the deviation in the state information to some extent to avoid significant degradation in performance.

Application Scenarios

In this section, we present an example where beam switching and handovers are combined to overcome blockage in our proposed software-defined mmWave mobile broadband system.

As illustrated in Fig. 3, a blockage occurs suddenly between AP1 and a mobile phone. In BSS1, this downlink flow is scheduled to transmit in the Mth time slot of the data transmission period. First, to ensure continuous connection, the local agent will command AP1 to switch its antenna

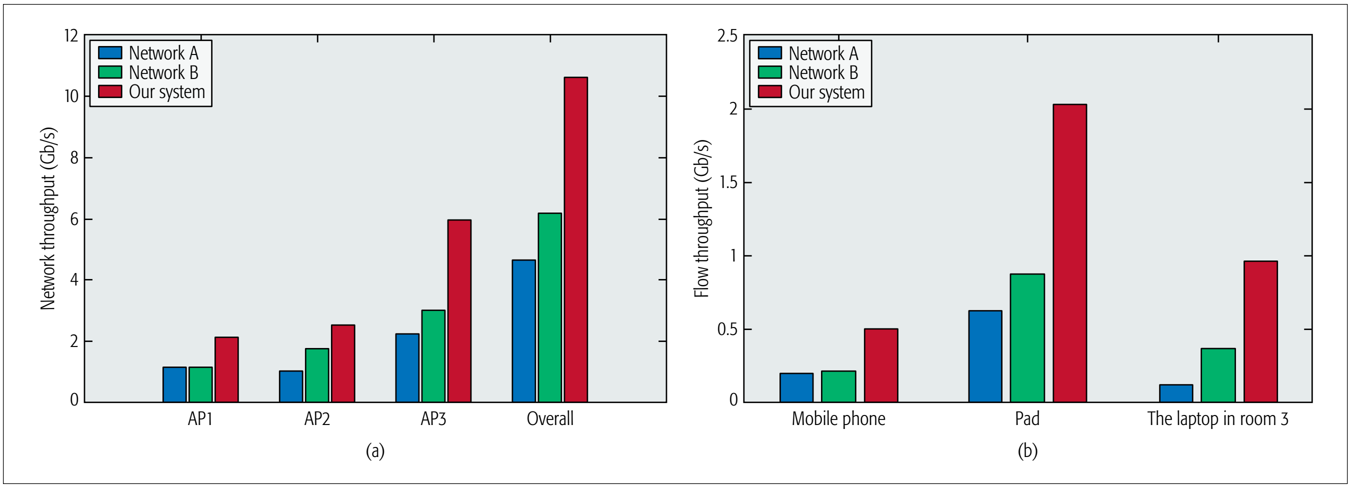

Figure 4. The network throughput and flow throughput comparison between our architecture and traditional networks: a) network throughput comparison; b) flow throughput comparison.

toward the wall to exploit the NLOS path for transmission temporarily without severe interference to current transmissions. At the same time, AP1 reports the blockage to the central controller through the measurement interface. The NLOS path has additional path losses and can only support a throughput of 1 Gb/s, while the QoS requirement (throughput) of this flow is 2 Gb/s. After the blockage has been reported to the central controller, to meet the QoS requirement of this flow, the central controller executes two actions. The first action is to check whether it is possible to schedule more time slots to this flow to meet its QoS requirement. Due to the heavy loads in BSS1, there is no additional time slot for this flow. Then the central controller executes the second action, which is to check whether there is an LOS path between the client and a neighboring AP. The central controller finds that there is one LOS path between the mobile phone and AP2, and the path can also support a throughput of 1 Gb/s if one time slot is scheduled for this flow. At the same time, the central controller finds that currently there is no client under AP2, and there are enough time slots in BSS2 to meet the QoS requirement of this flow. Thus, the central controller issues the instructions to AP1 and AP2 to perform the handover of the mobile phone through the control interface. After the handover, the packets of this flow are forwarded from the gateway to AP2, and in BSS2, time slots 1 and 2 are scheduled to this flow.

Performance Evaluation

We adopt a realistic network deployment to quantitatively evaluate the enhancement achieved by utilizing the software-defined cross-layer architecture for the mmWave mobile broadband system.

Targeted System

In the simulation, we target the scenario shown in Fig. 1. We adopt the superframe structure in IEEE 802.15.3c, where a superframe consists of the beacon period (BP), the contention access period (CAP), and the channel time allocation period (CTAP). There are at most 1000 time slots in CTAP, and time-division multiple access (TDMA) is adopted in CTAP. The duration of BP, CAP, CTAP, and each time slot is the same as that in [7]. A superframe is scheduled at each AP every 0.02 s, and the simulation time is 20 s. The network state information from each AP and the gateway is fed back to the control plane through the measurement interface during the intervals between superframes. The control flows from the control plane are also distributed to each AP and the gateway through the control interface during the intervals between superframes.

In the simulation, we compare our software-defined system with two traditional networks, denoted as *network A* and *network B*. In our system, an anti-blockage mechanism that combines beam switching and handovers between APs intelligently is applied. Besides, the selection of MCSs is achieved at both the local agent and the central controller according to the channel conditions, and the interference among BSSs is managed at the central controller. In contrast, no mechanism is adopted by *network A* to overcome blockage, while beam switching to exploit the NLOS path is applied by *network B*.

Results Analysis

We first compare the network throughput achieved by the two traditional networks to that obtained by our system. The throughputs attained by AP1, AP2, and AP3 as well as the overall network throughput are shown in Fig. 4a. We observe that our system increases the throughputs of AP1, AP2, and AP3 as well as the overall network significantly, compared to the two traditional networks. Our system improves the overall network throughput by about 128 percent compared to *network A*. Due to different traffic loads in different rooms, the increases of throughput achieved in different rooms are different. The increase achieved by AP1 is mainly due to the fact that in our network, when the blockage occurs in room 3, the local agent first exploits beam switching quickly to maintain connection, and then the central controller issues instructions to AP3 and AP1 to perform the handover of the laptop to achieve a high transmission rate. In the traditional networks, however, such beneficial handover

Motivated by the ideas of H-CRAN and SDN, we have proposed a software-defined mmWave mobile broadband system, which achieves intelligent and global control of the mobile network from the physical to network layer by a centralized controller.

will not happen due to the lack of cooperation between APs.

To evaluate the throughput enhancement for each flow achieved by our system, we also present the throughputs of three downlink flows to the mobile phone, the pad, and the laptop in room 3 in Fig. 4b. We can observe that our system improves the flow throughputs of devices significantly. Specifically, our system increases the throughput of the flow to the laptop in room 3 by about 162 percent compared to *network B*, and about 670 percent compared to *network A*, which is mainly due to the combined action of beam switching and the smooth handover between AP3 and AP1 to overcome blockage. Besides, the channel transmission rates in our system can be adapted to the varying channel conditions by the selection of MCSs more quickly compared to the traditional networks.

Conclusions

Motivated by the ideas of H-CRANs and SDN, we have proposed a software-defined mmWave mobile broadband system, which achieves intelligent and global control of the mobile network from the physical to the network layer by a centralized controller. We have also discussed its open problems and challenges, and quantitatively evaluated its performance advantages by simulations targeting a realistic system. This study thus provides a novel design for mmWave communications, and it opens up a new research direction for mmWave communications to make a significant impact on 5G mobile broadband.

Acknowledgment

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References

[1] J. Lee *et al.*, *Physical Commun.*, Special Issue on Heterogeneous and Small Cell Networks, 2014.

[2] K. Zheng *et al.*, "Energy-Efficient Wireless In-Home: The Need for Interference-Controlled Femtocells," *IEEE Wireless Commun.*, vol. 18, no. 6, 2011, pp. 36–44.

[3] IEEE 802.15 WPAN Millimeter Wave Alternative PHY Task Group 3c (TG3c); http://www.ieee802. org/15/pub/TG3c.html.

[4] IEEE P802.11ad/D9.0, "Draft Standard for Information Technology – Telecommunications and Information Exchange between Systems – Local and Metropolitan Area Networks – Specific Requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications – Amendment 4: Enhancements for Very High Throughput in the 60 Ghz Band," Oct. 2012.

[5] S. Singh *et al.*, "Blockage and Directivity in 60 GHz Wireless Personal Area Networks: From Cross-Layer Model To Multihop MAC Design," *IEEE JSAC*, vol. 27, no. 8, Oct. 2009, pp. 1400–13.

[6] J. Wang *et al.*, "Beam Codebook Based Beamforming Protocol for Multi-Gb/S Millimeter-Wave WPAN Systems," *IEEE JSAC*, vol. 27, no. 8, Oct. 2009, pp. 1390–99.

[7] J. Qiao *et al.*, "STDMA-Based Scheduling Algorithm for Concurrent Transmissions in Directional Millimeter Wave Networks," *Proc. ICC 2012*, Ottawa, Canada, June 10–15, 2012, pp. 5221–25.

[8] X. Zhang *et al.*, "Improving Network Throughput in 60GHz WLANs via Multi-AP Diversity," *Proc. ICC 2012*, Ottawa, Canada, June 10–15, 2012, pp. 4803–07.

[9] A. Gudipati *et al.*, "SoftRAN: Software Defined Radio Access Network," *Proc. ACM HotSDN 2013*, Hong Kong, China, Aug. 12–16, 2013, pp. 25–30.

[10] K. Zheng *et al.*, "An SMDP-Based Resource Allocation in Vehicular Cloud Computing Systems," *IEEE Trans. Industrial Electronics*, vol. 62, no. 12, 2015, pp. 7920–28.

[11] Z. Ding and H. V. Poor, "The Use of Spatially Random Base Stations in Cloud Radio Access Networks," *IEEE Signal Processing Lett.*, vol. 20, no. 11, Nov. 2013, pp. 1138–41.

[12] L. X. Cai et al., "REX: A Randomized Exclusive Region Based Scheduling Scheme for mmWave WPANs with Directional Antenna," *IEEE Trans. Wireless Commun*., vol. 9, no. 1, Jan. 2010, pp. 113–21.

[13] R. Ahmed and R. Boutaba, "Design Considerations for Managing Wide Area Software Defined Networks," *IEEE Commun. Mag*., vol. 52, no. 7, July 2014, pp. 116–23.

[14] J. Ning *et al*., "Directional Neighbor Discovery in 60 GHz Indoor Wireless Networks," *Proc. ACM MSWiM '09*, Tenerife, Spain, Oct. 26–30, 2009, pp. 365–73.

[15] Q. Chen *et al*., "Spatial Reuse Strategy in mmWave WPANs with Directional Antennas," *Proc. 2012 IEEE GLOBECOM*, Anaheim, CA, Dec. 3–7, 2012, pp. 5392–97.

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