High–Speed Mobile Networking Through Hybrid mmWave–Camera Communications

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ABSTRACT

The millimeter wave spectrum (mmWave) is already a forerunner for next–generation high–speed mobile networking due to its huge bandwidth availability, capable of Gbits/sec data rates. However, due to its high frequency, mmWave communication suffers from strong wireless attenuation thus limiting range, requiring line–of–sight and large bandwidth overheads for collision avoidance to handle multiple access. Camera communications or camera VLC offers potential for long range communication due to the wide field–of–view of cameras, yet, is largely limited in data rates due to the sampling rate (frame–rate) limitations in off–the–shelf camera devices. In this paper, we propose a hybrid system architecture for mmWave–Camera communications that can provide a baseline for co–existence of the two orthogonal technologies to address their fundamental challenges. While we explore its use–case and feasibility in designing high–speed wireless local area networks and vehicular networks, we also survey open research questions that emanate in this space.

CCS Concepts

•**Computer systems organization** → *Sensor networks;* •**Human-centered computing** → **Mobile computing;**

Keywords

Visible Light communication (VLC), Camera communication, Millimeter Wave, Hybrid, Wireless Local Area Networking (WLAN), Vehicular

1. INTRODUCTION

Millimeter wave communication (mmWave) is believed to be the key enabler of next generation cellular network (5G) and WLAN, providing huge bandwidth. mmWave operates in the 3–300 GHz band of the electromagnetic spectrum and can enable order of Gbps data rates. Its short propagation range and highly directional transmission enables spacial reuse of frequency [1, 2, 3], thus supporting multiple access wireless communication.

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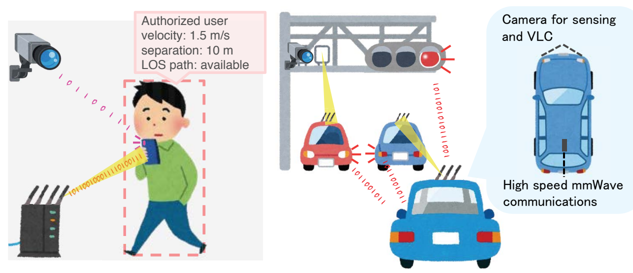

Figure 1: Application of hybrid mmWave communication and camera VLC in mobile access (left) and vehicular network (right). mmWave communications provides huge bandwidth. Camera VLC provides side channels and contextual information about user and obstacles, e.g. location, mobility, and LOS path availability.

However, unlike traditional WiFi mmWave does not easily travel through humans and materials. When a line of sight (LOS) path is blocked by obstacles (for e.g. pedestrians or vehicles in V2V links) the received signal strength sharply decreases due to the large absorption, diffraction & reflection [4, 5]. Due to the blockage problem, handling multiple access and mobility becomes extremely challenging in mmWave and incurs significant management overhead, requiring robust medium access control (MAC) techniques. The problems of blockage and MAC overhead problems become more significant in wireless communications within increasing frequency of operation.

The proliferation of light emitting devices and cameras has led to the increasing interest to use cameras for mobile communication[6, 7]. Camera VLC enables wireless communication using existing infrastructure (integrated cameras in mobile devices, surveillance and vehicles) and opens up plethora of opportunities for mobile networking applications. However, camera VLC systems are largely limited in practically achievable data rates due to the sampling rate limitations in off–the–shelf cameras.

To address the fundamental challenges in mmWave and Camera VLC, we propose the hybridization of the two technologies. With an interest to draw the best of both worlds from mmWave and Camera VLC technologies, in this paper, we propose a hybrid mobile networking architecture. In particular, we develop a proposal for hybrid mmWave–Camera communications network stack through a layered model. The key aspects of this design lie in the use of vision based sensing and communication in mmWave's MAC and networking modules, and the sharing of the physical medium without any bandwidth bottleneck (due to their orthogonality) to increase throughput.

Camera VLC, apart from a new modularity for wireless communication, also provides visual imagery from which rich contextual information about the mmWave medium can be deduced. For example, the mmWave links could adapt early based on the prediction a LOS blockage in near future using the camera link. On the other hand, mmWave links could be used as side (orthogonal) channels for managing multiple access links in mobile scenarios (for e.g. through cooperative forwarding), which can be very challenging in camera VLC. Figure 1 illustrates these aspects through two use–case mobile applications for hybrid mmWave–Camera systems.

We note that hybridization of VLC and radio systems have been proposed and developed in prior works [8, 9, 10, 11, 12]. However, the focus in those designs has primarily been using conventional photodiode receivers. The use of cameras brings about unique challenges, in particular perspective effects and hardware challenges (framerate limitation in off–the–shelf cameras) and energy. Moreover, prior work has not studied hybrid VLC systems in the light of mmWave communications; mmWave behaves fundamentally different to existing radio technologies like WiFi or LTE.

The main contributions of this paper are as follows:

- Design proposal of a network stack for hybrid mmWave–Camera communication.
- Survey of different applications that can be enabled by the hybrid architecture.
- Preliminary testbed design and feasibility exploration of camera assisted mmWave communication.
- Discussion of open research opportunities in designing hybrid mmWave–Camera VLC systems.

The outline of this paper is as follows: Section 2 discusses related work in hybrid VLC systems; Section 3 presents use–case applications of hybrid mmWave–camera VLC; Section 4 overviews our proposed hybrid system architecture along with a preliminary exploration of our testbed; Section 5 discusses open research opportunities; Section 6 concludes the paper.

2. RELATED WORK

VLC systems can be roughly be categorized into high data rate VLC and low date rate VLC [13]. High data rate VLC typically employs LED–photodiode VLC architecture where a single photodiode is used as receiver [14, 15]. Recent works in hybrid systems using VLC and radio communication propose to use the radio links for expanding the capabilities of high speed VLC links, i.e. coverage extension and full duplexing. Hybrid VLC–WLAN systems were discussed in [9, 10, 11], a hybrid VLC system with power line communication (PLC) was discussed in [8], and a heterogeneous network including VLC for 5G was discussed in [12]. In these architectures, radio communication such as WLAN or PLC provides uplink connectivity and downlink involves bandwidth aggregation of VLC and radio link traffic. However, these designs will suffer from frequency band shortage and strong interference [16] as the number of radio elements increase. The bandwidth constraints and interference will thus limit the performance of the conventional hybrid system.

In our prior work, we designed a MAC protocol using low data rate VLC as a control channel, referred to as visual recognition based medium access control (VRMAC), for enabling collision free medium access with small overhead of collision avoidance mechanism in WLANs [17]. This work observed that the efficient use of low data rate VLC can increase throughput performance more than traditional bandwidth aggregation in wireless systems.

Camera based VLC systems offer potential for long range links due to the wide field–of–view of cameras yet are limited in data rates due to the sampling rate (frame–rate) limitations in off–the–shelf camera devices. Most common applications of camera VLC in recent times have been for indoor localization, and mobile computing applications (screen to camera communication) [6, 18, 19, 20].

3. APPLICATIONS

In this preliminary work, we identify that hybrid mmWave–Camera communication can enable novel applications in (i) high–speed wireless LAN designs, and (ii) vehicular networking. While Figure 1 provides an illustration of the use–case in these areas, we discuss them at length here:

3.1 High–speed wireless LANs

A hybrid mmWave–Camera communication system can enable personal high speed wireless hotspots to mobile users. Due to the relatively short range and directionality of mmWave and camera VLC it is possible to create dedicated links between access points and mobile devices, where mmWave is used for high–speed communication and camera VLC providing a dedicated channel to the user. Such a wireless hotspot can enable ultra high speed wireless downlink access, particularly useful for disseminating rich contents in streaming applications. In addition, the camera VLC link can be used as a control channel to minimize the management overhead in the mmWave link; camera channel can provide an estimation of mmWave channel quality enabling *proactive link management*, such as smart handover if the mobile device moves from one area to another, and also handling multiple access in a dense mobile environment.

The hybrid mmWave–Camera communication system also enables wireless access networks providing secure network access and indoor location information. This is particularly suitable for large public venues such as airports and malls where security and location information are key. Camera VLC provides control channel for mmWave WLAN so that management overhead to handle security, location and user density in WLANs is reduced. Camera sensing enables computer vision based authentication and accurate location information, improving security and navigation, thus satisfying users. Such *context–aware* management of multiple WLANs enables efficient frequency usage and increases system capacity.

3.2 Vehicular Networking

Both, mmWave and camera VLC are very useful proponents for vehicle–vehicle (V2V) and vehicular to infrastructure (V2I) communication. A hybrid system consisting of mmWave communication and camera VLC can help address challenges due to mobility. mmWave equipped road–side units (RSU) and/or in vehicles can provide high speed V2V and V2I connectivity, enabling rich content dissemination and also enhancing vehicular crowd sensing. Camera VLC links between infrastructure and vehicles (traffic light to camera) or in between vehicles (car headlight/brakelight to camera) can help provide prediction of vehicular mobility; such as predicting traffic scenario, vehicular arrivals/departure. The use of cameras in vehicular networking opens up huge opportunities to get assistance from computer vision techniques in predicting mobility; number plate recognition using CCTV/traffic/vehicular cameras, stereo vision sensing to estimate traffic/vehicular density.

4. PROPOSED SYSTEM ARCHITECTURE

To design applications enabled by the combined benefits of mmWave and camera communications, we believe that it is important to first

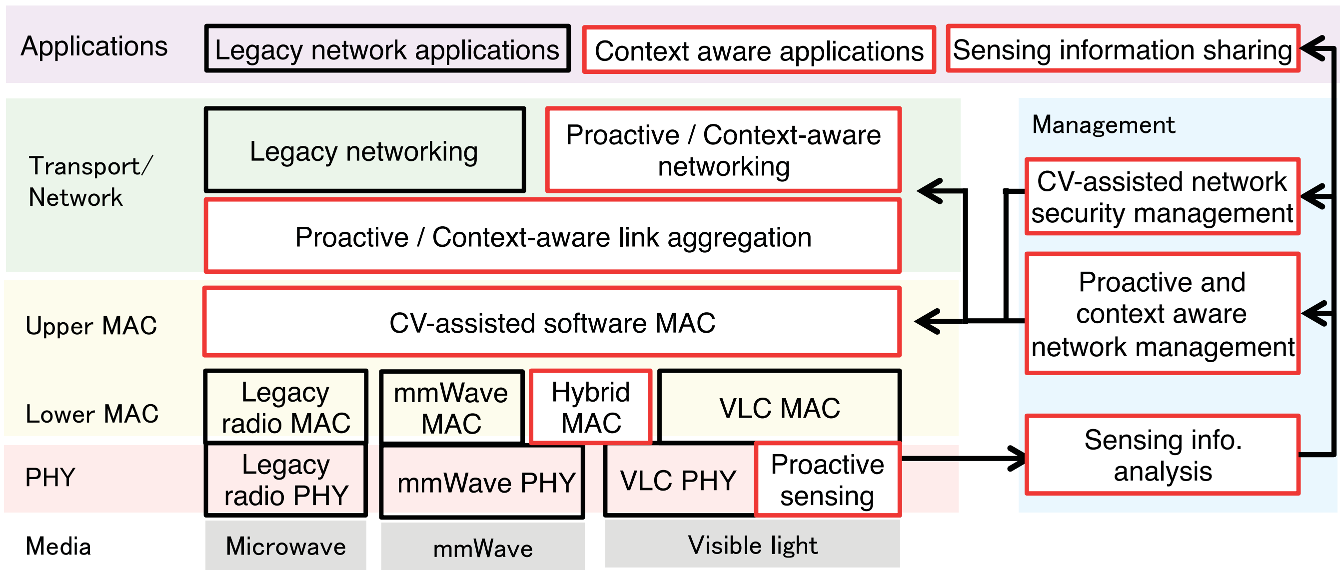

Figure 2: Layer model of proposed hybrid VLC and mmWave radio network stack. Blocks outlined in red are the new modules proposed by our design.

develop a hybrid system level architecture that combines these two technologies. We note that such architectures are not available today. In this regard, we propose a modular architecture that combines existing mmWave and camera VLC modules along with our proposed new modules into single networking stack. The key aspect of this design is the seamless association between the two technologies which is handled by the set of new modules that we propose to implement through this design.

In this work, we introduce our proposed hybrid system architecture through an overview of the key networking components and a description of the network stack layer model.

4.1 Networking Components

As shown in Figure 3 the hybrid system includes three key networking components: local wireless access, local wired network, and global network (Internet).

Local wireless access consists of the independent VLC and mmWave (radio) communication units. The goal here is to minimize the redesign of front–end wireless access components (radios, access points, integrated cameras) and maximize reuse of such existing infrastructure; to simplify design and minimize deployment cost.

Camera VLC also senses local communication environment and uploads sensing information to a local sensing manager on the local wired network. The local sensing manager aggregates sensing information and mines beneficial information such as user density, link quality estimation and blockage prediction for mmWave communications. The coordination between VLC and the mmWave units are provided using a coordinator on their local wired network.

The coordinator manages and control traffic by operating software defined networking (SDN) routers for coordinating wireless access. For the coordination, sensing manager provides information of local wireless environment to the coordinator. The sensing and other local information are uploaded to a server through Internet. This becomes very handy to enable context aware applications in mobile systems.

4.2 Layer model

We depict the network stack of our proposed hybrid architecture through a layer model as shown in Figure 2. We present the network stack as five layers: Physical (PHY); Medium Access Control (MAC), includes lower MAC & upper MAC; Transport/Network; Application; and Management. We treat that the PHY and lower MAC layers require hardware implementation as well, and the others are exclusively in software. In PHY and lower MAC layers, we include legacy PHY and MAC of existing mmWave ,VLC and other radio technologies, so that the hybrid system can accommodate legacy devices.

We introduce a novel aspect of *proactive sensing* in our PHY layer design. We define proactive sensing as a new functionality through this hybrid design that enables sensing (through the visual medium) and opportunistically handling the mmWave and camera communication link. In mmWave communications and camera VLC, link quality highly depends on geometry of communication environment since they requires LOS communications. Camera VLC can help obtain the location and mobility of users and obstacles by estimating the geometry and predicting its changes based on the sensing information.

The coordination for proactive sensing based communication is handled in the Hybrid MAC unit. Note that the rate of changes in mmWave links would require medium access procedures operating within order of microseconds delay. A hybrid MAC unit will enable a fast execution of the MAC in the mobile device itself. In upper MAC, we introduce computer vision (CV)–assisted MAC, which is software MAC operation based on camera–based sensing information. Computer Vision assisted MAC systems enable to know geometry and dynamics of the wireless environment; such as locations and mobility of mobile user and obstacles, which offers a potential for context–aware and proactive media access control.

Camera VLC provides a side channel for not only data communication but also managing mmWave communication by exchanging a channel state of mmWave communication and location of base stations, obstacles that can be used for location aware mmWave beam alignment and directional MAC protocol. An example is location–aware beamforming operation [21].

In pure mmWave systems, at the MAC layer, interference management and beamforming would add significant overhead thus ef-

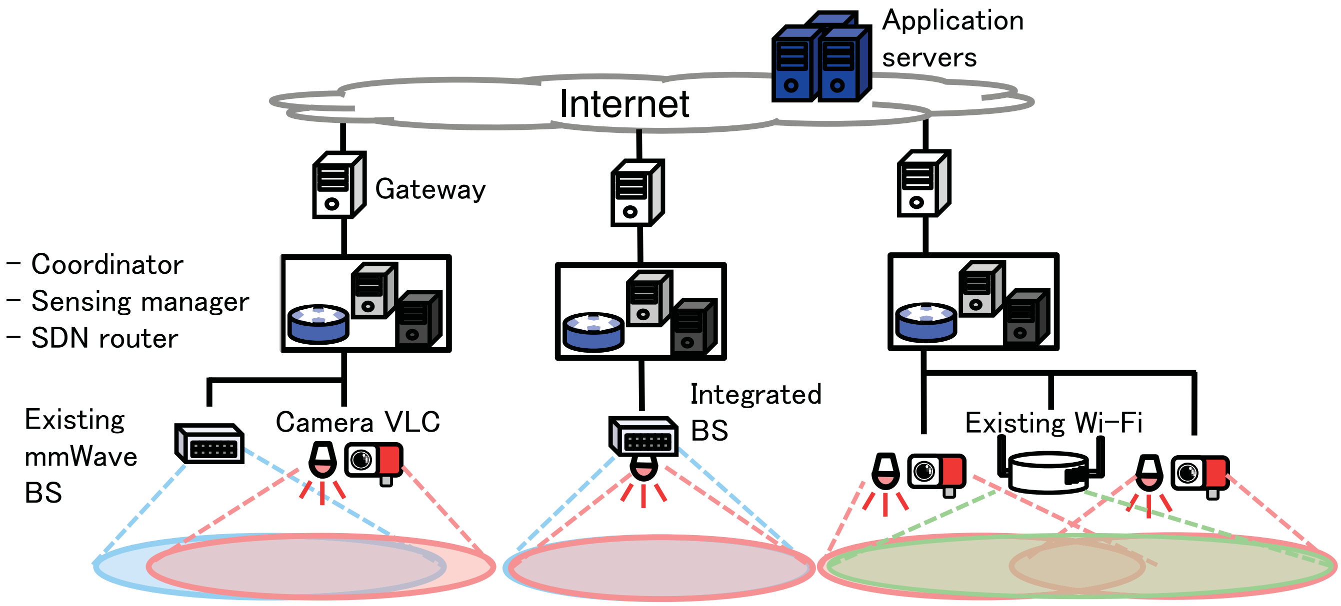

Figure 3: Proposed network architecture of hybrid mmWave–VLC system.

fectively reducing throughput. The sector sweeping operation using a directional antenna for beamforming causes latency. Knowing users' location can help reduce such overheads.

At the transport (also referred to as network) layer we define a module for proactive and context–aware link aggregation. Here, network traffic is managed and routed based on lower–layer camera sensing information. On the other hand, we retain the conventional multihomed/multipath wireless networking operations [22, 23] in this layer.

We define a management layer where the functionalities for local coordinators and sensing managers are defined. We also introduce a functionality of CV–assisted security management in this layer. Camera VLC can provide vital information of mobile users such as their face and motion, and based on such information, the security mechanisms for authentication and access control can be handled independent from the mmWave units. In this way, we can improve security and reduce overheads for management operations in radio communications. This is a new paradigm in the hybrid communication system.

Sensing functionality of the hybrid system enables context aware functionalities through the application layer. To ensure efficient usage of sensing information, information sharing mechanisms (for e.g through crowdsourcing) can be incorporated in this layer.

4.3 Preliminary Exploration

Testbed design. We have setup a simple testbed for implementing and experimenting with hybrid mmWave–Camera VLC systems. As shown in, Figure 4 this preliminary version of the testbed incorporates the latest IEEE 802.11ad (60GHz) mmWave based WLAN radios as well as a Microsoft Kinect camera (depth sensing camera). We maintain that a mobile device under test will equip a LED VLC transmitter unit, with the Kinect camera as the receiver.

Proactive handover. We conducted experiments to study the link quality when the LOS path in mmWave link is blocked by a walking human, and if such blockages can be proactively predicted using the camera. During the blockage we observed that the mmWave link almost reaches an outage for the current testbed

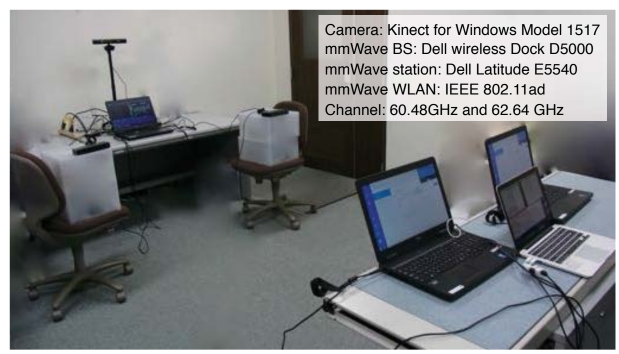

Figure 4: Our current testbed setup to study proactive handover in mmWave–Camera VLC systems

setup. We used the depth camera images to estimate the mobility of the human and predicted when a blockage could occur. Based on this prediction, the mmWave link is handed off proactively from one base station to another, maintaining the link. In the reactive handover scheme the system conducts the base–station handover after blockage is detected based on the reduced signal mmWave signal strength. Figure 5 shows the CDF of throughput in this setup, comparing the proactive, reactive and no–handoff schemes. [1] Our results show that the camera–assisted proactive handover reduced the effect of throughput degradation during blockage by 80% compared to a purely mmWave system. These early results attest the feasibility and usefulness of camera assisted mmWave systems.

5. OPEN RESEARCH OPPORTUNITIES

Designing a hybrid mmWave–camera is a challenging task as it involves the co-existence of two fundamentally different communi-

[1]We encourage the reader to refer to our prior work [24], that develops the proactive handover scheme for details of the this experimentation.

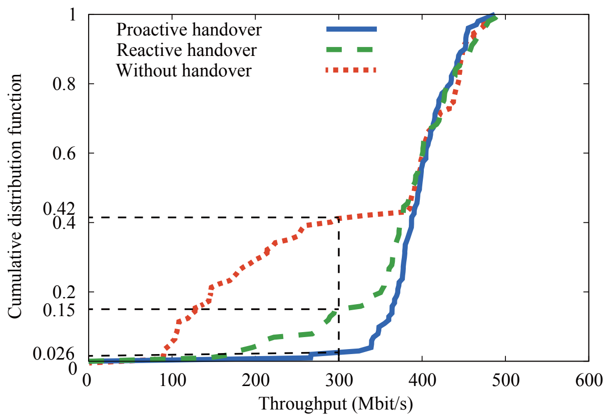

Figure 5: Cumulative Distribution Function of throughput. There are two base–stations and a work station using downlink TCP flow. The experiment involves a human walking across the room blocking the LOS path periodically.

cation technologies. This opens up many opportunities for research in this space.

5.1 Mining knowledge from camera images for wireless communications

Camera images contain vital information in the visual imagery; knowledge which helps determining and predicting communication quality such as geometrical topology of the area, and mobility of entities in the area. One approach to mine such information is through machine learning. In our recent work [25] we studied a human blockage prediction mechanism using Bayesian inference and auto regression model and demonstrated its feasibility for camera assisted mmWave communication. However, we note that work in this space are only in exploratory stages and there remains many open issues to resolve, particularly, prediction in multi user scenario and in vehicular networking.

5.2 Simultaneous communication and sensing on camera VLC

There is a plethora of work from the past using camera based sensing in mobile systems. Recent times have seen camera based communications gaining traction. However, the sensing and communication aspects have so far been discussed independently. The hybrid mmWave–camera VLC presents a huge opportunity for integrating benefits of camera sensing and camera communication into a single architecture. For example, the LED information in an image can help decode the communicated bits while the background scene in the image can be useful to the radio units to understand the 'wireless' environment.

5.3 Deployment strategy of mmWave radio base stations and cameras

Traditionally deployment strategies for cellular/WLAN radios [26] and cameras [27] have been developed independently. However, in the proposed hybrid system, deployment is a new challenge. In particular, mmWave communication and VLC are directional and are also subject to outage due to blockage. Hence, if we place the mmWave base station near a walkway or a camera at low elevation in the building, frequent human blockage will decrease quality of service (QoS) of the system.

5.4 Vision assisted networking

As discussed earlier, proactive handover is one feature realization of proactive networking. User mobility prediction and context awareness through computer vision based network management modules provide smart networking opportunities such as content pre–fetching from the base station and proactive association among network elements (nodes) based on lower layer information. On the other hand, the problem of dealing with prediction failure becomes relevant in this scope.

5.5 Energy management

In general, both mmWave and VLC are energy intensive communication systems, compared to their WiFi and Bluetooth counteparts. A combination of these two will require strong energy management strategies. Coverage extension in mmWave will require larger deployment of mmWave radios. mmWave devices typically consume more energy than other microwave band devices. To address the energy challenge, dynamic base station activation/sleeping approaches, as discussed in cellular networks [28] can be helpful. For example, cameras could be used as triggers for the mmWave transmissions. In general, the hybrid system makes the energy management problem very challenging as multiple factors have to be addressed at the same time; directionality, blockage–induced link quality degradation, and coverage difference of camera-based sensing and mmWave communication.

6. CONCLUSION

In this paper, we proposed a hybrid architecture for high speed mobile networking through mmWave–Camera communication. We developed a network stack for such hybrid communication systems and discussed exemplar use–case applications in WLAN access and vehicular networking. Our design proposes to leverage computer vision technology in mmWave communications, as well as use of mmWave links for expanding capabilities of camera VLC systems such as coverage range extension and multiple access. In this paper, we have essentially aimed to set a foundation stone in the exploration of the coexistence of mmWave and Camera communications, which are both emerging as front runners for usage in next generation mobile systems. We aim that the research scope of such an emerging hybrid system, as discussed in this paper, will inspire more work in this space.

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