mCRAN: A Radio Access Network Architecture for 5G Indoor Communications

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***Abstract*—Millimeter wave (mmWave) communication is being seen as a disruptive technology for 5G era. In particular, 60 GHz frequency band has emerged as a promising candidate for multi-Gbps connectivity in indoor and hotspot areas. In terms of network architecture, cloud radio access network (CRAN) has emerged as the most promising architectural alternative to enable efficient baseband processing and dynamic resource allocation in 5G communications. In this article, we propose micro-CRAN (mCRAN) -a multi-gigabit indoor network architecture which leverages availability of high bandwidth in 60 GHz frequency band. We have discussed in detail about the requirements and research challenges for various system modules for mCRAN based network architecture. We have also investigated the feasibility of IEEE 802.11ad MAC protocol for the proposed mCRAN architecture. We discuss the challenges related to 60 GHz beamforming, medium access mechanisms and network architecture, and propose solutions to address them.**

I. INTRODUCTION

Due to ever growing popularity of multimedia applications such as uncompressed video streaming, IPTV and online gaming, demand for high speed, high quality, reliable and affordable wireless communication technology is increasing. Currently researchers are working on defining next generation of wireless communication, i.e., 5G. Due to availability of large bandwidth in 60 GHz frequency band, 60 GHz mmWave technology offers an alternative for high speed indoor/hotspot communication. This is why it has been termed as a disruptive technology for 5G [1]. To provide energy efficient radio access, cloud/clean/collaborative radio access network architecture (CRAN) [2] is being seen as a promising alternative for densely packed base stations in 5G scenario. In CRAN architecture, baseband processing is carried in a centralized location to efficiently utilize the baseband signal processing resources which leads to simpler base stations.

The legacy 2G/3G/4G systems covering large areas were envisioned to support the same set of services both in indoor and outdoor environments. However, in the 5G era, traffic generated in indoors is predicted to be 80% of overall traffic. Hence, there is a need for paradigmatic shift from macro-cell mobile network approaches, where there is no differentiation between indoors and outdoors. Therefore, high capacity (multi-Gb/s order) indoor network architectures for 5G network are highly desired.

60 GHz wireless propagation is significantly different from 2.4/5 GHz because of its high path loss and limited ability to diffract around the obstacles. These characteristics make it suitable mainly for line of sight (LOS) communication [3]. Therefore, indoor areas separated by walls need installation of multiple access points to provide the uninterrupted coverage. Further, due to the limited coverage of 60 GHz signals, the overlapping area among 60 GHz access points (APs) is very small. This can trigger frequent handovers when a user moves in the indoor areas from coverage area of one AP to another AP. The frequent association and dis-association with APs can result in significant loss of data and thus an unpleasant user experience. To make network management easy, centrally managed network architecture with simple access points (cost effective) is highly desirable. A centrally managed network can provide smooth handovers and can also optimize the resources. Therefore, CRAN based architecture are best suited for 60 GHz indoor communication.

In this article, we propose an indoor network architecture called micro-CRAN (mCRAN). mCRAN employs 60 GHz frequency for radio access, and radio over fiber (RoF) technology to enable centralized base-band processing. In RoF systems, all the signal processing, resource allocation and network management functions are realized at a central location. Having a centralized architecture for network management and signal processing functions, RoF technology at 60 GHz -can facilitate the multi-Gb/s wireless communication for a better user experience and cost effective indoor applications in 5G era.

Remaining of this paper is organised as follows. Section II introduces the mCRAN architecture. In Section III the main building blocks used by mCRAN architecture are described. Section IV describes how main features, such as beamform-

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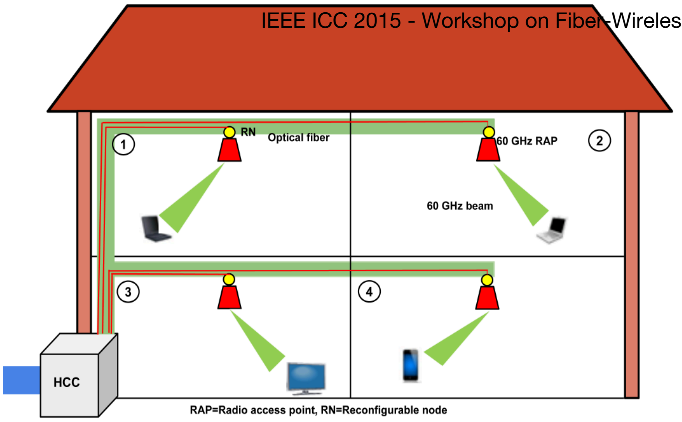


Fig. 1. A schematic of mCRAN architecture.

ing and beamsteering supported by this architecture can be realized. Section V evaluate IEEE 802.11ad MAC protocol in mCRAN architecture. The conclusions and recommendations for future work are provided in Section VI.

II. SYSTEM ARCHITECTURE

Fig. 1 shows the schematic diagram of mCRAN indoor network architecture. Centralized home communication controller (HCC) is responsible for radio access control, signal generation, distribution and processing. HCC monitors communication needs of the wireless devices spread over the home and takes care of setting up the communication links with these devices by controlling the radio beam-steering from the Radio Access Points (RAPs). Every room has at-least one RAP, which provides wireless connectivity to all the devices in the room and is connected to the HCC through a fiber optic cable via the optical network Nodes (RNs). Moreover, home automation network consisting of various sensors, can also be connected to the HCC using another fiber cable to optimize the resources.

III. HCC, RAP AND RN: STRUCTURE, FUNCTIONS AND REQUIREMENTS

HCC performs as a central control and management unit while the RN and RAP perform the remote control unit and access point. The detailed functions of HCC, RN and RAP are elaborated as follows.

A. Home communication controller (HCC)

HCC performs network management, routing, switching, modulation and up-conversion (frequency up conversion from baseband signal to RF signal with high frequency carrier) and finally modulate the 60 GHz RF signal over optical carrier. The main function of the HCC is to reconfigure the transparent fibre network for these RF signals (see Fig.2).

B. Radio Access Point (RAP) and Reconfiguration Node (RN)

On the instructions from HCC, the RN and RAP perform routing/reconfigurable bandwidth allocation and beam-steering, OE/EO (down/up)-conversion, respectively. The reconfigurable node (RN) and remote antenna point (RAP) are principally depicted in Fig.3. Here we show a Dense Wave Division Multiplexing (DWDM) ring based optical transport network, but any other wavelength distribution would work. The RN is defined as a remote process unit to configure the RAP. Its functions includes signalling detection, processing and insertion. The signalling is used to transmit the commands to the RN for dynamic reconfiguration of wavelengths. As shown in Fig.3, the signalling is detected after the asymmetric splitter. The detected optical signalling signal is then processed electrically by the logical circuit to drive the wavelength selection module and phase control module. The feedback signalling (uplink), such as status information will be sent back to the HCC via the signalling insertion module in the RN.

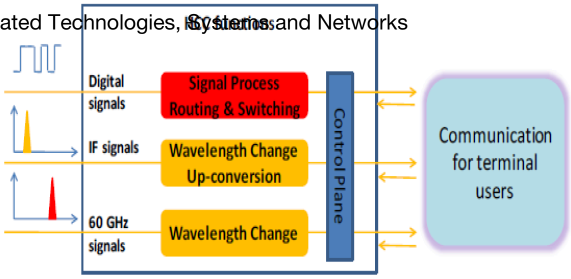


Fig. 2. HCC functions for the different Incoming signals.

Apart from wavelength reconfiguration, the RN would also support the control signal delivery for the antenna array in order to allow beam-steering /forming. The beam-steering could be realized via group delay control. The group delay can be controlled by using an optical phase shifter integrated circuit based on tunable micro ring resonators (MRRs). The exact group delay depends on the control signal (signalling). The RN is also responsible to translate the control signals from the digital optical domain into the analog electrical domain in order to drive the tunable MRRs. In order to support sensor networks, an additional transceiver can be used to support low frequency and low-speed communications consisting of low frequency photo diode and antenna, respectively.

The optical interface for signalling delivery (detection and insertion) between HCC and RN includes an asymmetric splitter, a selecting filter (optional) and a low-speed optical detector (photo-diode). The electrical interface for phase control (beam-steering) and signalling insertion between RAP and RN delivers control signals for beam-steering. The signalling modulated on the optical signal is detected and then processed to drive the phase control modules inside the RAP.

The optical signal dropped from WDM-Ring is amplified and coupled with a tunable optical phase control integrated network to allow mmWave beam-forming via the integrated photo-diode array and antenna array. The optical-electrical conversion is realized by using a photo-diode. The amplification is realized by integrating a mmWave amplifier to the photo-diode. For uplink transmission, the wireless signal is received by an antenna array and then is down-converted and

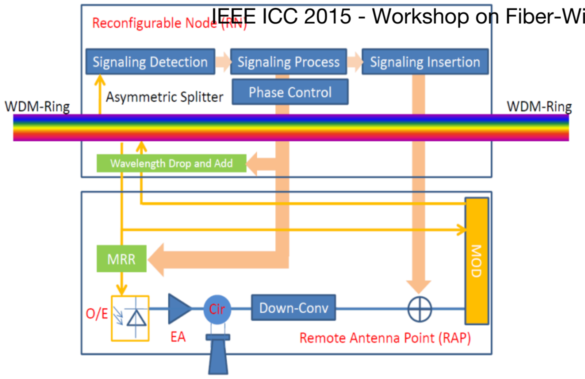


Fig. 3. RAP and RAN.

via an optical modulator converted from electrical to optical. The modulated optical signal is then transmitted back through another MRRs (optional) to the HCC. In the practical case, the RN and RAP are placed in the same location and thus can be integrated with each other. The selected wavelength can be directly delivered to the RAP using inter-chip connection.

IV. BEAMFORMING AND BEAMSTEERING

To overcome the high free space pathloss at 60 GHz frequency band, beamforming capable directional antennas are employed. Instead of transmitting in all directions, directional antennas confine signal power in particular direction of interest. To reach out to devices in different locations, radio beam is steered in different directions. Radio beams can be steered by phased array antennas where controlled differences in the phases between the radio signals radiated by the antenna elements determine shape and direction of the beam. For this, accurate and tuneable shifting of phases needs to be accomplished, which is particularly challenging when millimetre wave radio signals with complex modulation formats are involved and when fast beam steering is required. Beamforming considerably increases the amount of signal energy received by receiver. In other words, it requires less transmission power to achieve same amount of signal power at receiver which can have a significant impact on transmitter energy consumption.

Traditionally, beamforming is realized in electronic circuits. A time delay or phase shift can be realized at different stages [4]. RF beamforming realizes beamforming at RF frequencies and is done fully analogue [5]. Another emerging technique for beamforming is using optical circuits. Beamforming by optical techniques is achieved by deploying bulky dispersive fiber delay lines [6], and dispersive micro-ring structures [7] which dealt with only 1-dimensional beam steering. In case of broadband 60 GHz communication, electronic beam steering is not a suitable option as the phase shifter circuitry highly depends on the signal frequency and results in beam squinting. Therefore, optical phase shifters are more suitable for 60 GHz communication.

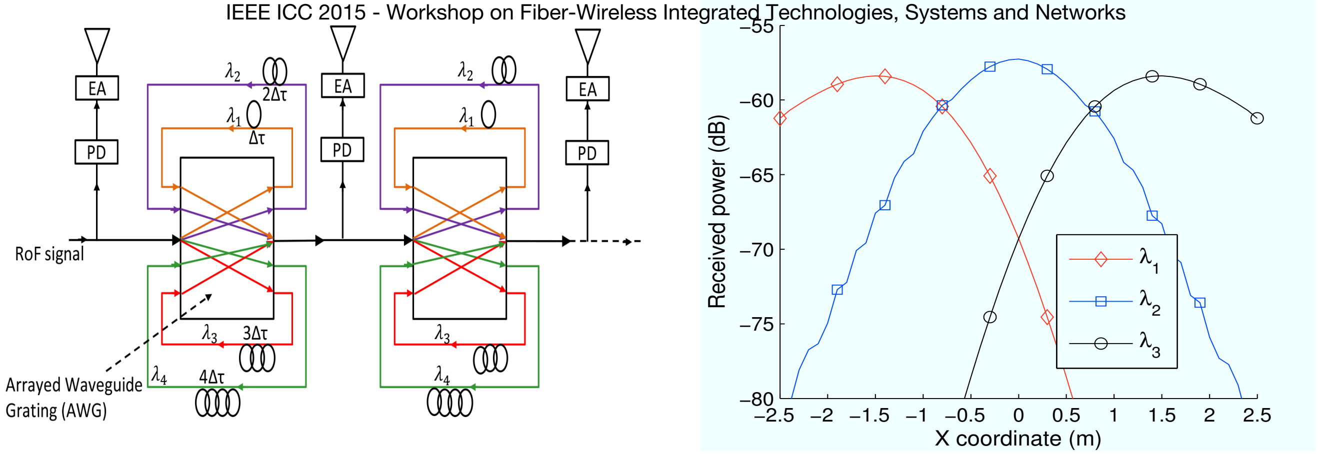
Beamforming in mCRAN architecture would be different from the traditional beamforming due to remote baseband processing. Controlling the beam-steering from HCC in electronic beamforming circuitry could be a difficult task and may need control signaling which should be strictly synchronized with the data transmission for each user. Apart from the dynamic capacity allocation capability, simple RAPs has been projected as the most important feature of RoF architectures. However, beamforming module increases the complexity of 60 GHz RAPs. Hence, it is important to have beamforming module such that it keeps the RAPs still simple. We propose to use a true time delay (TTD) based beamforming [8] which exploits the wavelength dependent dispersion property of fiber to steer the antenna beams in different directions. By employing TTD beamformer, beam steering can be remotely controlled from HCC by changing the optical wavelengths thus resulting in a simpler RAP module by avoiding extra control signal requiring strict synchronization.

Fig. 4(a) shows the schematic diagram of TTD beamformer. When RoF signal impinge on the arrayed waveguide gratings (AWG), AWG introduces delays $\Delta\tau$ which depends on the wavelength of RoF signal. RoF signals choose a path with specific delay$\Delta\tau_i$ which depends on the wavelength of the signal. In Fig. 4 we can see that RoF signals with wavelengths λ_1, λ_2, λ_3 and λ_4 undergo different delays $\Delta\tau$, $2\Delta\tau$,$3\Delta\tau$ and $4\Delta\tau$, respectively. The beam steering angle θ_i due to specific time delay among array element is given by,

$$\theta_i = \sin^{-1}(\frac{c.\Delta\tau_i}{d}) \qquad (1)$$

here c is the speed of light and d is the spacing among antenna elements. The delay $\Delta\tau_i = D.L_i.\Delta\lambda$ depends on the dispersion introduced by fiber length where D is the dispersion coefficient of fiber, L_i is the length of path traversed by RoF signal of wavelength λ_i, and $\Delta\lambda_i$ is the free spectral range of the AWG. Apart from the feasibility of steering radio beams remotely from HCC, TTD beamformer provides a squint free beam steering as steering angle θ_i in Eq. 1 is independent of the radio signal frequency. This is a desired characteristic as 60 GHz signals have large bandwidth, e.g., IEEE 802.11ad specify four channels in 60 GHz band where each of them is 2.16 GHz wide.

Fig. 4(b) illustrates the working principle of TTD beamformer by showing the power along center of the room for three different wavelengths. It can be seen how the change in the wavelength of RoF signal can steer radio beam into different directions in a 5 m×4 m room using three different wavelengths employing directional antenna mounted on the ceiling at 4 m height. Transmit power of antenna is 10 dBm with a beamwidth of 60deg, and have a Gaussian shaped antenna pattern. It can be observed that the TTD beamformer is a promising solution for remotely steering the radio beams and help in decreasing the complexity of RAPs. It can also be employed in 5G networks using mmWave radio frequencies where centralized base-band processing is much needed for closely spaced mmWave base stations.



(a) TTD beamforming block diagram

(b) Illustration of received power along a line passing through the center of room for different wavelength.

Fig. 4. Beamsteering using TTD beamformer.

V. FUNCTIONAL MANAGEMENT AND COMMUNICATION PROTOCOL STACK

HCC contains the control plane functions for optimizing the mCRAN communication infrastructure with respect to service demands, load balancing and energy consumption. Most important function of control plane in the proposed 60 GHz RoF architecture is to remotely configure the antenna array of RAP to beamform in the desired direction. This can be obtained appropriate wavelength selection if proposed TTD beamformer is used. Otherwise, separate control channels would be needed from HCC to RAP for beamforming mechanism in synchronization with the data channel.

Standards such as IEEE 802.15.3c [9] and IEEE 802.11ad [10] have defined the MAC and PHY specifications for short range communications at 60 GHz. Owing to the fact that IEEE 802.11ad is back compatible with the 802.11a/b/g/n for the fast session transfers among 2.4/5 GHz and 60 GHz frequency bands, we believe that IEEE 802.11ad will prevail over ECMA and IEEE 802.15.3c.

IEEE 802.11ad has proposed three PHYs: Control PHY with data rate 27.5 Mbps, SC PHY (data rate) and OFDM PHY with peak data rates of 7 Gb/s. IEEE 802.11ad defines a PBSS (Personal Basic Service Set) which is the operating area of network formed by 60 GHz wireless stations (STAs). One of the STAs in a PBSS works as the PBSS control point/Access Point (PCP/AP) to coordinate the channel access among STAs in the PBSS. Typical radius of a PBSS is about 10-20 m.

Timing in IEEE 802.11ad is based on beacon intervals (BIs) set by PCP/AP. Duration within two beacon intervals is divided into different access periods having different medium access rules. Fig. 5 illustrates the different access periods within a beacon interval which comprised of : (i) BTI (beacon transmission interval); (ii) A-BFT (association beamforming training); (iii) ATI (announcement time interval); and (iv) DTI (data transfer interval), during which data transfer happens; and it consists of CBAPs (contention-based access periods) and SPs (service periods). CBAPs periods employ CSMA/CA for STA channel access, while SPs periods are reserved using service period request (SPR) commands, after that the PCP/AP polls an STA during the ATI period. In order to incorporate standard IEEE MAC protocols in the proposed architecture, it is necessary to ensure that a smooth medium access is guaranteed. PCP/AP located in the HCC makes whole home area as part of one PBSS, and is responsible for coordination amongst the devices in rooms and scheduling data transmission at 60 GHz.

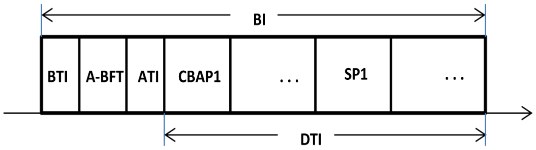


Fig. 5. IEEE 802.11ad beacon interval

Wireless networks MAC protocols have fixed inter-frame space timings (IFSs), e.g., DIFS,SIFS,MIFS etc. One of the important factor to determine these IFSs is air propagation delay. In RoF networks, fiber distribution network introduces extra delays which prevents direct use of wireless MAC protocols in RoF networks. Since, IEEE 802.11ad is designed to operate in a range of 10 m to 20 m in wireless medium, it is important to investigate the effects of extra delay introduced by fiber networks.

Fig. 5 shows the IEEE 802.11ad BI. During CBAP period, CSMA/CA is used and during SPs, TDMA based channel access is followed. Channel access using CSMA/CA is more affected than the TDMA based access as several IFs are involved. If channel is sensed busy, STA freezes its backoff counters. but if the channel is found to be idle for a DIFS duration, it resumes decrementing the back-off counter and transmit the frame after when backoff counter reaches zero. IEEE 802.11ad DIFS duration ranges from 4.2 to 6.5 μs. For a distance of 10 m in wireless medium, round-trip propagation time (t_{prop}) is 30 ns which is negligible. But in the presence of fiber, the extra propagation delay has to be taken into consideration. In order to allow CSMA/CA to work properly, either the maximum fiber length should be such that t_{prop} does not exceed the DIFS period or DIFS period should be modified. Speed of light in a fiber of refractive index of 1.62 is 194.81 m/μs. Thus, for a DIFS period of 4.2 μs, maximum allowable fiber length is 427 m to ensure that t_{prop} is always less than the DIFS duration. Otherwise DIFS need to be increased by the extra delay. However, ACK timeout has to be always increased by an amount of extra delay introduced by the fiber network to avoid the unnecessary retransmission.

Considering above modifications, we evaluated the normalized throughput performance of CBAP part and data throughput of the SP part of IEEE 802.11ad in mCRAN architecture. In our simulations, we assume that devices are uniformly distributed in a circular area of 10 m radius around RAP. Values of parameters used are taken from the IEEE 802.11ad. Signal conversion times from electrical to optical and optical to electrical domains are assumed to be negligible. All the simulations were done using MATLAB.

The Normalized throughput during CBAP periods employing CSMA/CA is defined as the fraction of time that the channel is used to transmit payload successfully. On the other hand, SP throughput is calculated as the effective data rate achieved at the MAC layer. S_{CABP_k}, the normalized throughput of k_{th} sector is defined as the fraction of time that the channel is used to transmit payload successfully.

$$S_{CAP_k} = \frac{P_s E[Payload]}{P_i T_i + P_s T_s + P_c T_c}. \tag{2}$$

Where $E[Payload]$ is the average size of payload packet and T_i, T_c, T_S are idle, collision and successful transmission durations, respectively. P_i, P_c and P_s idle, collision and successful transmission probabilities, respectively. These parameters were calculated using Bianchi's model [11] and IEEE 802.11ad [10]. Overall normalized throughput S_{CABP} for one RAP is the average of that of all the sectors in the room.

Fig. 6 shows the CBAP throughput for various lengths of fiber (300, 600 and 900 m). In the presence of fiber, CBAP throughput drops only by $2-3\%$ when using a fiber of 300 m as compared to when no fiber is used(see Fig. 6). Such a minimal drop in throughput is insignificant. Further, $4-6\%$ and $6-8\%$ of decay in throughput is observed for fiber length of 600 m and 900 m, respectively. A slight change in the DIFS and ACK timeout due to delay introduced by 300-900 m of fiber length does not affect the CSMA/CA performance significantly.

Further, we evaluate the SPs throughput for the different ACK schemes, constant physical channel bit error rate (BER) and packet size. Let ρ is the SP fraction of a BI, then average packet throughput during SP (S_{SP}) is,

$$S_{SP} = \rho \frac{L_{data}(1-(1-P_{suc})^{n_r+1})}{T_{avg}}. \tag{3}$$

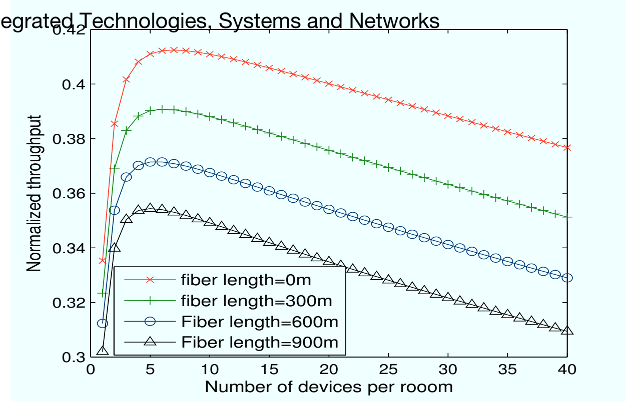


Fig. 6. CBAP throughput versus number of devices with various fiber lengths

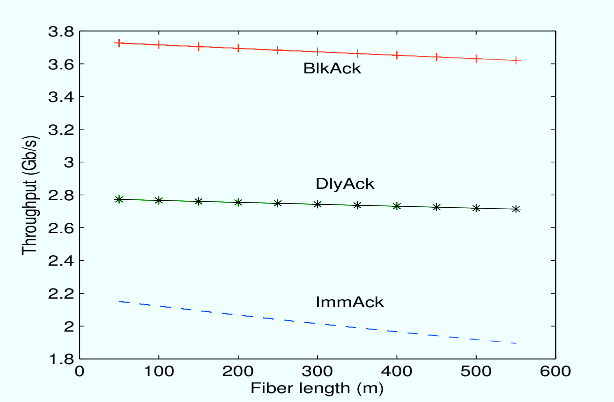


Fig. 7. SPs throughput as a function of fiber length with BER = 10^{-3} and frame size 20Kb and different ACK schemes.

Here T_{avg} is the average time taken by a frame transmission. Let T_{suc} is the time of a successful transmission and T_{fail} is the time taken by a failed transmission attempt and P_{suc} is the success probability of a frame, then average time taken by a frame after n_r retransmission attempts is given by,

$$\begin{aligned} T_{avg} = \sum_{i=0}^{i=n_r} & [P_{suc}(1-P_{suc})^i (iT_{fail} + T_{suc}) \\ & + (1-P_{suc})^{n_r+1}(n_r+1)T_{fail}]. \end{aligned} \tag{4}$$

Other than Immediate ACK (ImmAck), IEEE 802.11ad uses two more ACK mechanisms, delayed ACK and block ACK denoted as DlyAck and BlkAck, respectively [10]. Fig. 7 shows the SPs throughput for different ACK mechanisms, fixed BER=10^{-3} and varying fiber length from 0 to 1000 m. Optical fiber is assumed to be an ideal channel which is a reasonable assumption when compared with that of wireless channel. Packet size is 20 Kb. For base header transmission, common mode signaling rate is used. MCS12 of IEEE 802.11ad is used for the data frame which uses 16-QAM modulation scheme with a code rate of 3/4. To analyze BlkAck, standard aggregation mode is considered. We have taken the block of 8 frames for both the DlyAck and BlkAck. For BER of 10^{-3}, BlkAck gives the best performance amongst all the ACK mechanisms. ImmAck obtains the least throughput because, for each frame in ImmAck mechanism an ACK frame is mandatory. BlkAck and DlyAck throughput are less affected as compared to the ImmAck when fiber length is increased.

VI. CONCLUSION

In this paper, we proposed mCRAN -an indoor network architecture for 5G communications. The proposed mCRAN architecture consisted of 60 GHz radio access and an RoF based centralized network architecture. We discussed the various requirements of proposed mCRAN architecture. In preview of proposed mCRAN architecture, our main goal was to provide a unified view of RoF based 5G indoor/hotspot network architecture using 60 GHz frequency band from the perspective of physical layer, medium access control and network architectures rather than the standalone and isolated analysis at each layer. Complete system modules, their functionalities and requirements were analysed. We proposed to utilize TTD based beamforming for remotely steering the radio beams which can simplify the remote radio access points. Finally, we evaluated the performance of IEEE 802.11ad MAC protocol in the proposed network architecture. It was shown that by adopting some changes in the MAC protocol parameters, IEEE 802.11ad can be used in the proposed architecture. We believe that 60 GHz communication will play an important role in 5G networks where mCRAN architecture could be able to address many challenges of short range multi-Gb/s connectivity in indoor/hotspot environments.

VII. RELATED WORK

There are many articles available in literature on RoF technology for millimeter wave frequency band [12]–[16]. Majority of these articles have focused on wireless service delivery for long distances with main emphasis on physical layer technology. A novel 40 GHz frequency band RoF based architecture is proposed in [12] that integrates optical and wireless signal delivery. Techniques for remote radio signal generation, up-conversion and wavelength division multiplexing are presented. A hybrid star-tree based network architecture is proposed in [14] which incorporates wavelength division multiplexing for optical carrier and sub carrier multiplexing for radio signals. Huchard, et al [15] have evaluated the performance of IEEE 802.15.3c Physical layer modulations and coding schemes. Some researchers have investigated application of popular MAC protocols in the WLANs. In [17], Das et al., investigated the performance of RoF network employing IEEE 802.11a/g MAC and feasibility of 802.11a/g in RoF network was demonstrated using an experimental setup. In [18], an indoor network architecture based on RoF technology is proposed. In [19], performance of ETSI HiperLAN/2 and IEEE 802.11 is examined in RoF indoor networks. It is shown that centralized MAC protocols are better suited for RoF indoor networks.

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