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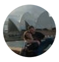
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Abstract *A fully-automated SDN-controlled real-time operation of a hybrid Fiber-Wireless 10Gb/s FSO and 5Gb/s mmWave link across 7km-fiber and 0.5m-radio distance resilient at all weather conditions is experimentally presented, supporting 25μs beam-switching and zero-touch hard handover via tunable SFP+ transceivers and simple all-passive 1x2 C-/O-band diplexers.*

Introduction

The increasing demand for massive broadband wireless connectivity and emerging Use Cases (AR/VR, Industry 4.0, IoT) keep scaling the Radio Access Networks (RAN) capacities towards the next crest of the wave of 6G [1]. In the IMT 2030 vision [2], 6G KPIs predict prohibitively high aggregate data rates beyond 100Gb/s to the antenna, extreme 1Gb/s user rate anywhere in the RAN, with affordable mmWave and THz links of >99.999% reliability service-availability, fully automated zero-touch network operation with no human intervention [3]. Optical-wireless links via Free Space Optics(FSO) or Fiber-Wireless (FiWi) mmWave links achieve fiber-equivalent capacity offering an appealing cost-effective solution to extend the coverage of the access or X-haul, as fiber is not always available or easily deployable, eg. in urban areas and emergency situations.

However, FSO/mmWave links are limited by different atmospheric conditions, with mmWave being impacted by rain [3], whereas FSO is mainly disrupted by turbulence, fog or snow [4], as conceptually shown in Fig. 1 Eventually, this requires innovative aerial channel monitoring and FSO/mmWave beam-combining, relaying or switching techniques, to automatically select between the optimum wireless channel and ensure practical, massive connectivity of future 6G RANs. Although various detailed theoretical studies of combining the two parallel paths are carefully investigating the impact of fading and channel response to optimized the addition of the two signals, these typically use complex Digital Signal Processing (DSP) [6][11]. Alternatively, simpler handover schemes activate a soft or hard handover switch-mechanism to select the best channel. Yet, their simplicity, these handover mechanisms require proper channel monitoring and feedback scheme [10][11], limiting recent demonstrations mainly to offline demonstrations, closed proprietary solutions [6][11] or FPGA-based selection of a few MHz channel [12], without any automated open-source SDN-controlled FiWi channel selection reported yet.

In this work, we experimentally demonstrate for the first time to our knowledge the real-time, fully-automated, SDN-controlled operation of a hybrid FiWi FSO/mmWave X-haul programmably transmitting via a 10Gb/s energy-efficient, lower-latency optical wireless channel or a 5 Gb/s FiWi mmWave channel. The hybrid FiWi X-haul link relies on wavelength tunable SFP+ transceivers, emitting across 7km fiber and 0.5m FSO or mmWave radio distance, reconfigurably selected via a simple, all-passive 1x2 C-/O-band optical diplexer. SDN channel selection is demonstrated in time-slotted operation with 25μs switching time, while the complete algorithmic workflow of zero-touch handover is experimentally validated, triggered after monitoring and surpassing a link-downtime threshold of 40s, e.g. due to adverse weather. The work aims to enrich the emerging 6G RANs with a broadband wireless technology and SDN-controlled fallback, opening a path for resilient 6G networks that exhibit self-healing of wireless outages at all weather conditions.

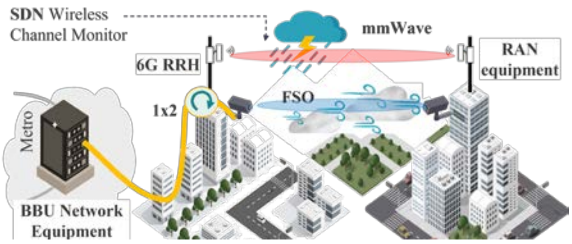

Fig. 1: Conceptual schematic of the proposed X-Haul link.

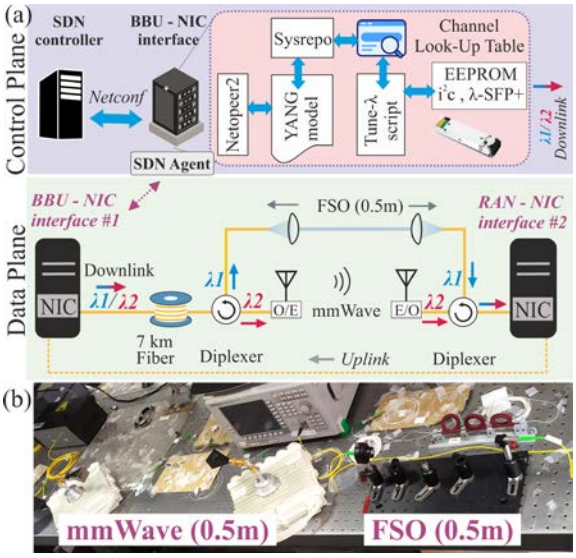

Fig. 2: (a) Experimental setup of the proposed Control and Data Plane and (b) photo of the mmWave and FSO links.

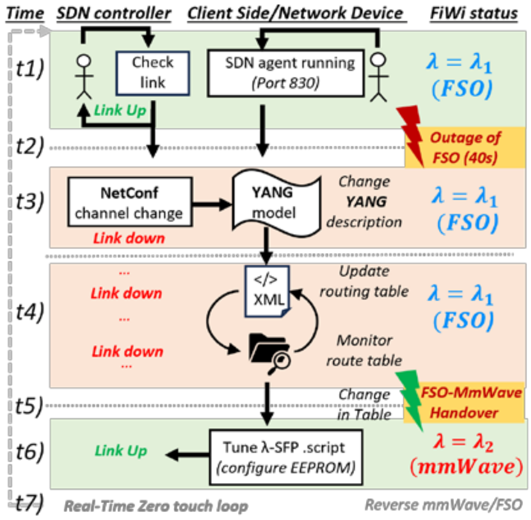

Fig. 3: SDN workflow for zero-touch handover.

Experimental setup and devices

An experimental setup was implemented for both the Control and the Data Plane in the downlink transmission, shown in Fig. 2 (a). The data plane comprises two servers exchanging real-time Ethernet traffic through the proposed hybrid FiWi FSO/mmWave link, with Server #1 hosting a CX6 NVIDIA Smart Network Interface Card (NIC) #1 to emulate the interface of a Basedband Unit (BBU) and Server #2 with CX6 NIC #2 that emulates the RAN equipment. The NICs are plugged with 10Gb/s wavelength tunable SFP+ transceivers. Towards the downlink, the SFP+ transceiver of NIC #1 transmits its traffic through a 7-km long Single-Mode Fiber (SMF) spool with a signal attenuation of 1.7 dB, before inserted to a C-/O-band diplexer. The two diplexer outputs are respectively fed to an FSO or a mmWave antenna. The FSO transmission was conducted using two aligned collimators placed at a distance of 0.5 m with 3.15 dB loss. On the other hand, the mmWave link utilized a pair of directive digital antennas designed for 5Gb/s traffic at 60-80GHz interfaced with SFP+ modules. At the RAN side, the two link outputs are similarly multiplexed via a C- /O-band diplexer and received by Server 2. Fig.2(b) shows a photo of the FSO/mmWave link.

A high-level overview of the Control Plane is shown at the top inset of Fig.2 (a), controlling the FiWi X-haul dataplane via its SDN agent. The NETCONF protocol [14] is used for the interaction of the controller with the agent, via the creation of custom YANG data models for the channel of the tunable SFPs and in-turn the FiWi FSO/mmWave X-haul topology. The open-source Sysrepo [15] and Netopeer2 [16] are used, avoiding proprietary SDN solutions. Sysrepo serves as a datastore for the YANG configuration defined by NETCONF, while Netopeer2 is a server managing NETCONF packets and storing them within Sysrepo.

The SDN workflow maps the two wireless channels of the link to two channel numbers of NIC #1 via the YANG model (eg. NIC_Tx_id 1) to two channel numbers '1' or '2' that correspond to different wavelengths. Once sysrepo data store is created, it instructs the selection of desired FSO or mmWave path via a custom SDN script is developed to access and tune the EEPROM configuration of the tunable SFP+ via an i2c interface, mapping the SFP-channel number of the YANG model to the selected wireless path of the sysrepo data-store. In turn, another script with periodic and infinite monitoring of the interface status automatically detects link failures, e.g. by adverse weather conditions and triggers a switch of the hybrid FiWi link to the alternate the path.

The SDN workflow operation is separated in four stages, as shown in Fig. 3. At time *t1*, Netopeer2 is initiated and the SDN controller continuously monitors the status of the interface. If the transmission link fails for more than 40 seconds, e.g. due to an outage of the FSO at *t2*, the SDN controller automatically issues a NETCONF command at time *t3* to alter the routing table, updating the channel entries in the YANG model stored in Sysrepo. A modification to the YANG model's description triggers an update to the configuration .xml file at time *t4*, which is automatically detected by the client device through a linux-daemon process based on inotify-tools [17]. Upon detecting a change, a parser is automatically activated to identify the updated values in the YANG description of the .xml file and at time *t6* it executes the command to tune the wavelength of the SFP+ modules, thereby properly changing the alternate wireless channel.

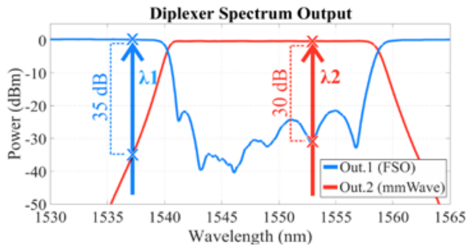

Fig. 4: Characterization of the 1x2 C-/O-band diplexer

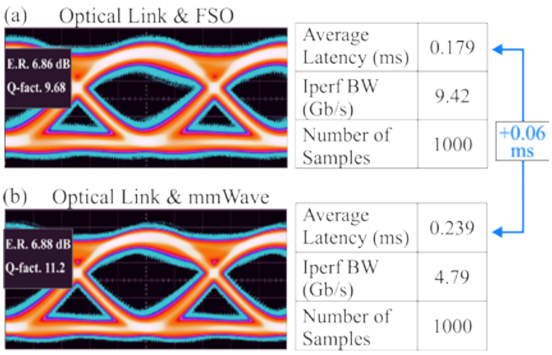

Fig. 5: Experimental results of the wireless links

Experimental wireless link characterizations

This section presents the static characterizations of two FiWi links and the dynamic zero-touch SDN controlled handover. Initially, to select the two wavelengths for the two wireless links, we characterized the diplexer using a tunable laser, swept between 1530nm-1565nm and recorded the optical power at its two outputs. The obtained spectra shown in Fig. 4 feature flat-top response centered at 1549 nm and a 3dB bandwidth of 18nm (red colour) or a complementary spectral response (blue) for the other output. The insertion losses were 0.8 dB, hence λ_1=1537 nm was selected for the FSO link and λ_2=1553 nm for the mmWave, allowing clear FiWi channel separation with a crosstalk of -35 and -30 dB respectively.

The static characterization of the FiWi FSO and mmWave links were conducted using eye diagrams of the optical transmission, shown in Fig. 5 as captured after the FSO and at the input of the mmWave antenna, as capturing the mmWave signal over the air was not possible during the experimentation. The results exhibit similar performance with Extinction Ratio (ER) around 6.88 dB, due to the short wireless indoor links. Traffic statistics between the two endpoint NICs using iperf achieved a maximum data rate of 9.42 Gb/s capacity for the FiWi FSO link and a 4.79 Gb/s for the FiWi mmWave link, as shown in Fig. 5, and latencies of 0.179 ms and 0.239 ms respectively, revealing a 0.06 ms latency-penalty and bandwidth limitation via the mmWave, owing to the electronic-process limitations for e/o/e and up-/down-conversion. These render the FSO as the preferred path at ideal weather conditions.

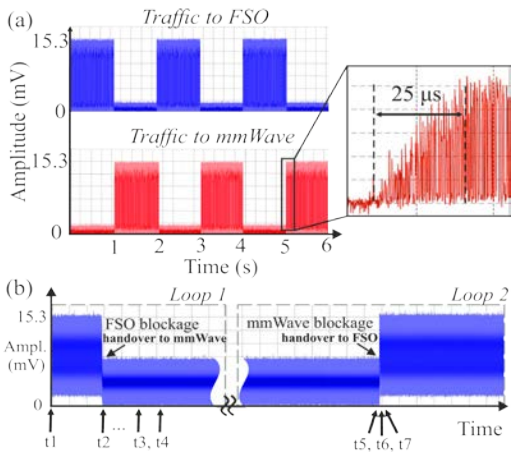

Fig. 6: Dynamic SDN-controlled operation.

An SDN-controlled experiment of time slotted operation at periodic pre-determined slots of 1s with wavelength routed FiWi downlink was tested to evaluate a dynamic on-demand wireless path selection. This was performed by interleaving a 80%-20% coupler in the optical links before each wireless path to monitor the real-time traffic circulated between the servers using a real time oscilloscope (RTO). Fig. 6 (a) shows the captured 1s slotted traffic, indicating a clear separation between the slots of the two FiWi channels. The inset at the beginning of a slot exhibits a rise time of 25µs for the wavelength-routed operation.

Finally, an FSO/mmWave real-time handover operation via an automated SDN process was tested and measured at the RTO using a setting for large time-recording of the 10Gb/s signal for 2s with an ultra-small sampling rate of 5 Ms/s that made the trace appear a bit 'blurry' in the vertical y-axis of amplitude shown in Fig. 6 (b). The seven time indicators t_1-t_7 of the handover workflow of Fig. 3 are marked in the trace. Firstly, an operating FSO link working properly since time *t1* was blocked at time *t2*, resulting in a wavelength switched handover operation that routed the traffic to the mmWave link after 40 seconds. At a later time, the mmWave link was in turn blocked in *t5*, that triggered a subsequent handover back to the FSO link. It worths noting that the test was performed only in the FiWi downlink direction, including all SDN control processes at NIC #1, to reduce the complexity, while in real bidirectional operation, all respective interfaces at the RAN side of the networks also need to be automated.

Conclusions

This work presents the first time real-time, fully-automated, SDN-controlled handover operation of a hybrid Fiber-Wireless FSO/mmWave link, opening a path for highly-resilient broadband FSO/mmWave links in 6G X-haul networks with self-healing capabilities at all weather conditions.

Acknowledgements

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