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Resilient SDN based Small Cell Backhaul Networks using mmWave Bands

Jonathan Vestin and Andreas Kassler

Computer Science Department

Karlstad University

Karlstad, Sweden

Email: {jonathan.vestin, andreas.kassler}@kau.se

Abstract—Due to the tremendous increase in traffic demand, current mobile access and backhaul networks face a capacity problem. To increase the capacity, one can deploy many small cells, which may be dynamically powered on where traffic demand arises. As a consequence, the backhaul network for dense small cell deployments needs to cope with the massive increase in user demands but rolling out fiber to each small cell is economically not viable. Recently, mmWave based mobile backhaul networks have raised a lot of interest because of the large chunk of available spectrum in the 60 GHz, and 70/80 GHz band. However, due to the specific propagation characteristic of mmWave spectrum, such links may face frequent outage. In addition, a more flexible design of the backhaul network is desired in order to cope with the diversification of service requirements. In this paper, we propose a small cell backhaul network architecture which is based on the concept of Software Defined Networking. In order to cope with the dynamics of mmWave links, we propose that the SDN control plane calculates for each backhaul link a set of backup links. Using OpenFlow Fast Failover groups, a fast local repair of a mmWave backhaul link can be achieved leading to a resilient backhaul mesh architecture. An evaluation of our concept in a network emulator demonstrates the effectiveness of our approach. Particularly how it leads to lower packet loss and consequently higher throughput.

I. INTRODUCTION

The ever increasing demand in wireless capacity requires a rethinking of current technologies at all aspects in order to achieve a 1000 fold increase in capacity. Despite introducing new technologies at lower layers such as better modulation and coding schemes or coordinated multipoint transmission, the predicted demand is much higher than what can be supported with new physical layer technologies in the short term. A common assumption to provide increased capacity at scale is to use a higher frequency band where more spectrum is available and to reduce cell size in order to increase spatial reuse. A dense deployment of small cells requires a wireless backhaul solution in order to avoid excessive cabling cost. Using mmWave frequencies (e.g., 60 GHz, 70-80 GHz) for small cell backhauling is particularly interesting as a large spectrum portion is available in that frequency band (e.g., 802.11ad can use up to 2.16 GHz wide channels).

However, high frequencies such as 60 GHz, the radio propagation exhibits different characteristics from typical radio waves using microwave frequencies in ranges up to 6 GHz. The differences are mainly attributed to increased attenuation of

around 20-40 dB caused by high free space loss and atmospheric absorption. In addition, exacerbated blockage and shadowing may lead to rapid variations in link quality which may lead to severely intermittent links changing its characteristics between Line of Sight (LOS), Non-Line of Sight (NLOS) and outage [1]. In order to compensate for the high path loss at these frequencies, directional beamforming antennas based on phased antenna array are typical. Such narrow beams can also be used to circumvent blockage by using a path that follows a reflection supported by specific materials [2]. Consequently, mmWave frequencies enable short range point-to-point (PTP) radio links following LOS or NLOS paths and the connection to the local aggregation gateway (typically co-located at the LTE eNodeB) would be realized with a mesh or tree based wireless multi-hop relaying architecture. Due to the high path loss and the narrow beams, the interference with other mmWave links can be reduced leading to a high degree of spatial reuse.

Backhaul operation is often dominated by proprietary solutions which hinder innovation. An important challenge to solve for small cell backhauling is an efficient but flexible forwarding architecture, which relays user data over the multihop wireless backhaul. Recently, authors such as [3] proposed to use Software Defined Networking for small cell backhauling. In SDN, a centralized controller installs flexible match/action rules that determine the forwarding behavior in the data plane. However, a forwarding configuration addressing the inherent resiliency challenges to cope with potentially instable backhauling links has not been addressed adequately before.

In this paper, we present a resilient forwarding configuration of an SDN based small cell wireless backhaul network. We focus on SDN based resiliency mechanisms, and use the concept of OpenFlow Fast Failover groups. In our proposal, the controller calculates for each link for each small cell node backup links towards the gateway. The main link and the backup link are both put into a Fast Failover group. The small cell node uses rapid link monitoring to locally detect if a link is in the outage stage, in which case the OpenFlow based Fast Failover locally switches to the backup link. Based on a mmWave link model, which we implemented in a network emulator, our experiments show that such local repair actions significantly improve the throughput and packet delivery ratio of mmWave based small cell backhaul networks.

The rest of the paper is structured as follows. In Section II, we present the concept of SDN based small cell backhaul networks

and discuss SDN based resiliency strategies. In Section III, we describe our preliminary evaluation and present experimental results. Finally, we conclude the paper in Section IV.

II. SDN RESILIENCY FOR MMWAVE LINKS

Recently, there has been lots of interest to use SDN for the control of forwarding decisions in small cell backhaul networks [4]. The SDN concept relies on a centralized control plane, which exercises control on forwarding decisions in the data plane. Consequently, the control and data plane are decoupled which allows a very flexible forwarding control. However, using SDN for small cell backhauling pose several challenges. This is because the performance and reliability of mesh based backhaul networks depends heavily on fast local reactions to topology changes, etc, where a centralized control plane is typically too slow to react. Consequently, some authors propose to see the mesh backhaul just as a black box and use proprietary routing and forwarding decisions, based on distributed protocols. Rather SDN is used to steer traffic to the correct ingress point in the proprietary backhaul [5]. In contrast to their approach, we propose to also let the forwarding decisions inside the backhaul be configured by the SDN control plane. We propose to exercise SDN based resiliency mechanisms using fast local restorations (e.g. implemented inside the dataplane of the small cell backhaul nodes), whenever local problems such as link outage transitions of the mmWave backhaul links are detected. This local repair mechanisms, which can be pre-installed, avoid the need to ask the controller how to react in case a neighbor cannot be reached any more, leading to a more robust data plane behavior.

SDN based local repair can be implemented by using Fast Failover groups [6]. A primary and a secondary action are put into the same group and the first live bucket in the group is executed. Consequently, the SDN controller for small cell backhauling calculates for each small cell a primary path towards the gateway. In addition, it would calculate also a backup path, which can be link or node-disjoint. Based on such path calculation, it will install forwarding rules for the primary path but will put an additional backup next hop into the Fast Failover group. Once data packets arrive at a small cell node which should be forwarded to the neighbor small cell using mmWave links, they will be forwarded according to the first port in the group table which port state is up. This requires an OpenFlow datapath implementation which uses for each neighbor a dedicated OpenFlow port. Once the primary port is detected to be down, the packets are automatically forwarded along the next active port, i.e., towards a different neighbor where we have an active link. This allows the Small Cell Node to perform a local failover instead of the SDN controller performing a centralized failover, significantly reducing the reaction time to failures in the mesh forwarding structure.

For detecting the link state, Bidirectional Forwarding Detection (BFD) [7] is a commonly used technology. It determines the state of a port by establishing a connection using a three-way handshake, and subsequently sending periodic control messages over the link. If no response message is received within a specified interval the link is considered down. The timeout

is determined by the control message interval T_i between subsequent BFD messages. Using a short T_i interval [8] we can rapidly detect and react to link failures. Consequently, small cell backhaul nodes would send periodic BFD messages to each neighbor backhaul node over the mmWave links to detect link states. Once BFD detects a link-down event, the link state is set to down, which triggers the OpenFlow datapath to start sending to a different neighbor (the one indicates as next in the Fast Failover Group table). Alternatively, MAC layer protocol messages could be used in order to infer the state of the mmWave backhaul links, which could be integrated into the OpenFlow datapath. A weakness with Fast Failover is that it can only perform local failover. If no alternative local path is available, e.g., all neighbors are not reachable anymore, crankback forwarding must be performed [8]. This means essentially that the packets should be sent back towards the source to a small cell node X, which has an alternative active path towards the destination. Crankback forwarding can potentially have large impacts on the latency. Such latency can be reduced significantly by introducing stateful forwarding in the dataplane using OpenState [9]. If packets arrive at a small cell forwarding node which does not have a next hop towards the destination because the link went down, the node would tag the packet, sent back towards the source, and as it reaches the small cell node X with a backup path, the state of that forwarding rule is changed in such a way that coming packets traverse the backup path already at the node X.

III. PRELIMINARY EVALUATION

We evaluated the feasibility of Fast Failover groups for localized re-routing in small cell backhaul networks based on mmWave links using the CORE emulator¹.

Figure 1. Small Cell Backhaul Evaluation Scenario

Figure 1 shows the network setup used for the evaluation. A small cell backhaul sender and a recipient are connected to a small cell backhaul network, which consists of three small cell backhaul nodes A, B and C. The distance, d , between nodes is 163 m between $C \leftrightarrow A$ and $C \leftrightarrow B$. All other links have a distance of 115 m. The numbers 1 and 2 represent the primary and the backup path respectively. We implemented a probability based model to emulate the properties of mmWave links, which over time changes the link state of each link based on d to be either in Line-Of-Sight (LOS), Non-Line-Of-Sight (NLOS) or outage condition (OUT). In general, the lower d , the higher the probability for LOS. The larger d , the higher the probability for NLOS and outage. For each test we perform, the link state change pattern is the same in order to achieve reproducible results. We scaled down the mmWave link capacities to be able

¹<http://www.nrl.navy.mil/itd/ncs/products/core>

to drive the emulation in real-time. We use 300 Mbps for LOS, 100 Mbps for NLOS while the links in OUT state have 100% loss. Link latency was configured to be 1 ms and we modified the queuing in the emulator to size of the buffer for the link emulation accordingly.

Figure 2. PLR and RTT (no Failover vs Failover) with 10 ms BFD interval.

Figure 2 shows the Round-Trip Time (RTT) and Packet Loss Rate (PLR) for two test scenarios, comparing a single forwarding rule (no failover) with Fast Failover Groups using a BFD interval of 10 ms. The test ran for 17 minutes, and was performed by sending UDP pings of 7 bytes every 20 ms from the sender to the receiver, which the receiver then replied to. The bars represent the average PLR averaged over 10 second intervals, while the lines represent the average RTTs. As we can see, using no failover, the RTT remains stable at around 6 ms (mean 6.22 ms) for the whole test. This is because there are a total of 6 hops between the sender and the receiver, each having a delay of 1 ms. The PLR on the other hand varied between 20% and 46% where the mean is 36%. In the scenario using Fast Failover with a 10 ms BFD interval, the RTT varied between 7.16 ms and 7.88 ms, with a mean of 7.51 ms. The increase in latency was due to the Fast Failover link. When the main link C↔A went into an outage state, BFD detected this, informed the OpenFlow datapath that the link was down and the next packet would be forwarded over the next active link C↔B. This increased the path length, causing an increase in the RTT. The PLR however, decreased to between 5.6% and 33%, with a mean of 19.2%. The decrease in PLR was due to the secondary link being used. When the primary link was in outage state, the secondary link may be in a LOS or NLOS state. As can be seen from the Figure, when the PLR was low, the RTT increased, as the longer path was used.

Figure 3. TCP throughput (no Failover vs Failover) with 10 ms BFD interval.

Figure 3 shows the TCP upload and download throughput of the small cell backhaul network as described above. The test was run using the network performance measuring tool flent², using the realtime response under load (4 bi-directional TCP flows + ping) test for 120 s. We can see that the total TCP throughput increases when we enable Fast Failover from 26.27 Mbps to 63.32 Mbps.

IV. CONCLUSION

In this paper, we have argued for the use of SDN based resiliency mechanisms such as Fast Failover groups for a SDN based small cell backhaul networks. In order to swiftly react to local problems, BFD detects links that go into outage state and pre-configured backup paths are used for fast rerouting. Such a local repair mechanism make it very interesting to apply SDN based control for the small cell backhauling problem. Our evaluation combines network emulation with a mmWave link model and shows that such local repair mechanism can significantly increase performance and packet delivery ratio. As future work, we intend to study how stateful re-routing based on OpenState can improve the performance further and we will also consider better path and backup path selection strategies for small cell backhaul networks based on mmWave links. Furthermore, it is important to investigate the effect of a macrocell, and how to dynamically calculate BFD timers to cope with fast channel attenuation.

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²<https://flent.org/>