Meshed Backhauling of Small Cells Using IEEE802.11ad at 60GHz

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***Abstract*— Wireless backhaul to small cells and remote radio heads is a key enabler for the cost-effective deployment of LTE-advanced and 5G when fibre is too costly. This paper presents a study of a millimetre-wave meshed backhaul deployment using a dynamic system simulator. IEEE 802.11ad technology at 60GHz is assumed. Results demonstrate the viability of the technology over multiple-hops (up to four in the example studied), and show the influence of the number of points of presence (POPs) and the number of radio channels available. The latency of the backhaul is approximately 0.5 ms per hop.**

Keywords—backhauling; IEEE802.11ad; mesh

I. INTRODUCTION

Network densification is a policy to increase the capacity of 4G and 5G mobile broadband. However, provision of backhaul or fronthaul to a small cell or remote radio head is problematic, and the preferred technology choice of fibre is too expensive in many dense urban environments where capacity needs are greatest. Several wireless alternatives exist in the sub-6 GHz, microwave and millimetre-wave bands [1]. This paper focuses on the millimeter-wave V-band at 60 GHz using the standardised IEEE 802.11ad technology [2,3]. This is a point to multipoint technology, typically requiring line of sight and offering link spans of 300-500m with phased-array directional antennae, Fig. 1. Wireless stations are grouped into a number of Personal Basic Service Set (PBSS). Each PBSS is managed by a PBSS Control Point (PCP) which allocates time intervals for each pair of stations in the PBSS to transmit according to traffic needs, quality of service demands etc.

In some millimetre-wave backhaul deployments, the small cell or RRH cannot be backhauled/fronthauled by a single link. Typical reasons are that the span to the POP (point of presence, aka gateway) is too long or blocked by buildings or other obstructions. In these circumstances, a multi-hop connection can be established. If there are more than one possible multi-hop path to the POP then the wireless backhaul network is described as meshed. This offers resilience in the event of a link failure and provides additional capacity for load balancing and other traffic engineering functionality.

Mesh wireless networks have been studied and deployed for many years, often using IEEE 802.11 technologies [4]. Millimetre-wave networks using IEEE 802.11ad and its successor IEEE 802.11ay have received a lot of attention recently [5,6] because the large channel bandwidth (2 GHz), directional antennae and sophisticated MAC promise high performance. They can be used to provide wireless connectivity to homes, buildings or small cells /Wi-Fi access points. Note, however, that there is no inherent mesh support, this must be engineered on top, for example, using switches, Fig. 1.

The link performance in the mesh is determined by the link budget which includes the impact of co-channel interference. Such interference is maximised in the case of a reuse 1 deployment using a single 2 GHz channel. This is potentially very problematic in grid deployments, like the one chosen for the paper, when multiple nodes are placed on a line with no intervening obstructions. A receiving antenna may be aligned directly towards the antenna of an interfering transmitter. This is exacerbated when the nodes are closely spaced, such that the path gain reduction for an overshooting transmission is small. The performance can then be interference-limited. An example of overshoot is shown in Fig. 1. Each mesh node comprises a network processor acting as a switch and four modems. Traffic is backhauled from a basestation via two mesh nodes to a POP which provides a fibre connection to the core network. The transmission from link 1 (Tx1-Rx1) overshoots to add interference at Rx2 which is attempting to receive data from Tx2 (link 2).

In this paper, we model a meshed backhaul network mapped to a cellular deployment in the Eixample district of Barcelona. The objectives are to design the mesh, including channel allocation and routing tables, and to assess the backhaul bandwidth per small cell and the latency to the POP using a dynamic system simulator. The sensitivity of the network performance to the number of channels and the number of POPs is explored. To our knowledge this is the first reviewed contribution on IEEE802.11ad meshing, although generic technologies have been studied [7].

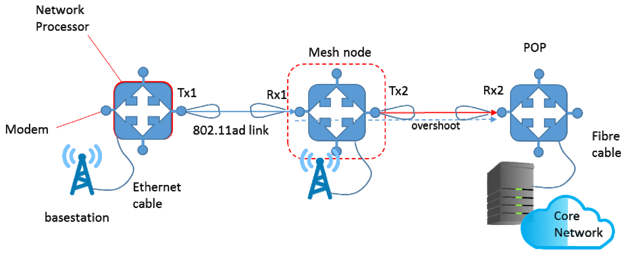

Fig. 1. Small cell backhaul using IEEE802.11ad millimetre-wave links

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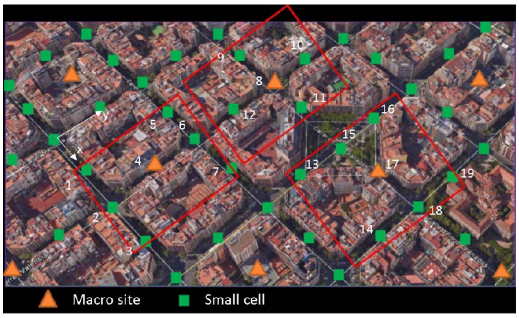


Fig. 2. Cellular deployment under study

II. NETWORK AND SYSTEM MODEL

Network deployment

The cellular deployment under study is shown in Fig. 2. There are 3 macro sites (nodes 4, 8, and 17), with fibre backhaul, that are POPs, and 16 small cells. The red rectangles represent potential clustering of small cells to POPs. The blocks are 133.3 m x 133.3 m giving an inter-site distance for adjacent small cells of 66.7 m. In the simulations, each node was offset from the ideal grid by a random distance within the range of +- 5 m in x and y directions to reflect the difficulty in the site placement.

A. *System simulator*

A dynamic system simulator developed by Blu Wireless using Matlab was used to model the backhaul network. This assumes that the links are formed using IEEE 802.11ad modems employing phased array patch antennae operating in the V-band (60 GHz). Simulation assumptions are in Table 1.

The simulator follows a sequence of steps:

1. Calculate the path gain matrix between nodes.
2. Design the PBSSs and assign channels.
3. Perform route calculation and static simulation to give indicative network performance (e,g, link rates, SNR, SINR).
4. Perform dynamic system simulation in which packets are generated, routed over the mesh with queueing and scheduling for each wireless hop

III. SIMULATION RESULTS

A. *Single Channel (Reuse 1)*

The PBSSs designed by the simulator assuming reuse=1 are shown in Fig. 3. Most PBSSs have only two STA, with the PCP being marked by a circle. However, in the upper right there are some 3-member PBSSs. The routing algorithm selects a subset of the PBSS links (called *routable links*), and we can see that each gateway serves a cluster of nodes, Fig. 4.

The impact of the interference is evident in Fig. 5. Without interference, all links would operate at MCS12 (4.6 Gb/s) since the SNR values are very high (the assumed SINR for MCS12 is 13.5 dB). With interference, four of the 32 routable links drop to MCS7 (1.92 Gb/s). In cases where the interference is high,

TABLE I. SIMULATOR FEATURES

Feature name	**Feature support**	**Notes**
Mesh topology	Supports generic topologies of mesh nodes, where each mesh node comprises a switching element and four IEEE 802.11ad STAs.	The definition of the PBSSs is part of the topology. A PBSS may have more than two stations (STAs) – often called point-to-multipoint
Routing calculator	Route calculation using Dijkstra method	
Radio Model	Thermal noise, worst-case interference, worst-case SINR, worst-case link throughput (and MCS) calculation	Path gains (including antenna gain) for links between STAs of a PBSS that beamform to each other, and path gains of interfering links/beams, are calculated using free-space model (Friis Equation). STAs that do not have line of sight of each other have zero path gain.
	Antenna gain=21 dBi, transmit power 17dBm	
	Rain and oxygen attenuation (combined) 25dB/km	
	Rate adaptation between MCS 1 and MCS12	Single carrier mode of IEEE 802.11ad (OFDM mode is now discontinued in the specification)
Traffic generation models	Constant bit-rate, constant bit-rate with jitter. Bidirectional.	The constant bit-rate with jitter traffic was used with variable packet size (IMIX). The rates were set equal for all nodes, and at values which the most heavily loaded links could support, without searching exhaustively for the maximum sustainable load.
MAC model	Scheduling of transmissions between STAs within each PBSS using Service Period Access	No support for spatial re-use (two STAs in same PBSS transmitting at same time) or relay
	Beacon header interval	
	Aggregation as specified in IEEE 802.11ad	
	Error probability per MAC protocol data unit (MPDU)	Configurable, set to 1%
	Block ACK	IEEE 802.11-2016 Block ACK scheme
	Simulated time	500ms
Delay modelling	Switching delay, delay MAC to switch, delay within the MAC (ingress queue, QoS queueing, retransmission queue, air interface transmission delay, reordering queue delay at receiver)	Switch delay=0.15ms, delay MAC to switch=0.07ms, scheduling advance=0.1ms, max pkt rate=2x10^6/s
Output KPIs	Throughput, latency per packet, queue depth, buffer memory fill (Tx (transmit) or Rx (receive)), inter-link interference matrix, link SINR	

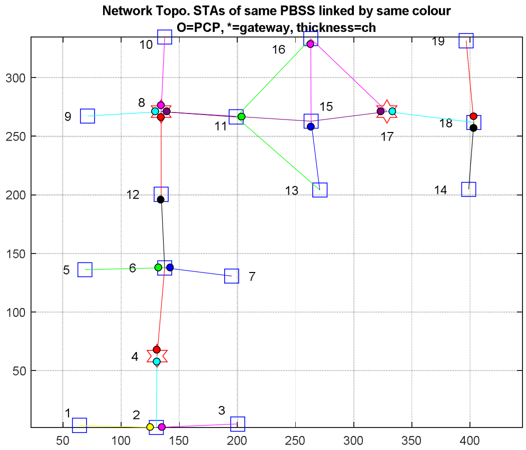


Fig. 3. Assignment of modems to PBSSs (reuse 1, 3 POPs)

there is typically a single strong interferer, see Fig. 5(b). At most there are two hops to a POP.

Using power control it should be possible to reduce interference and push up the rates of some of the links. A simple power control algorithm was tested: the Tx power of a MCS12 link is reduced so that the SINR value falls to the minimum value to support MCS12. Given that 40% of the candidate links for the routing algorithm (i.e. all the PBSS links) support MCS12 there is scope to raise the performance of other links. This is evident in fig. 5(c) where the 10-percentile link rate is raised from MCS7 to MCS10, a throughput gain of 60%.

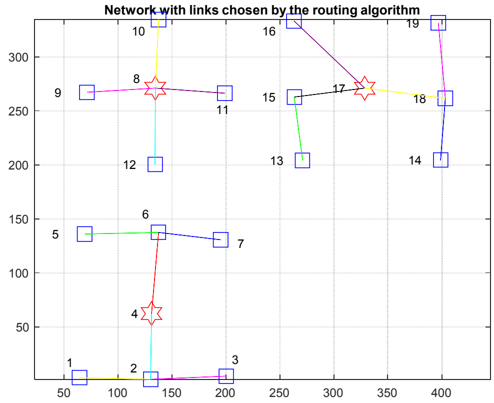
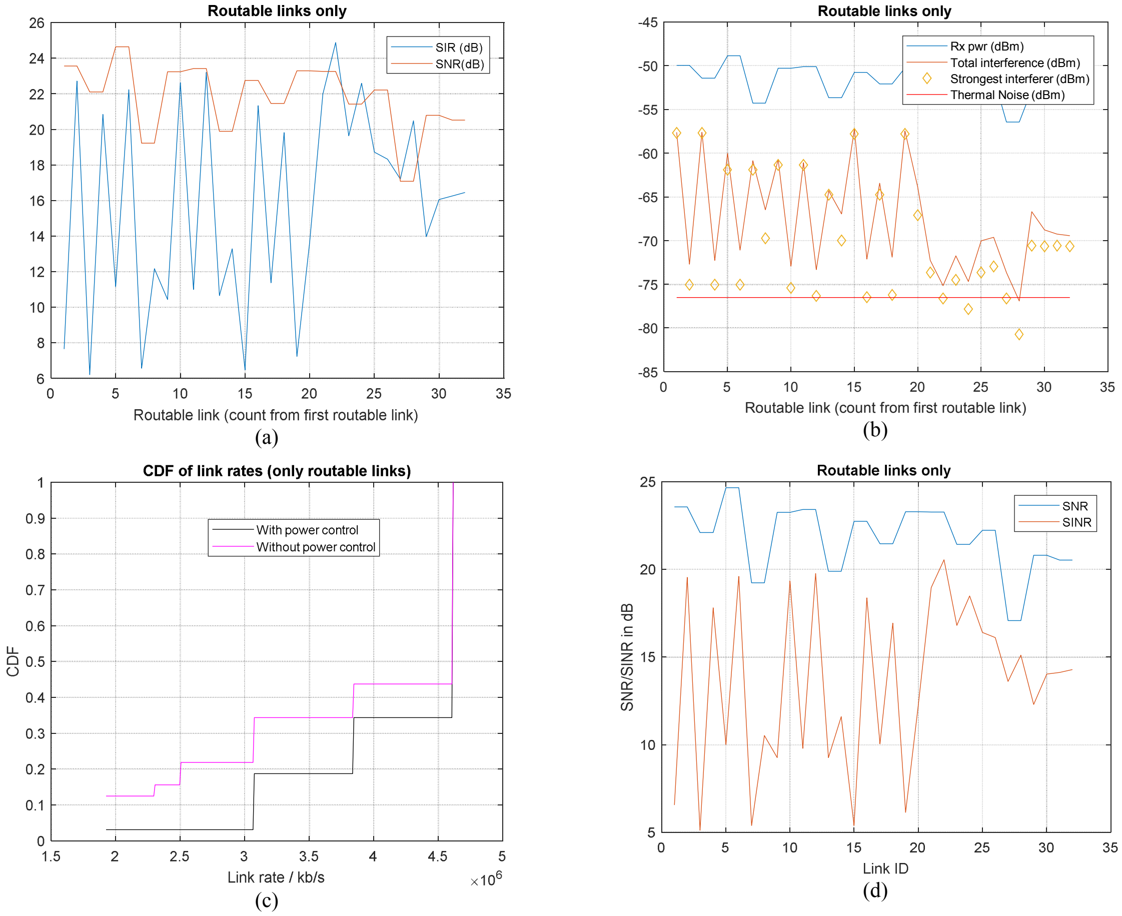


Fig. 4. Links chosen by the routing algorithm (reuse 1, 3 POPs)

For the dynamic simulation, we assumed that there was no power control because this functionality is dependent on the capabilities of the hardware (baseband and RF). The source traffic rate per node (uplink) was set to 100 Mb/s, and the sink rate (downlink) 450 Mb/s. This could represent the backhaul needs of a high-performance LTE-A small cell (with carrier aggregation, MIMO), or the fronthaul needs of an LTE cell using a high functional split, such as split C in [8].



(a)

(b)

(c)

(d)

Fig. 5. KPIs for reuse 1 and 3 POPs: a) SIR & SNR, b) interference power, c) link rates and d) SINR and SNR

The link rates are sufficient to serve the offered rate, even on links to the gateways which carry aggregated traffic. For example, the link between nodes 2 and 4 carries 1.65 Gb/s total traffic (associated with nodes 1,2 & 3).

Throughput and latency metrics are shown in Figs 6, 7 & 8. It is evident that the mean latency is approximately 0.5 ms per hop, for downlink or uplink. Thus, multiple hops will not meet the latency needs of CPRI or split A fronthaul [8]. Even with a single hop, the mean round-trip latency can only be reduced to approximately 100 µs by sacrificing throughput to 800 Mb/s for MCS12 [9]. This indicates the need for new, less delay-sensitive, functional splits to enable the utilization of today`s IEEE 802.11ad mmWave technology for fronthaul.

B. *Three Channels (Reuse 3)*

In Europe, 3 IEEE802.11ad 2 GHz channels are available. Here we add a 3-channel frequency allocation to the network planning to see the performance benefits. Power control is disabled. The channel assignment and PBSS design are shown in Fig. 9. The network links chosen by the routing algorithm are the same as with reuse 1 (see Fig. 4)

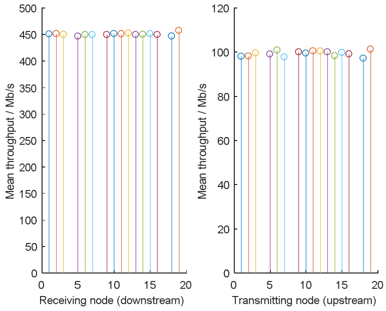


Fig. 6. Throughput per node (reuse1, 3 POPs)

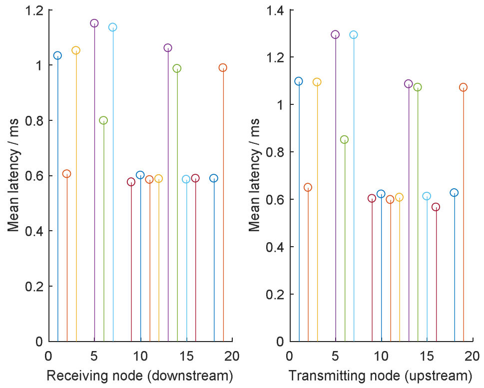


Fig. 7. Mean latency per node (reuse1, 3 POPs)

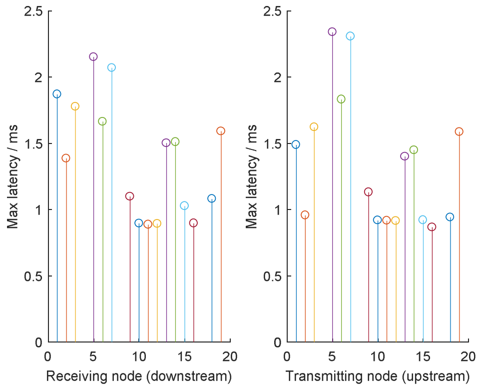


Fig. 8. Max latency per node (reuse1, 3 POPs)

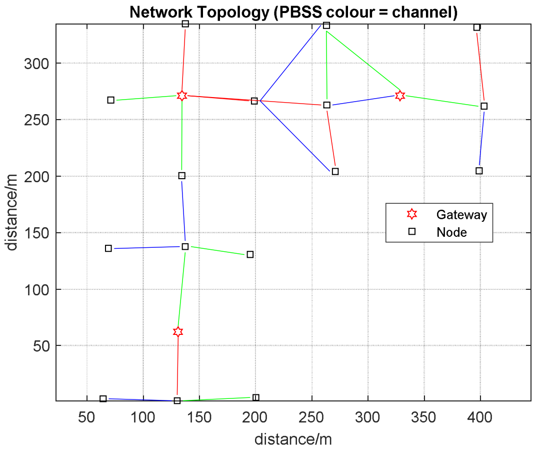


Fig.9. Network design of IEEE 802.11ad modems assigned to PBSSs showing colouring /channel assignment (reuse 3, 3 POPs)

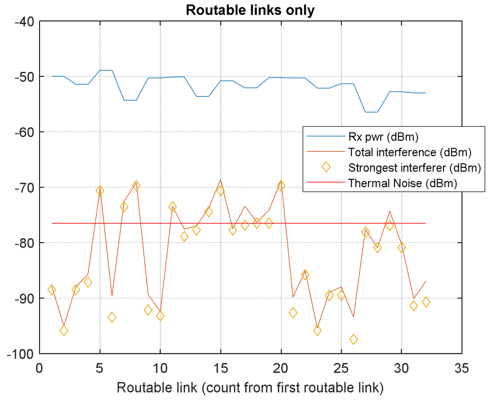


Fig. 10. Impact of interference (reuse 3, 3 POPs)

Looking at Fig. 10, it is clear that the interference is markedly reduced, with many links being thermal noise limited. All routable links now work at MCS12.

If we use the same offered traffic rates as the reuse 1 scenario (450 Mb/s downlink, 100 Mb/s uplink) there is a small reduction in latency, and the same throughput is maintained. However, the higher link rates mean that we can increase the traffic rates, to 750 Mb/s (DL) and 250 Mb/s (UL). It iwas found that the mean latency is approximately 0.5 ms per hop, for both downlink and uplink, with the maximum latency being approximately twice the mean value.

C. *Single POP performance assessment*

To evaluate the influence of the number of POPs the fibre backhaul from nodes 4 and 17 was disabled leaving a single POP at node 8. This will increase the hop count, raising the latency, and reduce the backhaul rates of the nodes because of the aggregation of traffic from the nodes.

The PBSS design algorithm chooses a number of 3 STA PBSSs. When the routing algorithm is applied the links selected form a tree topology, with the unused links available for failover.

The hop count is increased over the 3 POP networks studied above, with two nodes requiring 4 hops to reach the POP.

The reuse=3 network plan ensures that the interference levels are low, as evident by high SINR values. There are three routable links at MCS10, one at MCS11, and the remaining 32 use MCS12.

With the single POP, the backhaul rates per node are limited by the aggregation of traffic which culminates with the final hop to the POP. An offered load of 75 Mb/s uplink and 250 Mb/s downstream was found to be sustainable (no continuous buffer accumulation). Again, the mean latency is roughly 0.5 ms per hop, with the maximum latency only slightly higher.

Finally, Fig. 11 compares the offered load values for the three scenarios, and Fig. 12 compares the latency values. It is clear that the deployment of more POPs and using more channels increases the achievable backhaul rates. The latency depends largely on the number of hops, so it is driven by the number of POPs deployed rather than the number of channels used.

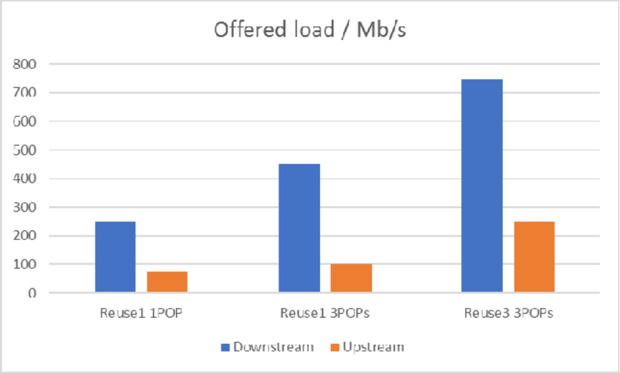


Fig. 11 Comparative traffic load per node for dynamic simulations.

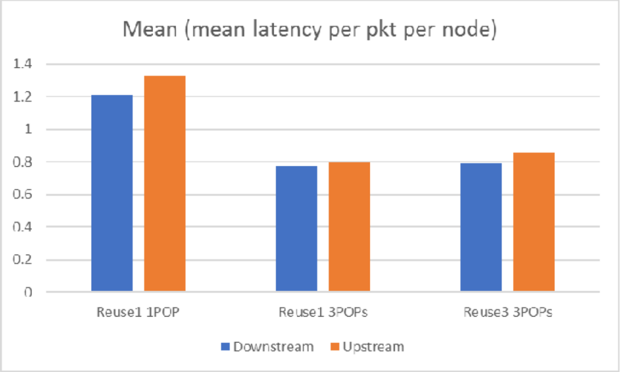


Fig. 12. Mean (mean latency per packet per node) in ms

Whilst this paper has focused on backhauling small cells, the same wireless technology is also suited to last mile internet provision to home, apartment blocks and businesses, known as fixed wireless access. Future work will consider the application to backhauling moving vehicles, in particular, buses and trains [10]. This presents new challenges: channel fading, handover and IP session continuity.

IV. CONCLUSIONS

A system simulator has been used to evaluate the performance of a mmWave meshed backhaul network deployment in the Eixample quarter of Barcelona. The IEEE 802.11ad technology at 60 GHz is assumed. The simulator estimates path and antenna gains between nodes, designs PBSSs including channel assignment, calculates routes and then sends packets over the mesh from small cells to fibre POPs. Even with a single channel it is possible to backhaul all the small cells. The latency is approximately 0.5 ms per hop. The deployment of more POPs and using more channels increases the achievable backhaul rates. The latency depends largely on the number of hops, so is driven by the number of POPs deployed rather than the number of channels used.

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