Modular Approach For Modelling The Hybrid Multi-hop Backhaul Performance

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Abstract

The backhaul is a cornerstone in the development of future cellular networks and not the least challenging. The difficulty of designing the future backhaul is in the expected range of performance metrics that is increasing in breadth and in rising standards. Novel ideas for solving the heterogeneous backhaul problem are frequently proposed. Tractable analytical models that capture the performance of such backhauls are crucial in order to verify and validate these ideas. We present the first modular and scalable framework for analytically modelling the performance of hybrid multi-hop backhauls, which employs technology-specific models of different performance aspects of each hop.

The views expressed here are those of the authors and do not necessarily reflect those of the affiliated organisations. The authors would like to thank the UK Engineering and Physical Science Research Council (EPSRC) and BT Research and Innovation for funding this research through an Industrial Cooperative Awards in Science & Technology (iCASE) studentship. We would also like to acknowledge the support of the University of Surrey 5GIC (http://www.surrey.ac.uk/5gic) members for this work.

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I. INTRODUCTION

Designing the next generation backhaul network is a major challenge. Apart from the pervasive extensions required to cater for the anticipated network densification, the performance requirements of these links are also highly exigent. Optical fibre networks are believed to be the only technology currently developed for migrating users fully to the 5G era. Nonetheless, fibre is not widely available and cannot be laid at the same pace as network growth due to the complicated process of trenching and the associated permit acquisition and cost. Wireless technologies in the millimetre-wave bands, especially the E-band (70/80 GHz) and D-band (141-174.8 GHz), are being developed as alternatives to fibre cables, for certain use cases, with promising potential [1]. A heterogeneous backhaul network is, therefore, unavoidable and perhaps favourable for the launch of 5G services. Recently, innovative resource allocation schemes have been designed to optimise the utilisation of the realistic constrained backhaul network in such a way that the network and users' quality of experience (QoE) is maximised (e.g., [2]). Nonetheless, capturing the hybrid backhaul performance in analytical models is of paramount importance and a prerequisite to the validation of novel backhaul optimisation schemes.

There are many recent works that propose possible ways for addressing this need, often based on stochastic geometry which models the network using elements of point process theory (PP). Authors in [3] propose analytical models that capture the delay and cost of four types of backhaul links: copper-based, fibre-based, millimetre-wave, and sub-6GHz technologies. However, their work assumes that a multi-hop backhaul connection consists of one type of technologies, while different connections may employ different technologies. In practice, though, backhaul connections are often hybrid in addition to being heterogeneous. References [4] and [5] focus on fibre-based backhaul performance modelling. In these works, analytical models for the delay incurred and availability in various topologies are proposed. The models are then used to validate novel schemes for backhaul-aware user association and WiFi offloading. Coverage and throughput derivations in a wireless cellular network are elaborated in [6] and used to develop a general and tractable framework for modelling and analysing joint radio access resource partitioning and offloading in a two-tier cellular network. Outage probability of multi-link wireless backhaul connections is studied in [7] and an analytical model is proposed that accounts for re-transmissions and selection combining.

Each of these works partially sheds light on some aspects of the problem at hand but none offers a scalable model that represents the hybrid nature of existing and anticipated multi-hop backhaul connections. To this end, we develop the first generic and modular analytical framework that is able to capture the performance characteristics of any multi-hop hybrid backhaul, based on the network topology, relevant distances, and mix of transport technologies used. The system model and analytical expressions are presented in Sections II and III, respectively, supported by a numerical example. We conclude in Section IV.

II. System model

5G users' QoE expectations differ greatly from what is offered by incumbent cellular generations. Firstly, 5G users cover a broad spectrum of "things" which include sensors, driverless cars, machines, and humans, each with very different capabilities and needs. Moreover, the applications running on devices have a wider set of QoE requirements, as opposed to the conventional quality measures, such as the user throughput or mean opinion score. The focal quality aspects in 5G are throughput, delay, cost, resilience, security and energy efficiency. These attributes are in principle all dynamic but are likely to vary at different frequencies and their fluctuation is triggered by different phenomena. The proposed system model builds on a set of characteristics that describe the performance of any link in the hybrid backhaul, as defined in Section II-A, and adapts to any given topology as elaborated in Section II-B.

A. *Backhaul constraints and characteristics*

The end-to-end performance of cells is determined by both the radio and the backhaul networks; in this work we propose an analytical modelling of the hybrid backhaul network characteristics. The current backhaul network, which transports incumbent cellular traffic, consists mostly of optical-fibre, copper, and microwave (6-13, 15-23, or 26-42 GHz) links. Some of these links are owned by the cellular operator, others are leased, and some are shared among multiple cellular operators. The 5G backhaul will build on the existing infrastructure and will expand its capillaries and reach to connect the numerous fast-spreading small cells, by relying on new technologies to fill in the gap where needed. The end-result is a hybrid backhaul network composed of a mix of various types of wired and wireless links. The approach we propose for modelling the performance characteristics of such a network is modular. In other words, the backhaul network consists of layers of nodes connected through various links, as shown in Fig. 1.

According to Fig. 1, each small cell s connects to a gateway g in layer $k = K$ through a number of links K_s which differs for every small cell s. Let $\mathcal{C}_l = \{\Theta_l, D_l, C_l, O_l\}$ and $\mathcal{C}_r$ be the sets of characteristics that describe the performance of link, l, and node (or router), r, respectively, where Θ_l (or Θ_r) is the throughput, D_l (or D_r) is the delay, C_l (or C_r) is the cost, and O_l (or O_r) is the outage probability. A hop, h_k, is defined as the connection between a node in layer $k-1$ and a node in layer k and its performance is determined by both, that of the link and that of the router in layer k.

B. *Topology of hybrid backhaul*

Until such times when globally ubiquitous backhaul solutions become available, cell-to-core mobile network backhaul connections are likely to be composed of multi-hops with multiple technologies. Several factors define the topology of such a backhaul and need to be analysed and modelled. Firstly, the number of layers K_s, corresponding to each small cell s, needs to be determined. Urban deployments are often connected through less than three or four layers; whereas, rural cells may require daisy chains, hence up to six or seven layers [8]. The number of layers is thus a variable with a probability density function that can be approximated by a Gaussian distribution and which differs according to the operator, country, and deployment scenario. Let λ_k be the density of nodes in layer k which follow a Poisson PP such that $\lambda_k \leq \lambda_{k-1}$. Let each layer k be characterised by a set of probabilities $\{p_{k,1}, p_{k,2}, p_{k,3}, ...p_{k,T}\}$ such that $\sum_{t=1}^{T} p_{k,t} = 1$, where each $p_{k,t}$ represents the fraction of links using technology t between layer $k-1$ and layer k, for $k > 0$. Let $t \in [1, T]$ be the index corresponding to the technology used, e.g., $t = 1$ corresponds to VDSL, $t = 2$ to G.fast[1], $t = 3$ to EPON, $t = 4$ to XG-PON[2], $t = 5$ to E-band, etc. For instance, for layer $k = 1$ (i.e., the last mile) the probability $p_{1,5}$ of wireless links would be higher than that of fibre links, whereas for layer $k = K$, probability $p_{K,4}$ of fibre XG-PON links is highest. Let X be the variable distance between two layers $k-1$ and k; it may be assumed to follow the following distribution, considering that nodes in lower layers associate with the closest upper nodes [6]:

$$f_X(x) = 2\pi\lambda_k \cdot x \cdot e^{-\pi\lambda_k \cdot x^2} \tag{1}$$

Thus, the mean distance between layers $k-1$ and k is $\mathrm{E}[X] = 1/(2\sqrt{\lambda_k})$ which increases when the density of nodes, λ_k, in the upper layer decreases. According to (1), the expected length of last-mile links connecting to nodes at $1\ \mathrm{node/km}^2$ (typical density of urban small cells' gateway) is 500 m, as shown in the zoomed window of Fig. 2. This matches actual data from a typical Western European mobile network operator. The data represents the distribution of the length of all the hops in the network and shows that backhaul links connected to the core network are the fewest and could reach more than 25 kilometres in length.

[1]Very-high-bit-rate digital subscriber line (over copper); Fast access to subscriber terminal (over copper).

[2]Ethernet Passive Optical Network (PON); 10Gbps capable PON.

III. Hybrid backhaul performance models

The performance metrics of the hybrid multi-hop backhaul are derived in this section and capture the expected end-to-end throughput, latency, cost and outage probability. For demonstration, a four-layers urban network is assumed in which layer zero contains the small cells and layer three the gateways. In this case, all links connected to the gateways are fibre-based, whereas links in other layers are a mix of VDSL and wireless (microwave) links, as shown in Fig. 1.

1) Throughput: The effective throughput of a hybrid multi-hop backhaul connection is constrained by the most limiting hop. Thus, the expected hybrid downlink throughput from gateway g at level $k = K$ to small cell s at level $k = 0$ can be expressed as follows:

$$\mathrm{E}[\Theta_{s,g}] = \mathrm{E}\Big[\min_k \Big\{\Theta_{k,t}\Big\}\Big] = \min_k \Big\{\mathrm{E}[\Theta_{k,t}]\Big\}; \forall t \in [1, T] \mid p_{k,t} > 0;\ \forall k \in [1, K] \tag{2}$$

where, $\mathrm{E}[\Theta_{k,t}]$ is the expected throughput of the hop h_k, that uses technology t. This reflects any adopted topology between the layers, e.g., redundant or paralleled hops. Fig. 4 shows $\mathrm{E}[\Theta_{s,g}]$ of the urban backhaul in Fig. 1 for different penetration of microwave/VDSL links and Fig. 5 for different node densities λ_k. Higher penetration of VDSL or lower node density in layer 2 have higher impact on $\mathrm{E}[\Theta_{s,g}]$ due to longer incurred distances; an impediment in both copper and wireless technologies, but more so in copper.

In these figures, the expected throughput of wireless hops is modeled based on (15) in [6], assuming a propagation exponent equal to four (worst case scenario). Fibre hops' throughput is not modelled as it is not limiting. We propose to model the throughput over a single-hop VDSL link as an exponential decay: $\Theta_c(x) = \Delta \cdot e^{-\delta \cdot x}$, where, x is the length of the copper line, Δ is the maximum achievable throughput and δ is the decay rate, both dependent on the technology and bandwidth used. As seen in Fig. 3, the proposed model fits with the actual measurements, once the parameters have been tuned. In the case of VDSL, these are found to be $\Delta = 105$ Mbps and $\delta = 1.14 \cdot 10^{-3}$. The expected unshared throughput over a VDSL link is thus derived as:

$$\mathrm{E}[\Theta_c] = \int_0^\infty (\Delta \cdot e^{-\delta \cdot x}) \cdot (2\pi\lambda_k \cdot x \cdot e^{-\pi\lambda_k \cdot x^2}) d(x) = \Delta \left(e^{-\frac{\delta^2}{4\pi\lambda_k}} - \frac{\delta}{\sqrt{\lambda_k}} \cdot \left(1 - erf\left(\frac{\delta}{2\sqrt{\pi\lambda_k}} \right) \right) \right) \quad (3)$$

Proof: The expression in (3) may be re-written as $\mathrm{E}[\Theta_c] = 2a \cdot \Delta \int_0^\infty x \cdot e^{-a(x+\frac{b}{2a})^2 + \frac{b^2}{4a}} dx$, with $a = \pi\lambda_k$ and $b = \delta$. This can be rewritten as the sum of two Gaussian integrals using variable replacement where $y = x + b/2a$, $M = 2a \cdot \Delta \cdot e^{\frac{b^2}{4a}}$, and I_1 and I_2 are known integrals with closed form solutions [9]:

$$\mathrm{E}[\Theta_c] = M \left(\int_{\frac{b}{2a}}^\infty y e^{-ay^2} dy + \int_{\frac{b}{2a}}^\infty \frac{-b}{2a} e^{-ay^2} dy \right) = 2\pi\lambda_k \Delta e^{\frac{\delta^2}{4\pi\lambda_k}} \left| I_1 - \frac{\delta}{2\pi\lambda_k} I_2 \right|_{\frac{\delta}{2\pi\lambda_k}}^\infty \quad (4)$$

■

2) Latency: The effective latency of a hybrid multi-hop backhaul connection is the cumulative effect of all delays incurred along the path, as shown below:

$$\mathrm{E}[D_{s,g}] = \mathrm{E}\Big[\sum_{k=1}^{K} \sum_{t=1}^{T} p_{k,t} D_{k,t} \Big] = \sum_{k=1}^{K} \sum_{t=1}^{T} p_{k,t} \mathrm{E}[D_{k,t}] \quad (5)$$

where, $\mathrm{E}[D_{k,t}]$ is the expected delay of the hop h_k that uses technology t. The expected latency of the backhaul in Fig. 1 is shown in Fig. 6 for different shares of wireless/wired links.

Calculating the average packet delay over any link entails looking at four phenomena: the propagation delay (D^p), the transmission delay (D^τ), the processing delay (D^r), and the queuing delay (D^q). The propagation delay is the time difference between the moment a packet is placed on one end of the line and the time it is received at the other end. Propagation delay is thus a function of the distance travelled and the refractive index $\tilde{n}$ of the propagation medium as $\mathrm{E}[D^p] = (1/2\sqrt{\lambda_k})/(\mathfrak{c}/\tilde{n})$, where $\mathfrak{c}$ is the speed of light. The transmission delay is the time taken to push all the packet bits on to the link, hence, is the ratio of the average packet size over the nominal capacity of the channel such as $\mathrm{E}[D^\tau] = \mathrm{E}[\epsilon]/\mathrm{E}[\Theta]$, where $\mathrm{E}[\epsilon]$ is the average length of a packet. The processing and queuing delays occur at the router and are often approximated jointly as a Gamma distribution with parameters that depend on the router, the given load, and technology as in [3]: $\mathrm{E}[D^{r,q}] = \phi \cdot (1 + 1.28 \cdot \lambda_{k-1}/\lambda_k) \cdot (\alpha + \mathrm{E}[\epsilon])\beta)$, where, ϕ and α are representative of the processing power of the router, and β is a factor representing the processing capability of the router with respect to the packet size $\mathrm{E}[\epsilon]$. The processing and queuing delays are often the dominant causes for latency in all technologies, even for wireless links that employ decode-and-forward mechanisms; thus, $\mathrm{E}[D_{k,t}] \approx \mathrm{E}[D^{r,q}_{k,t}]$.

3) Cost: The cost of a hybrid backhaul connection is also the aggregate effect of all expenditures incurred in all comprised links and routers, as expressed here:

$$\mathrm{E}[C_{s,g}] = \mathrm{E}\Big[\sum_{k=1}^{K}\sum_{t=1}^{T} p_{k,t}C_{k,t}\Big] = \sum_{k=1}^{K}\sum_{t=1}^{T} p_{k,t}\mathrm{E}[C_{k,t}]$$

where, $\mathrm{E}[C_{k,t}]$ is the expected cost of the hop h_k connecting layers $k-1$ and k using technology t.

4) Resilience: A multi-hop hybrid backhaul connection is only available if none of its hops is out of service. Thus, the collective outage probability of a multi-hop hybrid backhaul connection is expressed as follows:

$$\mathrm{E}[O_{s,g}] = 1 - \mathrm{E}\Big[\prod_{k=1}^{K}\prod_{t=1}^{T}\Big(1 - p_{k,t}O_{k,t}\Big)\Big] = 1 - \prod_{k=1}^{K}\prod_{t=1}^{T}\Big(1 - p_{k,t}\mathrm{E}[O_{k,t}]\Big) \tag{6}$$

where, $\mathrm{E}[O_{k,t}]$ is the expected outage probability of the hop h_k that uses technology t and reflects the redundancy scheme adopted. As the outage probabilities of different hops are uncorrelated, the expected value of the product can be assumed equal to the product of expected values.

IV. Conclusion

We have presented the first modular approach to capture the performance of future backhaul networks which employ heterogeneous technologies in multi-hop cell-to-core connections. The novel model adapts to the topology, technology-mix, and various hop lengths of any hybrid backhaul and captures its expected throughput, latency, cost, and resilience. Analytical expressions

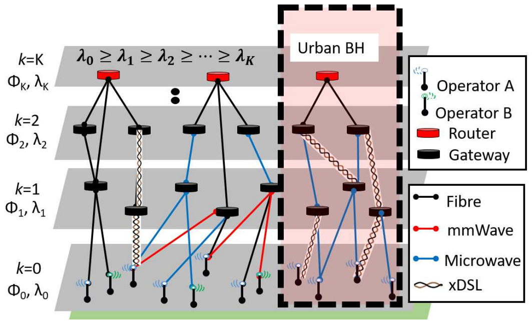

Fig. 1. System model representing a multi-hop and hybrid 5G backhaul. Shown nodes may be pre-aggregation ($k \neq K$) or aggregation ($k = K$) routers. This architecture allows for the representation of transport loops in the backhaul at any stage of the network. The highlighted section represents the urban backhaul example adopted.

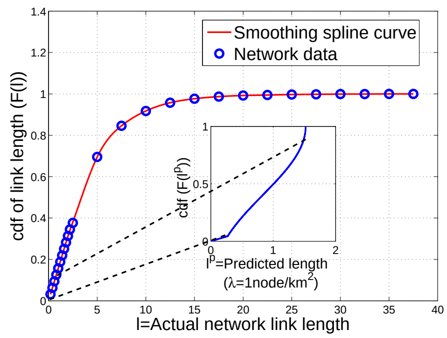

Fig. 2. Cumulative distribution function (cdf) of actual network-wide backhaul link length taken from a typical Western European operator. The zoom-in figure is generated using (1) for a 1 node/km^2 density and matches the actual data.

that model the throughput and latency of technology specific links are proposed and employed to demonstrate the usage of the approach. In a case study that represents an urban hybrid multi-hop backhaul, the impact of varying the share of wireless links on the effective throughput and cumulative latency are studied. Moreover, the model is also used to examine the effect of increasing the node density on the resulting throughput. Such analysis is vital in the evaluation of new backhaul schemes as it enable fast and realistic assessment without the need of simulations.

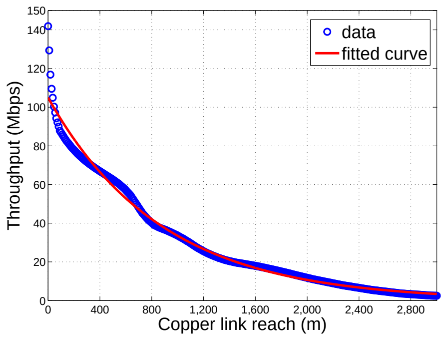

Fig. 3. Typical VDSL throughput variation over a range of copper line length. Blue dots represent measurements from a European internet service provider and the red curve is an approximation model assuming exponential decay.

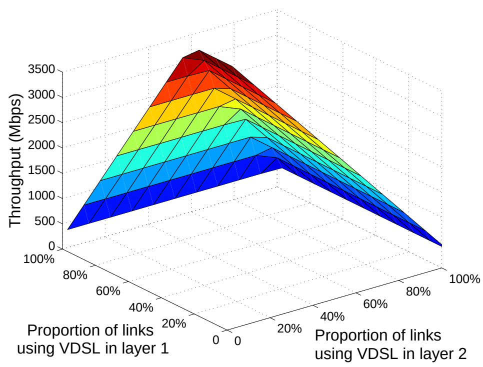

Fig. 4. Impact of varying the share of wireless/VDSL links on the expected throughput based on urban backhaul in Fig. 1.

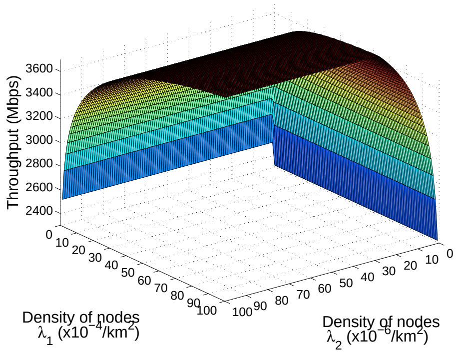

Fig. 5. Impact of node density on throughput for 50% wireless links in layer 1 and 70% in layer 2 based on urban backhaul in Fig. 1.

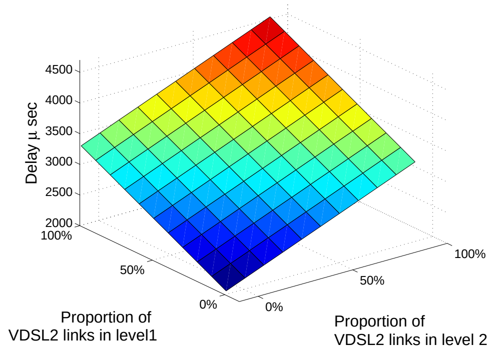

Fig. 6. Impact of varying the share of wireless/VDSL links on the expected delay based on urban backhaul in Fig. 1.

References

[1] ETSI- Millimetre Wave Transmission Industry Specification Group (mWT ISG), "Introduction to millimetre wave transmission industry specification group." [Online], Available: https://portal.etsi.org/Portals/0/TBpages/mWT/Docs/Introduction, Accessed 06/10/2016, 2015.

[2] M. Jaber, M. Imran, R. Tafazolli, and A. Tukmanov, "A distributed SON-based user-centric backhaul provisioning scheme," *IEEE Access*, vol. 4, pp. 2314 – 2330, May 2016.

[3] G. Zhang, T. Quek, M. Kountouris, A. Huang, and H. Shan, "Fundamentals of heterogeneous backhaul design - analysis and optimization," *IEEE Transactions on Communications*, vol. 64, no. 2, pp. 876 – 889, 2016.

[4] F. Aurzada, M. Levesque, M. Maier, and M. Reisslein, "FiWi access networks based on Next-Generation PON and Gigabit-Class WLAN technologies: A capacity and delay analysis," *IEEE/ACM Transactions on Networking*, vol. 22, pp. 1176–1189, Aug 2014.

[5] H. Beyranvand, W. Lim, M. Maier, C. Verikoukis, and J. Salehi, "Backhaul-aware user association in FiWi enhanced LTE-A heterogeneous networks," *IEEE Transactions on Wireless Communications*, vol. 14, pp. 2992–3003, Jun 2015.

[6] J. Andrews, F. Baccelli, and R. Ganti, "A tractable approach to coverage and rate in cellular networks," *IEEE Transactions on Communications*, vol. 59, pp. 3122–3134, Nov. 2011.

[7] D. Ohmann and G. P. Fettweis, "Minimum duration outage of wireless Rayleigh-fading links using selection combining," in *IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 681–686, Mar. 2015.

[8] J. Allen and F. Chevalier, "Report for Vodafone - Mobile backhaul market: Phase 1 report," 2014.

[9] E. W. Weisstein, "Gaussian integral." [Online], Available: http://mathworld.wolfram.com/GaussianIntegral.html, Accessed on 01/11/2016, Last update: Oct 2016.