WiHaul: Max-Min Fair Wireless Backhauling over Multi-Hop Millimetre-Wave Links

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ABSTRACT

The mobile networking community is pursuing densification of small cell deployments to address the capacity crisis inherent to the projected exponential increase in mobile data traffic. Connecting massive numbers of access points to the Internet using optical fibre is however both very complex and expensive. In this paper we tackle small cell backhauling wirelessly, building upon recent advances in millimetre-wave technology. We propose a resource allocation algorithm for aggregate data flows traversing such multi-hop backhauls, and specify WiHaul, a light-weight hierarchical scheduling protocol that enforces the computed airtime shares and coordinates multi-hop transmissions effectively. To achieve high throughput performance while ensuring low demand flows are satisfied, we adopt a max-min fair allocation strategy. Results we present show our solution attains max-min fairness through a non-trivial partitioning of the airtime budget available in cliques of sub-flows, which depends on flow demands, their paths, and the capacities of the links traversed.

CCS Concepts

•Networks → Network resources allocation;

Keywords

mm-wave; multi-hop; backhauling; max-min fairness

1. INTRODUCTION

Recent market surveys highlight increasing user preference for wireless Internet access and growing popularity of bandwidth-intensive applications, which substantially accelerate mobile data traffic demand worldwide [1]. In response, mobile service providers are shrinking cell coverage, while increasing the number of base stations deployed [2]. Such densification requires efficient backhauling, to transfer vast volumes of data between the access and core networks. To achieve high throughput performance while ensuring low demand flows are satisfied, we adopt a max-min fair allocation strategy. Results we present show our solution attains max-min fairness through a non-trivial partitioning of the airtime budget available in cliques of sub-flows, which depends on flow demands, their paths, and the capacities of the links traversed.

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tering low capacity links and increased competition are not unnecessarily throttled. This contrasts with max-throughput allocation strategies that favour large volume flows traversing high capacity links, as well as with round-robin schemes that allocate equal resources and lead to wastage in the presence of low demand flows. We expect max-min fair allocation will ensure flows with inferior demands receive as many resources as possible and assign no less resources to flows with high demands.

We show that when working with service periods (SPs), max-min fair allocation indeed exists and it is unique. We thus give a progressive filling algorithm that takes into account properties specific to multi-hop mm-wave networks, to compute per-hop airtime shares for each aggregate flow. The proposed WiHaul protocol then distributes the computed shares and enables concurrent transmissions between non-interfering links, to improve spatial reuse. Finally, we present numerical results that suggest max-min fair allocation of backhaul resources is achieved with a non-trivial partitioning of the airtime budget available in cliques of sub-flows, which depends on flow demands, their paths, and the capacities of links traversed.

2. MAX-MIN FAIR ALLOCATION

Our focus is on dense mobile broadband networks where LTE base stations and Wi-Fi access points serve end users, and are connected to the Internet wirelessly through multi-hop mm-wave links to gateways. We aim distribute backhaul resources among aggregate flows that originate at different base stations and are forwarded externally by the gateways (uplink), or enter gateways, are relayed by intermediary hops, and reach users through last hop access (downlink).

A key challenge specific to this task is ensuring aggregate flows are treated fairly while traversing the backhaul. Working with a certain type of fairness criterion is often contentious, as operators may favour equal throughput, equal airtime, or mixed allocations. To ensure less intensive flows are not starved, here we work with the max-min fair criterion [5] and thus seek to ensure flow demands are fulfilled in increasing order, where possible, while any remaining network capacity is shared among those with higher demands. This is equivalent to maximising the allocation of each aggregate flow, subject to two constraints, namely (i) the allocated throughput does not exceed the flow’s demand, and (ii) any increase in the allocation of that flow would not cause a decrease in that of others with already smaller or equal throughputs. In what follows we show that a max-min fair allocation in 802.11ad based backhaul exists and give a progressive filling algorithm to compute this. Having found the fractions of airtime to be allocated to each flow segment, we specify a protocol that coordinates the transmissions of all nodes and enforces these allocations.

**System Model:** We consider a network with \( B \) base stations that form narrow beams to communicate with their neighbours and denote \( c_{i,j} \) the maximum achievable data rate between an \((i, j)\) base station pair. According to recent measurements, interference is negligible at 60GHz when employing highly-directional beams and links between any pair of nodes can be regarded as pseudo-wired [6]. Therefore the problem we pursue is different to previous efforts in multi-hop wireless networks, since the system is free of secondary interference, but instead prone to terminal deafness. Further, given the envisioned small form factor of base stations, we expect these to be equipped with a single mm-wave interface and thus, unlike in multi-radio mesh networks [7], intra-flow competition occurs as base stations relay flows.

We denote \( F \) the set of flows traversing the backhaul and \( p_k \) the path of flow \( k \), i.e. the sequence of links this follows from source to destination. We are concerned with carrier-grade backhauling and thus consider multi-hop 60GHz networks that operate with the SP based paradigm, whereby some access points assign transmission times (SPs) in their neighbourhood [4]. By this mechanism a flow \( k \) is assigned an SP of duration \( t_{k,i,j} \) on link \( i,j \) and we find the vector

\[ t = \{t_{k,i,j} | k \in F, i,j \subset p_k\}, \]

that achieves max-min fair allocation of flow throughputs.

We note that single transceiver stations can only send to or receive from one neighbour at a time, and construct a conflict graph \( G(V,E) \) to model which flow segments \( s_{k,i,j} \) cannot be activated simultaneously, i.e. an edge exists between any two such vertices. We group conflicting sub-flows into cliques and note that a sub-flow can belong to multiple cliques. We also define conflict nodes in the original network topology, as those base stations that forward traffic on behalf of others. In the network example shown in Fig. 1, stations 3 and 4 are conflict nodes and we can build the equivalent conflict graph shown in Fig. 2.

Consider a flow \( k \) has a demand \( d_k \) and the end-to-end
throughput to be allocated is $r_k$. We will also incorporate a demand constraint to ensure the allocated rate does not exceed the demand of the aggregated flow, i.e.

$$r_k \leq d_k, \forall k \in F,$$

so that no resources allocated to a flow will be left unused.

Feasibility of Max-min Fairness: To verify whether a max-min fair allocation exists in a multi-hop mm-wave network, we first characterise the network’s rate region. We use the notion of conflict graph and denote $C$ the set of cliques. Any feasible max-min fair allocation must satisfy:

$$\sum_{k,i,j \in C_q} t_{k,i,j} \leq 1, \forall k \in F, \forall C_q \in C.$$

This clique constraint guarantees the total time consumed by all flow segments in a clique does not exceed 1, and can also be expressed as a constraint on the rates, i.e.

$$\sum_{k,i,j \in C_q} r_{k,i,j} \leq 1, \forall k \in F, \forall C_q \in C.$$

**Lemma 1.** The rate region of a multi-hop mm-wave backhaul network is convex.

**Proof.** Since we consider a SP-based method to schedule transmissions, the channel access in a clique can be seen as a single-hop time division multiplex (TDM) instance, which is known to have a convex capacity region [8].

Given that there is no secondary interference between transmissions and the throughput of a sub-flow $s_{k,i,j}$ in a clique $C_q$ is upper bounded by the throughput allocated in the preceding clique $C_{q-1}$ or by the total flow demand $d_k$, the network rate region is obtained by the appropriate intersection of the rate regions of the component cliques, thus it is convex. □

The following key result follows.

**Corollary 1.** Max-min fair allocation in multi-hop mm-wave networks exists and is unique.

**Proof.** By [9], max-min fair allocation exists in compact convex sets and if any max-min allocation vector exists, then it is unique. □

Finally, the network rate region has the free disposal property [9] since each element of the rate vector $\mathbf{r} = \cup_{k \in F} r_k$ is lower bounded by zero and any non-zero feasible allocation can always be decreased. It follows that a progressive filling algorithm can be employed to find the solution to the max-min fair allocation problem in polynomial time.

**Progressive Filling Algorithm:** To achieve max-min fair allocation of the backhaul resources under clique and demand constraints, we specify a progressive filling mechanism which we summarise in Algorithm 1 and whose operation we detail next. We start with all flow rates equal to zero and consider none of the aggregate flows have been allocated resources (lines 1–2). We refer to these as active flows. We gradually increase flow rates simultaneously, in steps of size $\epsilon$ (line 4) until one or more flows either meet their demands (line 6) or activate a clique constraint (line 13). If a flow’s demand $d_k$ is satisfied, we freeze the allocated rate $r_k$ to the demand and remove that flow from the active set (line 8), thereafter considering it inactive and its resources frozen.

When a clique is fully utilised, we stop increasing the rates of the flows traversing it and proceed with computing from scratch the rates these should be assigned according to the remaining airtime budget. To this end, we subtract from the total the fractions already reserved for inactive flows (line 18) and sum the inverse of the link capacities corresponding to active flows in that clique. The latter will allow us to provide all active flows with the same rate $R$ (line 23), while allocating airtimes to each sub-flow that are inversely proportional to the traversed link’s capacity (line 25), i.e.

$$t_{k,i,j} = \frac{t_{\text{left}}}{c_{i,j} \sum_{k,i,j,m \in F \cap C_q} (1/c_{i,j,m})}.$$

With the above it is straightforward to verify that airtimes $t_{k,i,j}$ sum to $t_{\text{left}}$, as required. Subsequently we freeze the rates $r_k$ of flows in clique $C_q$ and remove them from the active set (line 26). We repeat this procedure for the remaining active flows, until meeting their demand or activating other clique constraints. The progressive filling algorithm terminates when the set of active flows is empty (line 3).

Having obtained the airtimes to be allocated for each flow on each traversed backhaul link, the remaining task is to coordinate the transmission of base stations to ensure they steer for TX/RX towards the right neighbour at appropriate times and for the computed durations. Next we introduce, WiHaul, a scheduling protocol that implements this.

**Algorithm 1 Progressive Filling**

1: $r_k = 0, \forall k$ \hspace{1cm} \triangleright Initialisation
2: $F_0 := F$ \hspace{1cm} \triangleright Set of active flows
3: while $F_0 \neq \emptyset$ do \hspace{1cm} \triangleright Loop until all flows allocated
4: \hspace{1cm} $r_k += \epsilon, \forall f_k \in F_0$ \hspace{1cm} \triangleright Increase rates of all active flows with same step
5: \hspace{1cm} for $\forall f_k \in F_0$ do \hspace{1cm} \triangleright Flow satisfied
6: \hspace{2cm} if $r_k \geq d_k$ then \hspace{1cm} \triangleright Flow satisfied
7: \hspace{3cm} $r_k := d_k$
8: \hspace{3cm} $F_0 = F_0 \setminus \{ f_k \}$ \hspace{1cm} \triangleright Remove from active set
9: \hspace{1cm} end if
10: \hspace{1cm} end for
11: \hspace{1cm} for $q = 1 : |C|$ do \hspace{1cm} \triangleright All cliques
12: \hspace{2cm} $t_{k,i,j} = r_k/c_{i,j} \cup s_{k,i,j} \in C_q$ \hspace{1cm} \triangleright Time consumed by each flow segment in $C_q$
13: \hspace{2cm} if $\sum_{s_{k,i,j} \in C_q} t_{k,i,j} \geq 1$ then \hspace{1cm} \triangleright Clique constraint
14: \hspace{3cm} $t_{\text{left}} = 1$ \hspace{1cm} \triangleright Total airtime budget
15: \hspace{3cm} $S = 0$ \hspace{1cm} \triangleright To obtain airtime shares
16: \hspace{2cm} for $\forall s_{k,i,j} \in C_q$ do \hspace{1cm} \triangleright All sub-flows
17: \hspace{3cm} $t_\text{left} = t_{\text{left}} - t_{k,i,j}$ \hspace{1cm} \triangleright Airtime reserved
18: \hspace{2cm} else \hspace{1cm} \triangleright Weight by capacity
19: \hspace{3cm} $S = S + 1/c_{i,j}$
20: \hspace{2cm} end if
21: \hspace{1cm} end for
22: \hspace{1cm} $R = t_{\text{left}}/S$ \hspace{1cm} \triangleright To use for all active flows
23: \hspace{1cm} for $\forall f_k \in F_0$ do \hspace{1cm} \triangleright Rate & airtime
24: \hspace{2cm} $r_k = R/(t_{k,i,j}) = r_k/c_{i,j}$ \hspace{1cm} \triangleright Rate & airtime
25: \hspace{2cm} Freeze $r_k, F_0 = F_0 \setminus \{ f_k \}$
26: \hspace{1cm} end for
27: \hspace{1cm} end if
28: \hspace{1cm} end for
29: \hspace{1cm} end for
30: end while

**3. WIHAUL PROTOCOL**

Terminal deafness is a major challenge in mm-wave networks and unless stations know to which neighbour to steer their beams, when, and for how long, some will be locked out and frame loss will increase, leading to overall performance degradation. To overcome these issues and to convey the airtimes allocated to each sub-flow on each link, and attain max-min fair rates as computed previously, we pro-
pose a network-wide service period (SP) assignment protocol based on a scheduling hierarchy.

To decide the position of a base station $i$ in the scheduling hierarchy, WiHaul takes into consideration the following:

1. Hop distance to the gateway, $H_i$;
2. Conflict state, i.e., $L_i = 1$, if node $i$ is a conflict node, and $L_i = 0$, if it is a leaf node;
3. Node’s unique ID (this can be the IPv6 address).

The protocol first considers all conflict nodes eligible candidates for acting as scheduling coordinators. Among these, the one with the lowest hop distance value ($H$) is designated as the root coordinator and placed at the top of the scheduling hierarchy, namely at Level 0. During announcement transmission intervals (ATIs) of beacon intervals, the root coordinator collects information including flow demands and link capacities, runs the progressive filling algorithm, and computes the airtimes to be assigned to each flow on the links forming their path. Remaining nodes with $L_i = 1$ will be involved in the scheduling, and their level depends on the difference between their $H$ value and that of the main coordinator, $H_c$, i.e., $Level_i = |H_i - H_c|$.

At each level of the hierarchy, a node accepts the time allocated by its parent and assigns SPs to its children. If two or more nodes on the same level share the same child, the node with the smallest ID takes priority and will be the one scheduling. In turn the child informs the other candidate parents of the assigned time, to resolve the tie and avoid conflicts. This process is repeated until all computed SPs have been disseminated to all stations. Subsequently, nodes periodically switch their beams towards the corresponding neighbours for TX/RX during the assigned SPs.

We illustrate WiHaul’s operation in Fig. 3 for the simple topology in Fig. 1, to which we add a 7th station that could communicate with both 1 and 2 (potential scheduling tie). Here, 4 has the lowest $H$ value, so it is the root coordinator and a Level 0 node. The adjacent neighbours of 4, i.e., 6, 3, and 5, form up Level 1. Then, both 1 and 2 are connected to one of the Level 1 nodes, so they will be placed on the next level. Finally, the last $L_i = 0$ node, i.e., 7, is at the lowest level. WiHaul assigns airtime from the top to the bottom of hierarchy. In this case, 4 computes the time allocation for each flow segment and assigns SPs to Level 1 nodes. 5 and 6 simply accept the assigned time, and 3 will further allocate time for 1 and 2, avoiding over-lapping with the schedule assigned between 3 and 4. On the next level, since 1 has a lower index compared to 2, it will make scheduling decisions for 7, which will inform 5 to avoid conflicts.

In practice, to adapt to the dynamics of physical channel conditions and the changing flow demands, the root coordinator will periodically collect the link and flow information, run the progressive filling algorithm and re-schedule flow segments. This can take place across multiple ATIs, whose periodicity depends on the beacon interval (typically 100ms). The progressive filling algorithm’s runtime is a function of the highest flow rate divided by the step-length, which is configurable, and the total number of flows.

4. RESULTS

To evaluate the performance of the proposed max-min fair allocation scheme for multi-hop mm-wave, we consider the topology shown in Fig. 1 and examine the end-to-end flow throughputs and airtime fractions allocated, using Matlab.
flows. For this purpose we consider links have implications on the airtime distribution among cliques, changes in the capacity of the link carrying these and 2Gb/s. Though as some flow segments belong to both cliques, is fully utilised and flow demands are again fixed at 1, 1, the airtime of both cliques in the considered network (Fig. 1)

fore with MCS 12 and 14, and we vary the bit rate on the same capacity (MCS 4), links
demands are fixed and capacity of the network in Fig. 1 operating with heterogeneous link rates, when Figure 5: Flow throughputs (left) and allocated airtimes (right) for the network in Fig. 1; heterogeneous link rates; demand of Flow 3 increases. Time allocations for the network in Fig. 1; fixed demands and capacity of l1,3 increases; more time available for f3 in C2 as c3,4 increases. All flow rates increase. Numerical results.

Cascaded cliques: Lastly, we examine a scenario where the airtime of both cliques in the considered network (Fig. 1) is fully utilised and flow demands are again fixed at 1, 1, and 2Gb/s. Though as some flow segments belong to both cliques, changes in the capacity of the link carrying these have implications on the airtime distribution among all three flows. For this purpose we consider links l1,3 and l2,3 have the same capacity (MCS 4), links l4,5 and l5,6 operate as before with MCS 12 and 14, and we vary the bit rate on l5,4, which is shared by f1 and f2. Observe that as f1 and f2 experience identical link rates, they equally share the airtime available in both cliques. As the quality of l5,4 improves, f1 and f2 consume less resources in C5, which in turn leads to a larger fraction of time allocated to f3, and hence larger throughput not only for f1 and f2, but also for f3.

We conclude that max-min fair allocation of end-to-end throughputs in multi-hop mm-wave backhauls is achieved with a non-trivial partitioning of the airtime budget within cliques, which depends on flow demands, their paths, and the capacities of the links traversed.

5. RELATED WORK

Recent studies suggest highly directional mm-wave links can be modelled as pseudo-wired, since collision induced losses are negligible [6]. Consequently, terminal deafness is a key challenge when scheduling transmissions/receptions [3]. Chen et al. propose a directional cooperative MAC protocol, in which the user device selects an intermediate node to relay the packets to the AP, when the multi-hop path exhibits higher SNR than the direct link [10]. However, the deafness issue is not specifically addressed therein, while resource allocation in multi-hop mm-wave backhauls with fairness guarantees is yet to be investigated.

Max-min fairness was first considered for flow control in wired networks [5]. It was subsequently observed that the existence of max-min fairness is a geometric property of the set of feasible allocations, and if a max-min fair vector exists, then it is unique [9]. 802.11 rate region is proven log-convex, and station attempt probabilities and burst sizes in 802.11 mesh networks were derived for max-min fair regimes [7]. However, this holds in multi-channel mesh points communicating with multiple neighbours simultaneously via different interfaces, which is unfeasible with small form factor mm-wave devices equipped with a single interface.

6. CONCLUSIONS

In this paper we addressed max-min fair rate allocation in mm-wave backhauls built upon IEEE 802.11ad by designing a progressive filling algorithm and a hierarchical scheduling protocol to enforce the computed airtime shares and coordinate multi-hop transmissions. Preliminary results suggest max-min fairness requires non-trivial partitioning of the airtime budget in cliques of sub-flows, which depends on flow demands, their paths, and the capacities of traversed links.

7. REFERENCES