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Urban Wireless Multi-hop x-Haul for Future Mobile Network Architectures

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***Abstract*—This paper presents a mobile network deployment analysis aimed at understanding the potential use of high frequency (mmWave) wireless 'x-haul' to deploy new urban street level micro cell sites. A highly detailed 3D environmental model of central London is constructed and the line-of-sight (LOS) propagation paths between real rooftop cell sites and street level lamp posts calculated in order to simulate all of the potential wireless x-haul paths across the urban environment. Analysis is subsequently carried out to quantify the number of new lamp post mounted micro cell base stations that could be x-hauled using a multi-hop wireless transport solution such as 3GPP Integrated Access and Backhaul (IAB). Results highlight the viability of mmWave wireless transport in real urban environments. Findings also outline the fundamental requirements that a multi-hop wireless transport solution must meet in order to maximise its potential as a lower cost and time-to-market alternative to a fully fibred network.**

***Index Terms*—mobile network, deployment modelling, millimeter wave (mmWave), x-haul, IAB**

I. Introduction

The concept of small cell or street level inclusive heterogeneous mobile networks have been the long term goal of network operators since the adoption of single frequency networks. While many reasons may be attributed to the relatively low volumes of micro cell deployments over the last twenty years the principal draw back to large scale network densification is often the deployment cost associated with securing, backhauling and maintaining such a large volume of mobile infrastructure sites [1]. Studies have shown that $<1\%$ of cells in an established network have an inter-site distance (ISD) <200m [2] - the ISD considered by 3GPP to represent sub-macro cell density (Urban Micro cell UMi) [3].

When considering the capacity growth and spectral efficiency anticipated in a mature 5G deployment, a ubiquitous fibre backhaul network represents the most desirable means of delivering promising new architectures such as centralised/cloud radio access network (C-RAN) [4], distributed MIMO [5] and cell-free massive MIMO [6]. The practical constraints of network planning and design however, mean that alternative transport technologies often represent a more achievable footprint and cost at scale [7]. To date the most widely deployed fibre backhaul alternative for street level cells has been with multi-hop wireless solutions as in Fig.1 where a large choice of frequency bands and technology solutions are possible. Whilst considerable effort has been placed into the wider study of wireless multi-hop backhaul both in terms of optimal path selection [8] and performance [9], such studies have largely been constrained by use of simulated or environmental approximations. Before detailed theoretical approaches are employed it is important to bound the backhaul network deployment feasibility in an accurate real-world environment using deterministic datasets such as that used in this study.

The recognition of the deployment challenges with small cell densification has been particularly evident in recent years with the standardisation of new RAN architectures such as Integrated Access and Backhaul (IAB) within the 3GPP Release 16 specifications [10]. The IAB objective is to minimise the deployment complexity and cost associated with backhauling new street level cells into the network [11]. While the initial standardisation efforts are primarily envisaged for higher layer functional splits and re-encapsulation of 'child node' midhaul/backhaul onto mmWave (>24GHz) access bands, the same deployment barriers still remain for more forward looking RAN architectures. Centralised/cloud RAN approaches seeking to benefit from centralised signal processing of a multitude of geographically separated access points will be dependent on a more stringent lower-layer (fronthaul based) protocol split. The fronthaul interface must therefore be capable of supporting extremely high capacity, low latency transmissions between a centralised processing unit and a low complexity radio head. Such transport requirements are unlikely to be compatible with 3GPP FR2 channel bandwidths or those available in traditional microwave transport bands (6-42GHz) [12] and so any wireless based fronthaul transport solution will likely be underpinned by dedicated higher frequency bands such as D-band (130-174GHz). In D-band, the available channel bandwidths and propagation characteristics align well with the capacity and ISD requirements of ultra-dense networks [13]. There are many initiatives seeking standardisation of new lower layer functional split transport interfaces such e-CPRI [14] and the O-RAN Alliance. It is these efforts which ultimately set the requirements on the transport solution to deliver them. If the long term ambitions of fully coordinated cell-free architectures are to be realised in the face of practical consideration we must understand the viability of a generic wireless x-haul deployment scenarios and the extent to which wireless transport has a role to play

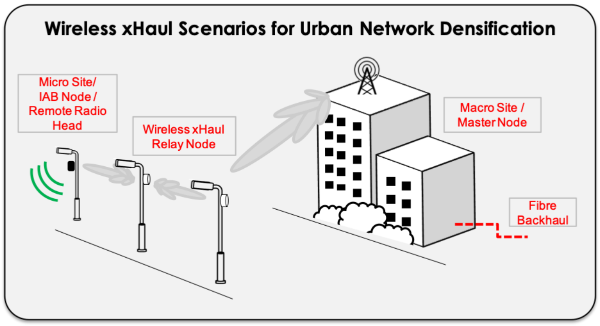

Fig. 1: Wireless multi-hop x-haul scenarios.

in delivering the RAN architectures of the future.

In this study, two new contributions are presented aimed at understanding the real-world deployment requirements of wireless multi-hop transport in realistic dense network deployments. In Section III a cell site demand model is proposed which seeds the 3D environmental model outlined in Section II with new lamp post based street level cells. Here, findings highlight the maximum cell density that could be achieved in a typical urban environment before selection of suitable lamp post infrastructure sites become suboptimal. In Section IV we analyse the LOS paths of the newly built dense cell topology. Results characterise the necessary radio link properties of a high capacity multi-hop transport solution that could connect the new sites to existing macro cell or fibre backhaul locations.

II. Environmental Model

To understand the potential of street level wireless multi-hop transport in ultra-dense RAN deployments a representative city environment is built based on publicly available LiDAR surveys [15]. Here, central London is chosen as a representative urban environment where the resolution of the 3D environmental model is 0.5 m. This provides sufficient resolution to capture detailed urban features such as foliage and street canyon obstructions crucial to accurate mmWave blockage/propagation analysis Fig.2. The model is also built up with existing 3D BT/EE mobile base station sites as well as 3D lamp posts datasets in the same area . The result is a static digital surface model (DSM) suitable for LOS ray tracing between adjacent lamp post sites which represent potential new urban micro cell (UMi) or relay node infrastructure sites and the high frequency wireless x-haul transmission paths between them.

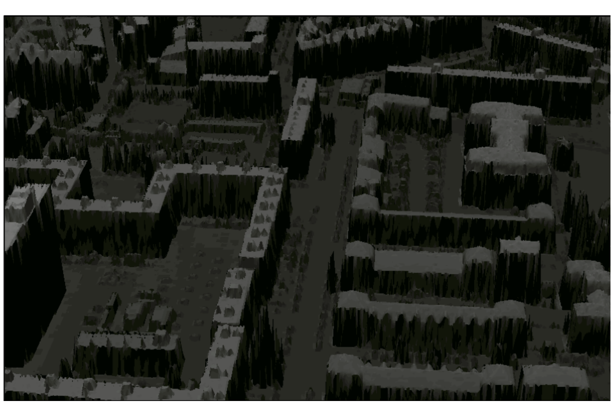

Fig. 2: DSM 3D rendering of central London.

A 2.5 sq km sample area of the central London DSM is chosen where an exhaustive search algorithm is applied to identify all of the unobstructed LOS paths between lamp posts. Each propagation path is classified as LOS where a vector path between each end point is not intercepted by pixels from the underlying 3D surface model (i.e. terrain, buildings or foliage). The LOS analysis results in the discovery of a full mesh of all the possible propagation paths between lamp post sites in the central London study area. In total 136,578 propagation paths between 2226 urban lamp posts (at their native height) are analysed for all possible LOS links. The same area of central London is also covered by 35 existing urban macro cell sites (UMa). The equivalent LOS propagation paths are also calculated between these rooftop based macro sites and the same street level lamp posts within their coverage area - the statistical characteristics of which have previously been reported in [16]. The resulting system model in Fig.3 is a full mesh topology of potential LOS x-haul paths across the urban landscape which can be used to quantify the requirements of high frequency wireless transport solutions in future dense cell network architectures as discussed in Section I.

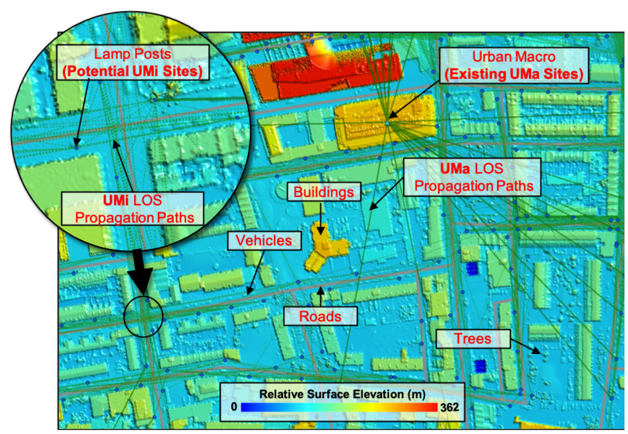

Fig. 3: DSM line-of-sight x-haul full mesh topology.

III. Ultra Dense Demand Model

Before any meaningful deployment scenarios can be investigated the environmental model and its full x-haul path topology need to be seeded with the future expectation of new site locations and densities that could address the anticipated capacity growth in the network. In this study a theoretical demand model is developed where base station density is built up with the objective of minimising the mean ISD distribution of the target area. The study area of central London used is covered by 35 existing macro cell sites with a mean ISD of 305 m as in Fig. 4 which serve as the starting point. A Delaunay triangulation graph is constructed based on the existing macro

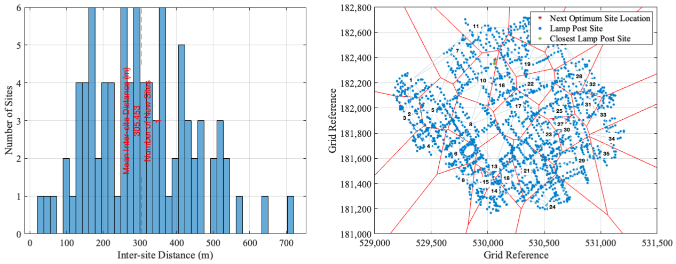

Fig. 4: Existing ISD distribution of study area (no new sites).

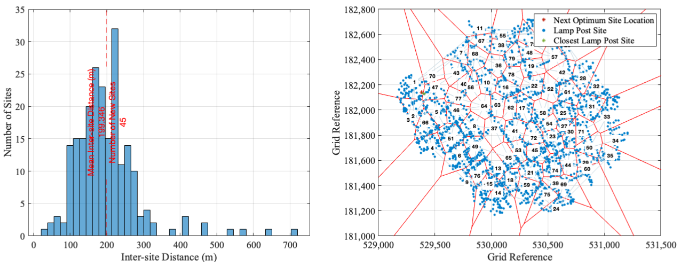

Fig. 5: ISD distribution built to 200 m (45 new sites).

cell locations where the triangulation edges represent the ISD between adjacent cells. The demand model is designed to sequentially add new street level micro cell sites to the lamp post nearest to the incentre of the largest Delaunay triangle. A greedy heuristic optimisation algorithm (Algorithm. 1) aims to maximise the reduction in the current ISD distribution iterating one new cell at a time until the target ISD is met. It is recognised that utilising the circumcentre of the largest Delaunay triangle for placement of each new cell would represent a more optimal solution (where the circumcentre is exactly equidistant from each of the two cell locations that it bisects) however this has the potential to create boundary conditions at the graph edge where cells are placed outside the graphing area. From Fig. 6 (reversed x-axis) it can be seen that for an ISD orientated network deployment, the utilisation of street level lamp post cells holds a near linear density growth only up to ~209 m. A linear regression fit of the data maintains an R^2 value greater than 0.99 until approximately 209 m. Beyond 209 m the cell density enters a more exponential growth profile with diminishing gains for each new site built. This suggests that the use of lamp post or existing street level infrastructure would not be a cost effective deployment scenario for higher cell densities because suitable lamp posts become limiting and cell placement is sub-optimal. As a result, an optimum ISD (from a build/cost perspective) rounded to 200 m is assumed for subsequent analysis. Coincidentally, an ISD cell density of 200 m also aligns with 3GPP UMi ISD deployment assumptions [3]. For a target ISD of 200 m, 45 new street level sites would be required in the study area as shown in Fig. 5. Modelling of the network growth through cell density rather than a more conventional geo-spatial user/traffic demand allows the underlying radio technology and associated configuration of the serving sites to be abstracted away.

With the optimum density of lamp post based cells identified, the 3D physical model can be rationalised into a 2D logical graph problem as shown in Fig. 7. Here, the vertices of the graph represent potential infrastructure locations and the undirected edges represent discovered 3D LOS paths that could be used by a high frequency wireless x-haul solution. The new demand sites represent nodes in the graph which require backhaul and the existing macro sites represent nodes already with backhaul. All other nodes in the graph are remaining lamp posts which may be traversed as 'relay nodes' via the graph edges. In the basic form the graph edge weights are given by physical distance however this can readily be equated to more meaningful performance metrics such as capacity, latency or availability when subsequently applied to specific x-haul interfaces or wireless transport capabilities.

Algorithm 1: Ultra Dense Demand Model

Data: Current_Sites; Potential_Lamp_Posts
while *Current_ISD > Target_ISD* **do**
  Let *dt* = Delaunay Triangulation of Current_ Sites;
  Let *optimal_cell_location* = incentre of largest face in *dt*;
  Let *optimal_lamp_post* = closest point in Potential_Lamp_Posts to *optimal_cell_location*;
  if *optimal_lamp_post has > 0 LOS paths* **then**
    Current_ Sites ← Current_Sites + *optimal_lamp_post*;
    Potential_Lamp_Posts ← Potential_Lamp_Posts - *optimal_lamp_post*;
  else
    Choose next closest point to *optimal_cell_location* in Potential_Lamp_Posts;
  Current_ISD = ISD of Current_Sites;

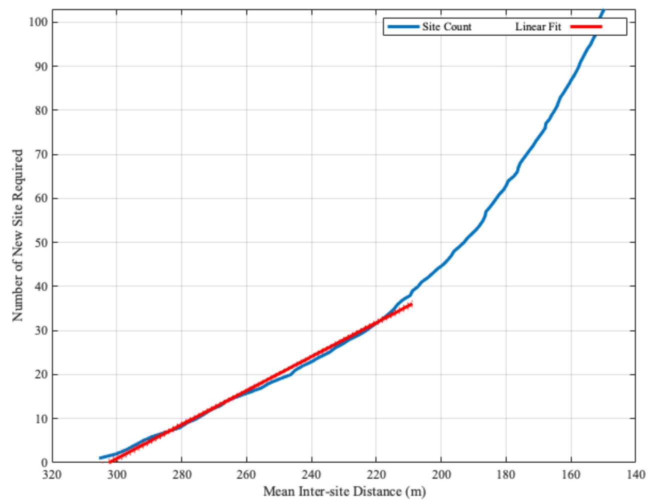

Fig. 6: New cell sites required to meet the target ISD.

IV. Wireless Multi-hop Transport Characteristics and Results

The extent to which wireless x-haul could support the anticipated urban cell densification requirement is assessed through analysis of the undirected node-graph model built in Section III. In the extreme scenario where no new fibre

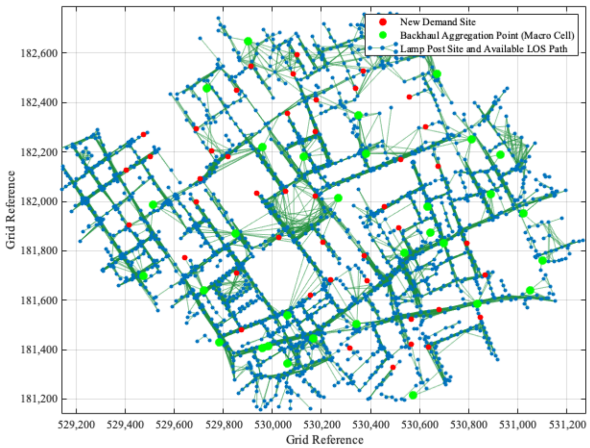

Fig. 7: Logical LOS topology and new cell sites.

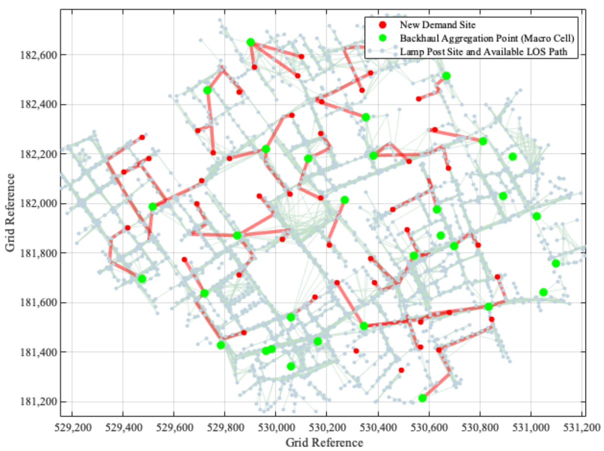

Fig. 8: Optimal x-Haul path determination for new cell sites.

backhaul points are added to the transport network the only core network ingress points in the x-haul topology graph are those of the existing rooftop macro sites. In such a scenario any new street level micro cell sites can only be backhauled into the network via these existing macro sites where it is assumed that there is sufficient capacity (or upgrade capability) to aggregate multiple new street level cell sites. As such we consider the analysis of traversing the graph edges (LOS paths) from each new micro cell lamp post location toward the optimal macro site. This 'no new fibre' scenario represents the upper bound or maximum deployment opportunity of a wireless x-haul roll out.

A Dijkstra shortest path algorithm is utilised to select the optimal route between each newly added micro cell site and its closest macro site backhaul point. The optimum path selection in terms of minimum hop count and minimum distance (in the event of multiple candidate routes) is chosen as a minimal cost oriented deployment. The resulting paths in Fig. 8 are a disconnected subgraph of the overall LOS topology graph in Fig. 7. The optimal x-haul path properties are analysed at 25 m ISD intervals as the site density increases. The number of new sites, the number hops required to reach a backhaul position and the hop length distribution are shown in Fig.9 - 10 and summarised in Table I.

For a mean ISD of 200 m, only 4% of the 45 new sites required could not reach a backhaul point using the discovered LOS mesh topology. Furthermore, 82% could reach a backhaul ingress point within 3 hops (i.e. via 2 relay sites or fewer). A 3 hop limit represents the anticipated practical constraint of multi-hop solutions such as IAB for capacity and latency reasons [17]. In total, 96% of new sites could reach a backhaul point with an unconstrained hop count – the maximum hop requirement observed was 5 (i.e. via 4 relay sites). Analysis of the hop length distribution in Fig.10 highlights the upper bounds of the link budget necessary for solutions looking to address future wireless x-haul deployments. For a 200 m ISD a maximum hop length of 237 m and an average of 107 m was required. The maximum hop lengths observed for each ISD interval typically results from the final hop towards the rooftop macro cell. A multi-hop wireless solution capable of operating within these bounds whilst meeting the capacity, latency and availability targets of transport interfaces used in new RAN architectures would be capable of capturing the vast majority new site demand without the need for new fibre installations. In this 'no new fibre' scenario, to achieve a 200m ISD density would require existing backhaul points to support an additional 2.25 micro cell sites on average with the maximum observed being 4 additional micro cell sites.

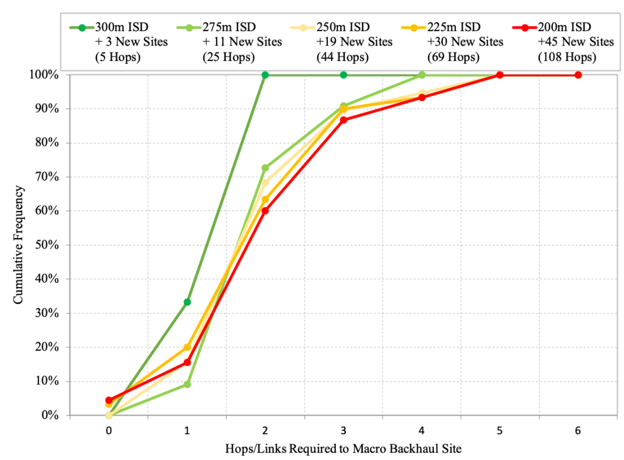

Fig. 9: Hop count distribution for new cell sites.

V. Conclusions

In this study we identify the fundamental requirements of a wireless x-haul transport solution capable of meeting future network densification needs. A deployment rather than a technology led approach is considered using a real-world 3D network topology and environmental model to understand the ideal characteristics of a multi-hop urban transport solution.

Findings show that with sufficiently detailed environment planning data that allows accurate LOS path discovery, 96% of new street level micro cell sites (whether small cell, IAB

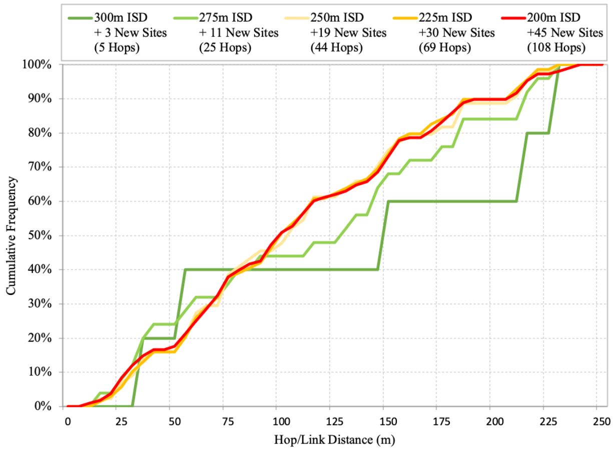

Fig. 10: Hop length distribution for new cell sites.

TABLE I: Summary of x-haul Hop Characteristics.

Target ISD	New Cells Re-quired	New Hops Required	Max Hop Length	% of New Sites Backhauled
300m	3	5 *(2 relay sites)*	230m	100% *(100% ≤3 hops)*
275m	11	25 *(14 relay sites)*	230m	100% *(91% ≤3 hops)*
250m	19	44 *(25 relay sites)*	230m	100% *(89% ≤3 hops)*
225m	30	69 *(39 relay sites)*	230m	97% *(87% ≤3 hops)*
200m	45	108 *(63 relay sites)*	237m	96% *(82% ≤3 hops)*

node or fronthaul based remote radio head) could potentially be x-hauled via the existing macro cell transport network using a mmWave multi-hop extension. Whilst it is unlikely that a wireless only transport solution offers the optimal solution when analysis is expanded to consider some of the capacity and latency constraints of multi-hop radio, this study does highlight the underlying potential of high frequency wireless transport to offer a more cost effective and shorter time to market solution than a fully fibred alternative. As such, future work will focus on overlaying link-level modelling of promising spectrum bands and technologies that could underpin the transport network of future dense network deployments.

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