



Universal Broadband: Geospatial Analysis and Cost Modelling

Network & Cost Module Documentation

v1

9 August 2017

Prepared for:



Cartesian: Universal Broadband – Network & Cost Module Documentation

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Contents

1	Introduction.....	5
2	Scope	7
	Relevant Costs.....	7
	Geographic Coverage	7
	Broadband UBC Definition	7
	Technology Options.....	8
	Timeframe	8
	Model Approach.....	8
3	Technologies in Scope	9
	Overview.....	9
	FTTC (VDSL2 and LR-VDSL)	9
	Technology Overview	9
	Network Components	11
	G.Fast.....	12
	Technology Overview	12
	Geospatial Modelling of the Technology.....	14
	Network Components	14
	FTTP	16
	Technology Overview	16
	Geospatial Modelling of the Technology.....	17
	Network Components	17
	Fixed Wireless Access (FWA).....	19
	Technology Overview	19
	Network Components	19
	Satellite.....	20
	Technology Overview	20
	Network Components	21
	Exchange (for All Technologies)	21
	Overview.....	21
	OCR (Optical Consolidation Rack)	22
	OLT (Optical Line Termination)	22
	Exchange Accommodation Costs	23
	Other Costs	23
4	Geospatial Model Implementation and Assumptions.....	25
	Approach	25
	Data Preparation	27
	Cabinet Technologies Module.....	27
	Dense Clusters Module	29
	FTTP	30
	G.Fast	30
	FTTP and G.Fast Costs.....	30
	Dispersed Premises Module.....	31
	FWA versus FTTP	31

Cartesian: Universal Broadband – Network & Cost Module Documentation

FTTP Only (FWA Switched Off).....	33
Satellite Module	33
Technologies Available	33
Quality Assurance.....	34
5. Network and Cost Modules - Implementation and Assumptions.....	39
Overview of Network and Cost Modules	39
Network Module	39
Overview of Network Module Sheets	39
Bandwidth Demand.....	41
Dimensioning of ‘Physical’ Network Assets	41
Dimensioning of ‘Customer-related’ Components.....	41
Calculate the Buy and Retire for Different Elements	42
Cost Module	43
Overview of Cost Module Sheets	44
Unit Capital Costs	45
Unit Operating Costs	45
Element Unit Costs Trends.....	47
Calculation of Total Costs and Module Outputs	49
6. Glossary	50
7. Data Sources.....	53

Cartesian: Universal Broadband – Network & Cost Module Documentation

List of Figures

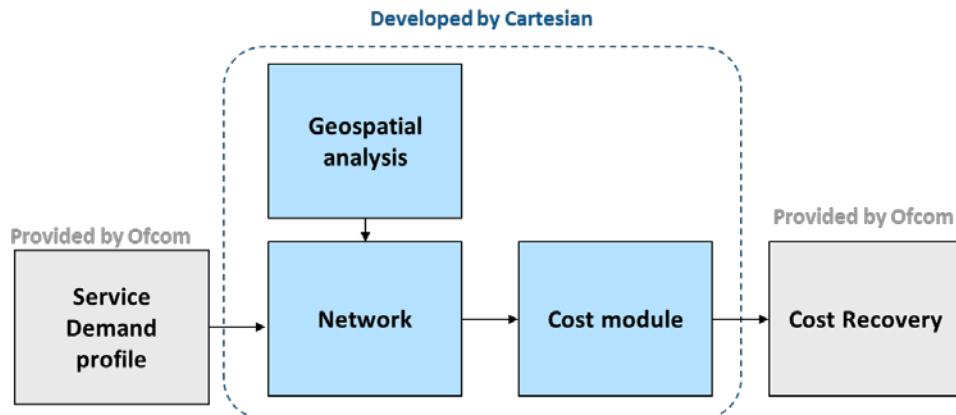
Figure 1.	Overall UBC Model Architecture	5
Figure 2.	Definition of Broadband UBC Scenarios in Scope	7
Figure 3.	High Level Network Architecture: Segments in Scope	9
Figure 4.	Access Network FTTC (VDSL2 and LR-VDSL) Physical Architecture.....	10
Figure 5.	Maximum Copper Loop Length for VDSL and LR-VDSL.....	11
Figure 6.	FTTC Network Components Used in the Analysis	11
Figure 7.	Access Network: G.Fast Physical Architecture	13
Figure 8.	Maximum Copper Loop Length for G.Fast	13
Figure 9.	Access Network: G.Fast Geospatial Model Architecture	14
Figure 10.	G.Fast Cost Items.....	15
Figure 11.	Access Network: FTTP Physical Architecture	16
Figure 12.	Access Network: FTTP Geospatial Model Architecture.....	17
Figure 13.	FTTP Cost Items.....	17
Figure 14.	Access Network: FWA Physical Architecture	19
Figure 15.	FWA Cost Items Considered in the Geospatial Model	20
Figure 16.	Access Network: Satellite Physical Architecture	20
Figure 17.	FWA Cost Items Considered in the Geospatial Model	21
Figure 18.	Network Topology inside the Exchange (Common to FTTC, FTTP and G.Fast)	21
Figure 19.	List of OCR Subcomponents	22
Figure 20.	List of OLT Subcomponents.....	23
Figure 21.	Other NGA Cost Items Used in the Bottom-Up Model	23
Figure 22.	High Level Architecture of Geospatial Model	25
Figure 23.	Approach to Geospatial Analysis.....	26
Figure 24.	Details of Premises Excluded from Geospatial Analysis.....	27
Figure 25.	Coverage Area of LR-VDSL Cabinet for Scenarios with DL 10 Mbps (3.5km)	28
Figure 26.	VDSL and LR-VDSL Costs for Geospatial Model.....	29
Figure 27.	Dense Cluster (Blue Properties) Identified with DBSCAN	30
Figure 28.	FTTP and G.Fast Costs for Geospatial Model	31
Figure 29.	FWA Algorithm.....	32
Figure 30.	FWA Costs for Geospatial Model	32
Figure 31.	Satellite Costs for Geospatial Model.....	33
Figure 32.	Techsets Analysed	33
Figure 33.	Premises and Cost per Premises by Scenario.....	35
Figure 34.	Technology Mix by Scenario.....	36
Figure 35.	Scenario B1: Technology Mix and Cost per Premises	37
Figure 36.	Scenario B1: Technology Mix by Available Technologies.....	38
Figure 37.	Network Module Overview	39
Figure 38.	Element Dimensioning Approach.....	42
Figure 39.	Asset Lifetimes by Equipment Type	43
Figure 40.	Cost Module Overview.....	44
Figure 41.	Composition of Unit Operating Costs in the Bottom-Up Model.....	45
Figure 42.	Linear Cost Trends by Category in Bottom-Up Model (Capital Costs)	48

Cartesian: Universal Broadband – Network & Cost Module Documentation

1 Introduction

- 1.1 In March this year, Ofcom consulted on its 2017 Wholesale Local Access (WLA) market review. The market review includes detailed bottom-up modelling of a superfast broadband network using Fibre To The Cabinet (FTTC) to inform the proposed charge control on BT, and Cartesian was hired by Ofcom to assist with this.
- 1.2 In April, the Digital Economy Act 2017 received royal assent. The Act contains enabling powers for a broadband universal service obligation (USO) to be specified by secondary legislation.
- 1.3 On 30 July 2017 DDCMS And BT announced a voluntary commitment from BT to provide a Universal Broadband Service (referred to as ‘Universal Broadband Commitment’ or ‘UBC’), the details of which have not yet been finalised. Ofcom is now consulting on proposals to include the efficiently incurred costs associated with implementing the UBC in the WLA Charge control (WLACC).
- 1.4 To enable Ofcom to be in a position to include any efficiently incurred costs by BT associated with WLA-specific elements of any universal broadband service in the current WLA market review, should that prove necessary, Ofcom commissioned Cartesian to carry out a detailed cost analysis, taking into consideration a range of input variables and potential deployment scenarios.
- 1.5 Cartesian’s analysis sought to address two key questions: (i) what is the most cost effective combination of access technologies that will meet the UBC objectives in a given scenario; and, (ii) what are the WLA-specific costs of such a deployment.
- 1.6 To address these questions, Cartesian developed three separate but inter-related models:
 - The Geospatial analysis calculates the most cost effective technology mix, and produces a set of results which are used by the Network module;
 - The Network module takes the outputs from the Geospatial analysis and the service demand forecasts (Ofcom provides the Service Volume module) to dimension the access network;
 - The Cost module calculates the capital and operating expenditure required to build and operate the dimensioned access network.
- 1.7 The outputs from the Cost module are used by the Cost Recovery module, developed by Ofcom, to calculate how costs are recovered over time and across services. Figure 1 below shows the relationship between the modules.

Figure 1. *Overall UBC Model Architecture*



Source: Cartesian

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1.8 This document provides an overview of Cartesian's methodology and results:

- Section 2 defines the scope of the analysis;
- Section 3 describes the access network technology options;
- Section 4 describes the Cartesian's methodology for determining the most cost-effective combination of technologies and its costs; and,
- Section 5 sets out the results.

1.9 This report accompanies version [to be inserted] of the cost model.

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2 Scope

Relevant Costs

2.1 The objective of the analysis is to determine the incremental costs that BT would efficiently incur were it to fulfil the UBC (excluding the cost of any fixed wireless deployment).

Geographic Coverage

2.2 The geographical scope of the analysis is the market proposed in the WLA MR as being the UK excluding Hull. In this area, BT has Significant Market Power (SMP). The scope includes all premises in this area not receiving the broadband universal service. The assessment of premises not receiving the required service takes into account commercial deployment by BT, rollout under state aid programmes such as BDUK and deployment by other telecoms providers.

Broadband UBC Definition

2.3 The detailed scope of the broadband UBC was still being discussed when the modelling was being undertaken. Consequently, the initial scope included three scenarios:

- i. Downstream speed above 10Mbit/s; No minimum upload speed
- ii. Downstream speed above 10Mbit/s; Minimum upload speed above 1Mbit/s; Committed Information Rate¹ (CIR) = 1.5 Mbps
- iii. Minimum downstream speed above 30Mbit/s; Minimum upload speed above 6Mbit/s; CIR = 10 Mbps

2.4 The source of the data on premises eligible for the Universal Broadband service is Connected Nations 2016. Due to the variable nature of broadband performance over copper lines, Communications Providers (CPs) provided a predicted speed range for the Connected Nations report. Therefore, for each scenario we were provided with two datasets: one using an ‘optimistic’ line performance (20th percentile minimum guaranteed access line speed provided by CPs); and another one using a ‘conservative’ line performance (80th percentile). Therefore, the total number of scenarios doubled to six:

Figure 2. *Definition of Broadband UBC Scenarios in Scope*

	Scenario A1	Scenario A2	Scenario B1	Scenario B2	Scenario C1	Scenario C2
DL / UL / CIR	10 / - / -		10 / 1 / 1.5		30 / 6 / 10	
Range	Optimistic	Conservative	Optimistic	Conservative	Optimistic	Conservative
Eligible Premises	1,338,995	3,945,992	2,562,222	4,123,085	3,501,294	5,436,829

Source: Ofcom, Cartesian

¹ Committed Information Rate is the minimum guaranteed throughput that a network must deliver for the service under normal operating conditions.

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Technology Options

2.5 The analysis considers the following broadband access technologies:

- VDSL2 deployed at the Cabinet (VDSL2/FTTC)
- Long-Reach VDSL deployed at the Cabinet (LR-VDSL/FTTC)
- G.Fast deployed at the distribution point
- Fibre to the Premises (FTTP)
- Fixed Wireless Access (FWA)
- Satellite

2.6 In addition to assessing the most cost-effective combination of all the above technologies, the analysis considers scenarios in which subsets of the technologies are included.

Timeframe

2.7 Time periods in the analysis are financial years (FY), i.e. April to March. The cost model considers a 12-year period, from 2017/18 to 2028/29.

2.8 The analysis assumes that broadband UBC deployment starts in 2017/18. The deployment profile is flexible in the cost model: the number of years and intensity of the network rollout each year are input parameters.

Model Approach

2.9 An incremental approach has been followed in the model, which includes only those components that are specific to the broadband UBC service. We have assumed that the UBC deployment will use available spare capacity at existing FTTC cabinets deployed by BT, both from BT's commercial roll-out and in BDUK areas². BT's FTTP areas are deemed not to contain UBC-eligible premises given FTTP's performance, therefore we don't assume any re-use of existing capacity. We also assume we can reuse a percentage of BT's existing ducts and poles across the various segments of the access network where new cable would be required (more details in section 3).

2.10 The network module employs a scorched node approach.³ In this context, *node* refers to the Exchange, PCP and FTTC Cabinets: The bottom-up model uses route lengths that are derived from the distances between the actual locations of BT's assets and the UBC-eligible premises.

² We have predicted the spare capacity at the FTTC cabinets in 2020/21 which is the point to which the commercial cabinets in the WLA CC model the commercial cabinets were dimensioned to meet expected demand. To do so, we calculated the average increase in FTTC lines per cabinet from the WLA model, and applied this to the figures of current FTTC subscribers per cabinets, which was provided by BT via Ofcom.

³ In a scorched node approach, the existing network nodes are considered to be fixed. All other network elements can be optimised.

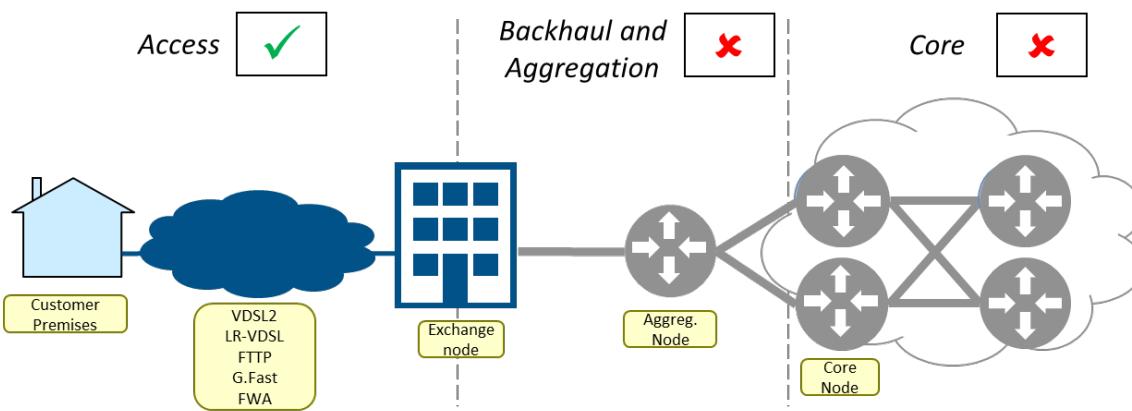
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3 Technologies in Scope

Overview

- 3.1 The analysis comprises the access network segment from the premises to the Exchange node for all the technologies in scope (except for Satellite, which is treated as a reseller service). Figure 3 provides a high-level overview of the network architecture, identifying the segments in scope for the model.

Figure 3. *High Level Network Architecture: Segments in Scope*



Source: Cartesian

- 3.2 As per paragraph 2.9, only those network elements which are specific to the UBC are included in the geospatial analysis and cost model. In the following sections, we detail the characteristics of each technology and how we modelled them at the geospatial analysis.

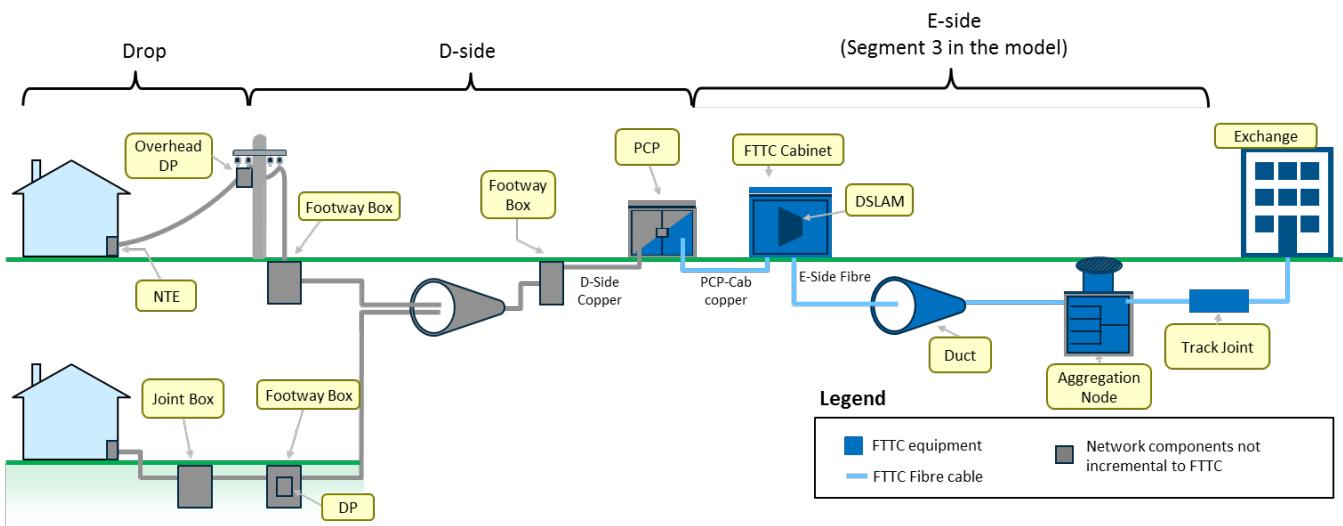
FTTC (VDSL2 and LR-VDSL)

Technology Overview

- 3.3 The two Fibre-to-the-Cabinet (FTTC) technologies in scope for the model, VDSL2 and LR-VDSL, have the same physical topology: the existing copper infrastructure from the premises to the PCP is reused, and next to the PCP an FTTC cabinet is deployed. Inside each FTTC Cabinet is a DSLAM, which multiplexes the VDSL2/LR-VDSL connections from a number of subscribers into an Ethernet link connected to an Exchange. BT Openreach uses VDSL2 for its national Generic Ethernet Access-FTTC access product. See the high-level architecture in the figure below.

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Figure 4. Access Network FTTC (VDSL2 and LR-VDSL) Physical Architecture



Source: Cartesian

- 3.4 LR-VDSL is a modified version of VDSL, designed to deliver higher broadband speeds on longer-length copper loops. Openreach ran a small-scale technical Proof of Concept of LR-VDSL in May 2016 and started a trial in March 2017 in nine geographic locations⁴. The key changes over VDSL2 are listed below⁵:
- Changes to the VDSL protocol to enable it to synchronise on long loops. As approval of the amendments to the protocol is expected for late FY 2017/18, Openreach will use an existing VDSL2 profile (8b) which allows a higher transmit power to boost performance of existing lines, but does not allow synchronisation over long copper loops.
 - Removal of Power Spectral Density (PSD) shaping for low frequencies and boosting it for the LR-VDSL frequencies.
 - Enabling vectoring
- 3.5 The downside of LR-VDSL is that it introduces crosstalk into exchange-based broadband, e.g. ADSL, ADSL2/2+. As a result, ADSL customers (including any variants of ADSL) that are served on copper lines that pass through a LR-VDSL cabinet will need to be migrated to VDSL / LR-VDSL to avoid service degradation. A cost item for ADSL migrations is included in the analysis.
- 3.6 The performance of VDSL2 and LR-VDSL heavily depends on the length of the copper subloop from the cabinet to the premises. In our analysis, we have used values of maximum loop lengths for each FTTC technology and scenario that are consistent with those used in Ofcom's December USO report.⁶ In our analysis, we use Ofcom's recommended values of maximum loop lengths for each FTTC technology and scenario, shown in the table below (lengths are adjusted by a factor of [1.3] to determine the maximum radial distance from the cabinet).

⁴ Long Reach VDSL: Overview, Trial Update and Industry Consultation

⁵ More details in Openreach's document 'LR-VDSL GEA-FTTC Delivering faster broadband to more customers, Industry Consultation'.

⁶ Estimating the cost of broadband Universal Service Obligation, available at https://www.ofcom.org.uk/_data/assets/pdf_file/0027/95580/annex6.pdf

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Figure 5. **Maximum Copper Loop Length for VDSL and LR-VDSL**

	Scenarios A-B (10Mbps DL)	Scenarios C (30Mbps DL)
VDSL	1.9 km	1.3 km
LR-VDSL	3.5 km	1.8 km

Source: Ofcom

Network Components

3.7 To model the FTTC technologies, we have used the same list of network components and capacity values as in the model developed by Cartesian for Ofcom's recent WLA consultation⁷. The model report (Annex 20 in the WLA consultation) explains the components in detail, detailing the subcomponents included in them. The table below summarises the list of the FTTC network components:

Figure 6. **FTTC Network Components Used in the Analysis**

Element	Drivers	Capacity	Description
Cabinet DSLAM (Types 1 / 2)	Subscribers	128 / 288	Includes also equipment in the cabinet to ensure correct working (e.g. battery back-up, security system, fan, Power Supply Unit, etc.)
DSLAM Access Card (Types 1 / 2)	Subscribers	32 / 48	Type 1 Cabinets fit 4 Access Cards Type 2 Cabinets fit 6 Access Cards
DSLAM GE Port	CIR and Cabinet	1000 Mbps	We assume an 80% utilisation of the bandwidth, and a minimum of 1 port per Cabinet. Therefore, number of ports = MAX (800/CIR, 1)
Cabinet Power Connection	FTTC Cabinet	1	Includes Survey and pre-work, Power Certification, Electricity Meter supply, Telemetry Line
Cabinet Civils	FTTC Cabinet	1	Includes Concrete Base, earthing mat, Tube Intercept Joint
Cabinet Certific. Managed Service	FTTC Cabinet	1	Includes Power Duct, Power Joint and Management of power connection
PCP Re-shell	PCP Cabinets	0.18 ⁸	Required for those PCP with insufficient capacity to fit Tie Cables from the FTTC Cabinets.
PCP Connector	PCP Cabinets	1	Required to connect the copper cables from the DSLAM to the PCP
PCP Duct to FTTC Cabinet	FTTC Cabinet	1	Includes the duct installation, for the average length between FTTC Cabinets and their PCPs (WLA model)

⁷ <https://www.ofcom.org.uk/consultations-and-statements/category-1/wholesale-local-access-market-review>

⁸ This number has been randomised to maintain confidentiality.

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Copper to Cabinet (Types 1 / 2)	FTTC Cabinet	1	Includes the cable and cable joint, for the average length of copper cable between FTTC Cabinets and their PCPs (WLA model)
Segment 3 Fibre	Metres / PCP Cabinets	1	In the geospatial analysis, we calculate the average Segment 3 ⁹ fibre length per PCP Cabinet (referred to in the model as 'FTTC Cabinet Location'). The cost includes the installation and splicing of a 48f cable ¹⁰
Segment 3 Fibre Testing	GE port	1	Includes the cost of testing a fibre from the Cabinet back to its Exchange
Segment 3 Duct and Pole	Metres / PCP Cabinets	1	We use the same average length as with the fibre cable cost item. We used a blended unit cost of self-build and existing duct ¹¹
Segment 3 Track Joint	PCP Cabinets	0.05 ¹²	Passive elements to aggregate and distribute the fibre from the Exchange to the Cabinet. We use the same proportion of Track Joints and Aggregation Nodes per PCP cabinet as in the WLA model
Segment 3 Aggregation Node	PCP Cabinets	0.7 ¹³	
ADSL Migration (LR-VDSL only)	ADSL subs in LR-VDSL cabinets	1	We have estimated the unit cost of migrating an ADSL customer to LR-VDSL by adding the cost of a CPE ¹⁴ , and the labour cost of an on-premise installation.

Source: Ofcom, BT, Cartesian

G.Fast

Technology Overview

- 3.8 G.Fast is a variant of DSL which is optimised for delivering very high speeds over very short copper loops. The G.Fast DSLAM multiplexes the copper connections from a number of subscribers into a port connected to a local Exchange
- 3.9 G.Fast DSLAMs may be deployed at the cabinet or closer to the end-user premises. In our analysis, we only consider the latter which is usually referred to as FTTdp (Fibre To The distribution point).¹⁵ The figure below depicts the high-level architecture for the FTTdp deployment of G.Fast.
- 3.10 Openreach is currently deploying cabinet-based G.Fast by connecting the PCP with fibre and fitting an extension pod to the cabinet to house the G.Fast line cards¹⁶. In the future it is expected that

⁹ Segment 3 refers to the estimated route distance between an FTTC Cabinet and its Local Exchange.

¹⁰ After running a sensitivity analysis on the cost of a fibre cable for different fibre counts, using data from the WLA cost model, we found little variance, e.g. a 24f cable costs only 4% less than a 48f cable. Therefore, we have assumed that we use a 48f cable across both segments 1 and 2 for all fixed technologies.

¹¹ We used the same mix of duct and poles as in the report commissioned by Ofcom 'Estimating the cost of a broadband Universal Service Obligation'. For segment 3, it corresponds to 20% self-build and 80% re-use of existing duct.

¹² This number has been randomised to maintain confidentiality.

¹³ This number has been randomised to maintain confidentiality.

¹⁴ Following advice from Ofcom, we only consider the cost of the CPE in the geospatial analysis, but it will not be included in the UBC Network Cost Model.

¹⁵ G.Fast at the cabinet is not considered as it has a shorter reach than VDSL2 and LR-VDSL which makes it less suitable for serving UBC-eligible premises from the cabinet.

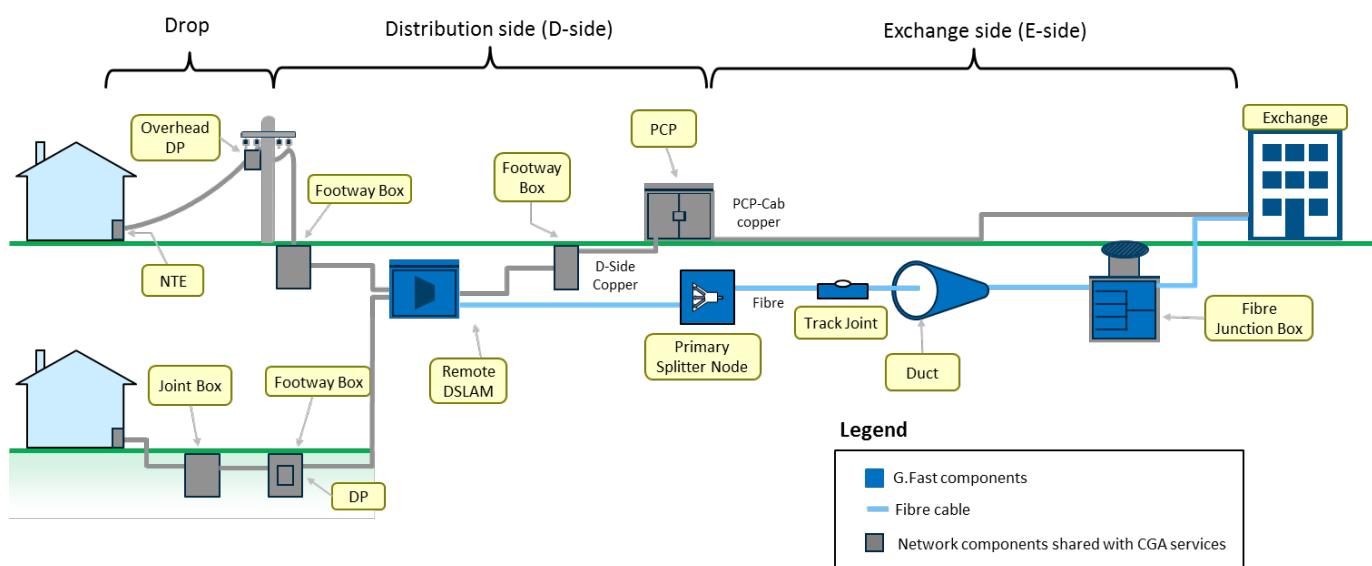
¹⁶ For more detail information about the G.Fast Pilot please refer to BT's STIN 520: <http://www.sinet.bt.com/sinet/sins/pdf/STIN520v1p0.pdf>

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Openreach may deploy G.Fast deeper into their network using FTTdp¹⁷ – i.e. smaller nodes closer to the premises, to achieve its target of connecting 10 million homes by 2020¹⁸.

- 3.11 In the study, we only considered GPON for connecting the G.Fast DSLAM back to the exchange, in order to reduce the cost of deployment. The alternative would have been considering point-to-point connections between the G.Fast DSLAM back to the Exchange, but that would have implied using a larger number of ports and fibre, deploying active equipment for elements, increasing the cost per premises.

Figure 7. **Access Network: G.Fast Physical Architecture**



Source: Cartesian

- 3.12 As in the case of FTTC technologies, G.Fast performance is heavily dependent on the length of the copper loop from the DSLAM to the premises. This report will use Ofcom's recommended values of maximum loop lengths, which can be seen on the table below¹⁹. The Geospatial model adjust the length of the copper loop to get the radial distance from the DSLAM. The factor applied to do that conversion was [1.3].

Figure 8. **Maximum Copper Loop Length for G.Fast**

Scenarios A-B (10Mbps DL)	Scenarios C (30Mbps DL)
500 metres	450 metres

¹⁷ See Figure 1 of the BT's STIN 518: <http://www.sinet.bt.com/sinet/SINs/pdf/STIN518v1p0.pdf>

¹⁸ See page 85 of BT's "Annual Report & Form 20-F 2017" (http://www.sinet.bt.com/governance/2017_BTPLC_Annual_Report.pdf) and page 55 of BT's "Q4 2015/16 Results and Capital Markets Day Conference Call Transcript" <https://www.sinet.bt.com/Sharesandperformance/Quarterlyresults/2015-2016/Q4/Downloads/Webcast/q416-transcript.pdf>

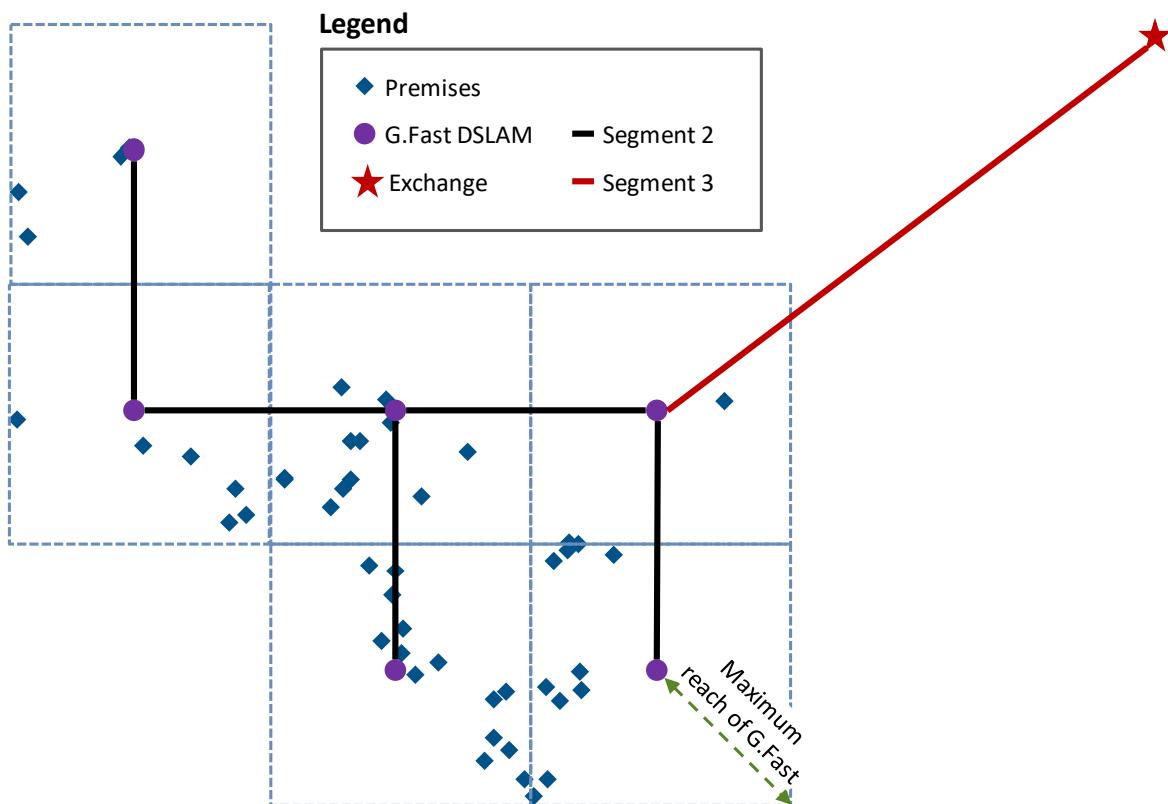
¹⁹ Values used in the previous USO report commissioned by Ofcom, *Estimating the cost of broadband Universal Service Obligation*

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Source: Ofcom

Geospatial Modelling of the Technology

- 3.13 The figure below shows what distances were considered in the Geospatial model when modelling G.Fast technology. A grid was overlaid in order to respect the distance limitation of the technology. The distance to interconnect all the G.Fast DSLAMs is referred to as Segment 2, while the minimum distance to connect to the local exchange from the nearest G.Fast DSLAM is Segment 3.

Figure 9. **Access Network: G.Fast Geospatial Model Architecture**

Source: Cartesian

Network Components

- 3.14 The table below summarises the main cost component for G.Fast deployment. We used BT's FTTrN cost and network assumptions to inform G.Fast-specific costs, and we re-used cost components from FTTC if relevant.

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Figure 10. *G.Fast Cost Items*²⁰

Element	Volume Driver	Capacity	Description
Remote Node DSLAM	Subscribers	16	Cartesian Assumptions
Hybrid Closure	G.Fast DSLAM	1	Cartesian Assumptions
Power Box	G.Fast DSLAM	1	Cartesian Assumptions
Copper Intercept Joint	G.Fast DSLAM	1	Cartesian Assumptions
Primary Splitter Node (PSN)	Subscribers	128	<p>Using a PSN with overall capacity of 128 ports, as per BT's FTTP modelling assumptions. We assume the same port utilisation as with FTTP (see Figure 13) with an effective capacity of 80% of 128 ports. This component includes the following subcomponents:</p> <ul style="list-style-type: none"> • Primary splitter node • FTTP tube intercept joint • Blown fibre tube • Blown fibre unit • Optical joint
Segment 3 Track Joint	G.Fast Cluster	0.05	<p>Passive elements to aggregate and distribute the fibre from the Exchange to the Primary Splitter. We use the same proportion of Track Joints and Aggregation Nodes per G.Fast Cluster as for FTTC</p>
Segment 3 Aggregation Node	G.Fast Cluster	0.7	
Node Primary Tray	Subscriber	32	Using BT's FTTP data, each PSN has a capacity of 4 Node Primary trays with an overall capacity of 32 ports, and a planning limit of 32 ports
GPON Port	Subscribers	32	We assume the same unit cost as a GE port from the WLA model. With regards to capacity, we assume the use of a GPON per Node Primary Tray, which delivers sufficient egress bandwidth to support the CIR of all scenarios
Segment 3 Fibre	Metres / G.Fast Cluster	-	In the geospatial analysis, we calculate the average Segment 3 fibre length per G.Fast cluster. We use the same unit cost as for FTTC Segment 3 fibre
Segment 3 Fibre Testing	GPON port	-	Assuming the same unit cost as E-side fibre testing in the WLA model
Segment 3 Ducts and Poles	Metres / G.Fast Cluster	-	We use the same average length as with the fibre cable cost item. We used the same blended unit cost of self-build and existing duct as with FTTC's Segment 3 Ducts and Poles
Segment 2 Fibre	Metres between G.Fast DSLAM in Cluster	-	In the geospatial analysis, we calculate the average Segment 2 length (see paragraph 3.13). We use the same unit cost as for G.Fast Segment 2 fibre

²⁰ Please note that for the purpose of calculating the numbers in this table, we have ignored BT's utilisation assumption. Therefore the numbers contained in this table represent the cost elements being used at maximum capacity.

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Segment 2 Fibre Testing	G.Fast DSLAM	1	Assuming the same unit cost as G.Fast's Segment 3 fibre Testing. Cartesian Assumptions.
Segment 2 Ducts and Poles	Metres between G.Fast DSLAM in Cluster	-	We use the same average length as with the fibre cable cost item. We used a blended unit cost of self-build duct, existing duct, self-build poles and existing poles ²¹

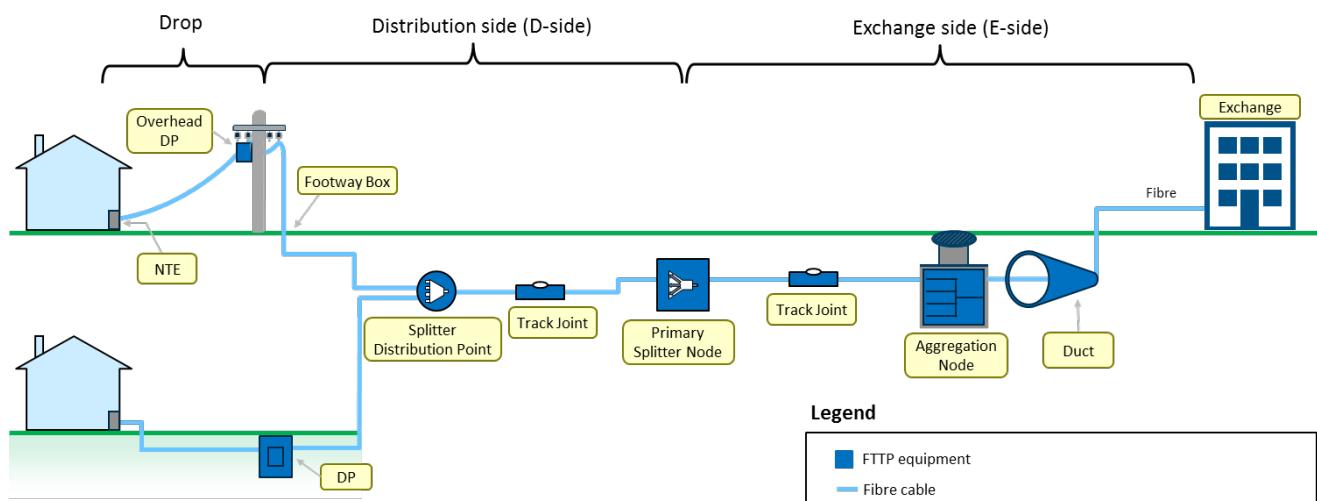
Source: Ofcom, Cartesian, BT

FTTP

Technology Overview

- 3.15 With FTTP, fibre is used end-to-end from the local exchange to the premises. The benefits of using this technology are that there is no need for active components between the exchange and the premises, fibre cables can reach long distances without affecting the performance of the signal and, fibre cables need less maintenance than the copper cables.
- 3.16 Unlike DSL technologies, which reuse elements of the existing copper-loop, deployment of FTTP requires new network construction. For this reason, FTTP is relatively more expensive and we only consider it in areas that cannot be reached by cabinet-based DSL. FTTP is most cost-effective where premises are close together (reducing the construction distance).
- 3.17 Similarly to G.Fast, we only considered a PON deployment for FTTP, in order to reduce the cost per premise. The alternative would have been considering FTTP PTP but this would have increased the total cost of deployment, making it a less attractive technology to deliver a Universal Broadband service.

Figure 11. **Access Network: FTTP Physical Architecture**



Source: Cartesian

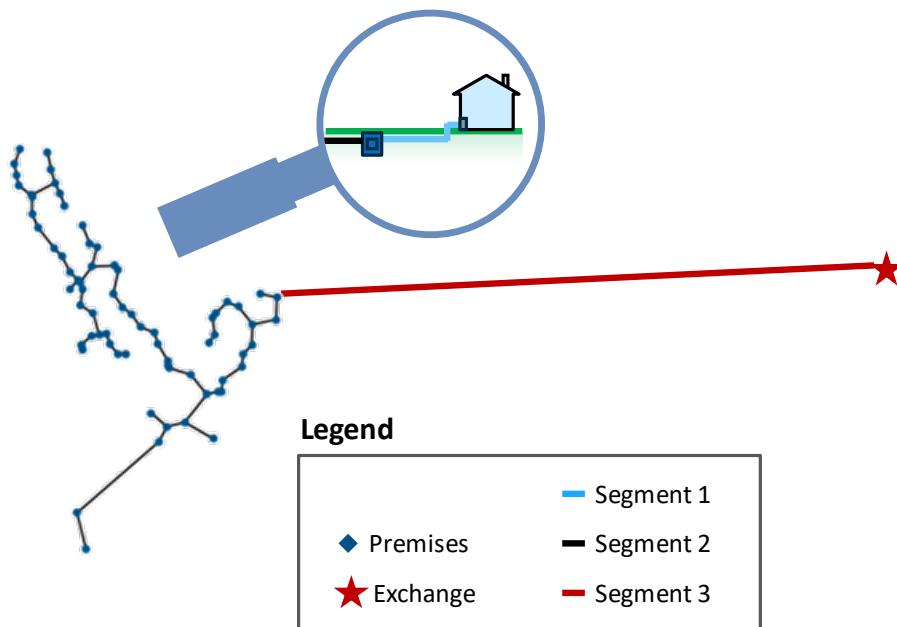
²¹ We used the same mix of duct and poles as in the report commissioned by Ofcom 'Estimating the cost of a broadband Universal Service Obligation'. For segment 2, it corresponds to 45% self-build duct, 30% existing duct, 0% self-build poles and 25% existing poles.

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Geospatial Modelling of the Technology

- 3.18 Figure 12 shows the distances that were considered in the Geospatial model when modelling FTTP technology. Segment 1 is the fibre drop between the FTTP subscriber and the Distribution Point. Segment 2 connects the Distribution Points back to the location of the nearest premises to the exchange, which we take to be the logical point at which to aggregate the GPON. Segment 3 refers to the distance between this aggregation point and the local exchange.

Figure 12. *Access Network: FTTP Geospatial Model Architecture*



Source: Cartesian

Network Components

- 3.19 The table below summarises the network components considered FTTP deployment:

Figure 13. *FTTP Cost Items²²*

Element	Volume Driver	Capacity	Description
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²² Please note that for the purpose of calculating the numbers in this table, we have ignored BT's utilisation assumption. Therefore the numbers contained in this table represent the cost elements being used at maximum capacity.

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Primary Splitter Node	Subscribers	128	<p>Optical splitter with overall capacity of 128 ports, as per BT's FTTP modelling assumptions. The PSN can support four Primary Trays with 32 ports each, but we use BT's recommended planning rule of leaving \times spare ports, effectively using only \times ports. Therefore, the overall PSN capacity is \times ports. This component includes the following subcomponents:</p> <ul style="list-style-type: none"> • Primary splitter node • FTTP tube intercept joint • Blown fibre tube • Blown fibre unit • Optical joint
Primary Tray	Subscriber	32	Tray for fibre management. As per point above, we use an effective capacity of 32 ports. We use unit costs from BT's FTTP modelling assumptions
Secondary Splitter Node	Subscriber	32	Second level of optical splitting. Each Secondary splitter has a maximum capacity of 32 ports, but we using BT's planning rule of only \times ports
Secondary Tray	Subscriber	8	Using BT's FTTP modelling assumptions, each Secondary splitter supports four trays, for fibre management. Each has 8 ports, with \times left as spare
GPON Port	Subscriber	32	Port on optical equipment at the exchange facing access network. We assume the same unit cost as a GE port from the WLA model. With regards to capacity, we assume the use of a GPON per Primary Tray, which delivers sufficient egress bandwidth to support the CIR of all scenarios
Segment 3 Fibre	Metres / Cluster	-	In the geospatial analysis, we calculate the average Segment 3 fibre length per FTTP cluster. We use the same unit cost as for FTTC Segment 3 fibre
Segment 3 Fibre Testing	GPON Port	1	Optical fibre testing during network commissioning. Assuming the same unit cost as FTTC's Segment 2 Fibre Testing. Cartesian Assumptions
Segment 3 Ducts and Poles	Metre / Cluster	-	We use the same average length as with the fibre cable cost item. We used the same blended unit cost of self-build and existing duct as with FTTC's Segment 3 Ducts and Poles
Segment 3 Track Joint	Cluster	0.05	Passive elements to aggregate and distribute the fibre from the Exchange to the Primary Splitter. We use the same proportion of Track Joints and Aggregation Nodes per FTTP Cluster as For FTTC
Segment 3 Aggregation Node	Cluster	0.7	
Segment 2 Fibre	Metre / Premises	-	Fibre within the FTTP cluster. In the geospatial analysis, we calculate the average Segment 2 length (see paragraph 3.13). We use the same unit cost as for G.Fast Segment 2 fibre
Segment 2 Fibre Testing	Subscribers	8	Optical fibre testing during network commissioning. Assuming the same unit cost as G.Fast's Segment 3 fibre Testing
Segment 2 Ducts and Poles	Metre / Premises	-	Ducts and poles used to carry the Segment 2 fibre. Using the same blended unit cast as with G.Fast's Segment 2 Ducts and Poles

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Segment 1 Fibre	Subscribers	1	Fibre drop between the Distribution Drop and the premises. It is only deployed to those premises subscribing to an FTTP service. Using aggregated unit cost from Ofcom's previous USO report. ²³ Cartesian assumptions.
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Source: Ofcom, BT, Cartesian

Fixed Wireless Access (FWA)

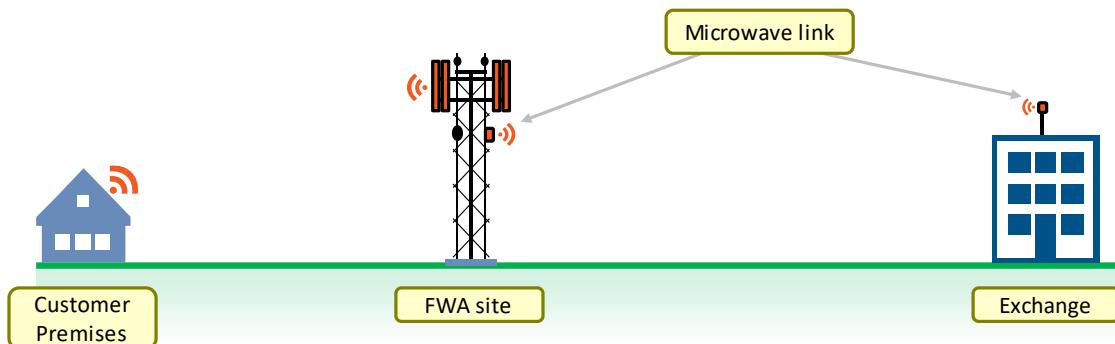
Technology Overview

3.20 FWA uses radio rather than cables to deliver a broadband service to the premises. FWA can be point-to-point or point-to-multipoint, Cartesian consider the latter for this study. Several variations of FWA can be found in the market and each has a use case, for example:

- Wi-Fi: domestic, business and hotspot
- WiMAX: Wide-Area network
- 4G: mobile networks, wide-area network and short-range network
- 5G: mobile network and short-range network

3.21 In a previous report commissioned by Ofcom²⁴, FWA technology was analysed for two radio frequency bands, sub-1GHz and 5.8GHz. In this report, we have adopted the sub-1GHz configuration described in the Ofcom commissioned report, i.e. a maximum reach of 10km and a throughput of 69 Mbps per site. The final capacity of the FWA site, in terms of subscribers that can serve, will be determined by the CIR of each scenario. The sub-1GHz configuration was chosen because is the best suited for remote and dispersed locations. See the high-level architecture in the figure below.

Figure 14. **Access Network: FWA Physical Architecture**



Source: Cartesian

Network Components

3.22 The stylised cost used for this technology simply takes into consideration the capacity and coverage to estimate the number of sites required. A full radio planning exercise would improve the estimates. The objective of this analysis is to serve as an input to the Cost Model – which does not include wireless

²³ Estimating the cost of broadband Universal Service Obligation

²⁴ Estimating the cost of broadband Universal Service Obligation, report commissioned by Ofcom (Dec 2016)

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technologies, and as so it serves only to identify remote and dispersed premises. The table below summarises the network components considered in the Geospatial model:

Figure 15. ***FWA Cost Items Considered in the Geospatial Model***

Element	Volume Driver	Capacity	Description
FWA Site	Subscribers	Scenario A: 138 Scenario B: 69 Scenario C: 6	All the necessary equipment and infrastructure needed for a site: <ul style="list-style-type: none">• Active equipment: transmitters, amplifiers, eNodeB, backhaul router, power supply and associated fees• Mast: tower (mix of built and rented), including tri-sector antennas and microwave link• Shelter: Infrastructure, power, air conditioning and battery backup
Antenna at the Customers' Premises	Subscribers	1	Antenna placed at the customer premises to receive and send the wireless signal

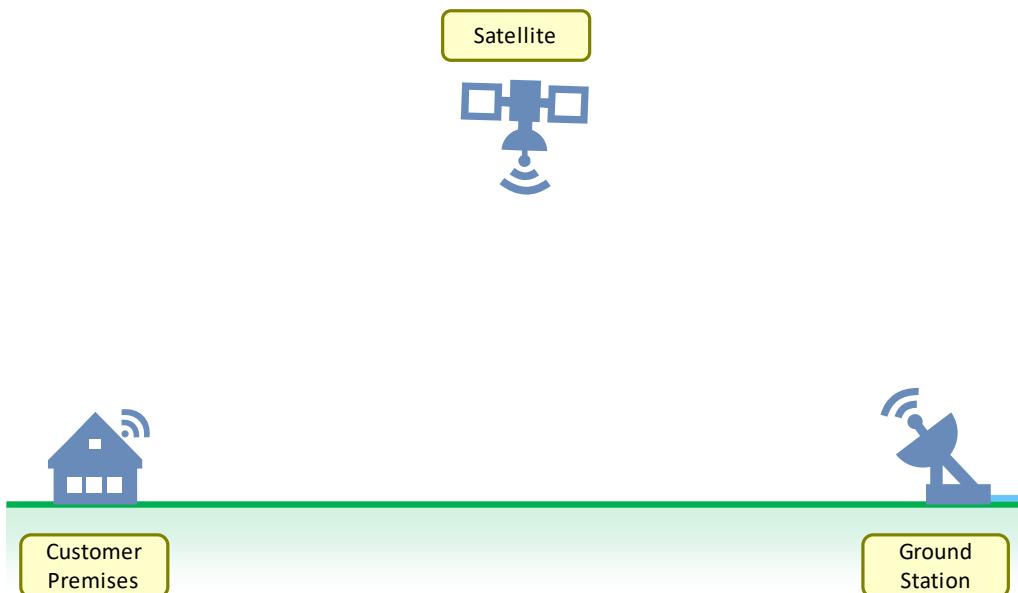
Source: Ofcom

Satellite

Technology Overview

3.23 Satellite broadband uses a satellite to relay signals between the customer premises and a ground station. Where Satellite broadband is used, it is assumed that the network provider would resell the services of current broadband satellite providers. Below is a high-level depiction of the architecture.

Figure 16. ***Access Network: Satellite Physical Architecture***



Source: Cartesian

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Network Components

3.24 Given that the network provider would only resell the service, for the Geospatial model we assumed the current prices of broadband satellite. Since satellite services for consumers imposed limits on the data consumption, instead of taking the speed for each scenario, the plan with the maximum data cap was selected as the alternative option. Additionally, it is good to note that satellite broadband services would only apply for scenarios A and B. Scenario C does not have satellite as an alternative since there are no current consumer satellite broadband services that provide 30Mbps for download, 6Mbps for upload and a CIR of 10Mbps.

Figure 17. **FWA Cost Items Considered in the Geospatial Model**

Element	Volume Driver	Capacity	Description
Annual Subscription	Subscribers	1	Price of the subscription to the service that provides the highest data cap for consumer packages (independent of the speed – usually up to 22Mbps for download and up to 2Mbps for upload)
Antenna at the Customers' Premises	Subscribers	1	Antenna placed at the customer premises to receive and send the wireless signal

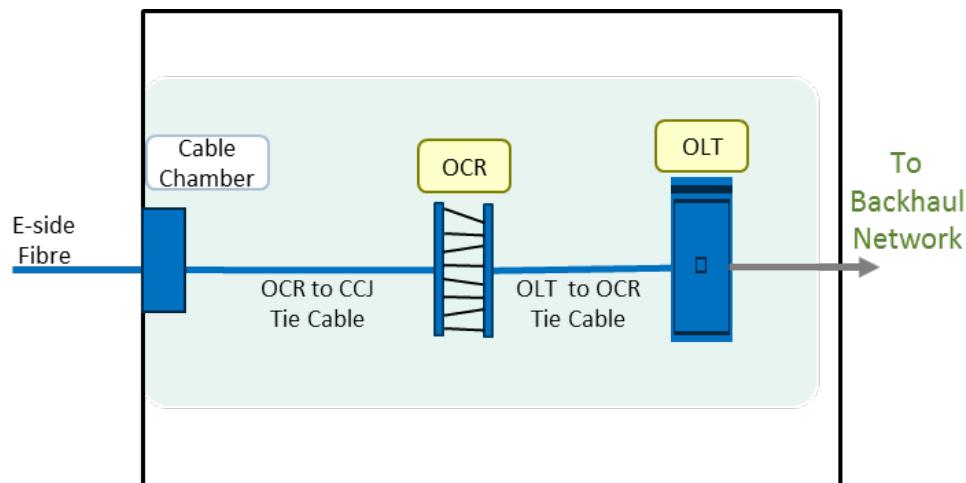
Source: Cartesian

Exchange (for All Technologies)

Overview

3.25 At the Exchange, the bottom-up modelled network includes the Optical Consolidation Rack (OCR), the Optical Line Termination (OLT) and the Tie Cables between them. Figure 18 below illustrates the modelled topology.

Figure 18. **Network Topology inside the Exchange (Common to FTTC, FTTP and G.Fast)**



Source: Cartesian

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OCR (Optical Consolidation Rack)

3.26 The OCR is used for the splicing of the OCR Tie Cable into fibre cables for direct connection to the active equipment (in this case, the OLT). The OCR constitutes an efficient alternative to the traditional Optical Distribution Frame (ODF). The OCR is comprised of a few subcomponents highlighted in the table below:

Figure 19. *List of OCR Subcomponents*

Element	Description	Capacity
OCR Chassis	Metal cabinet enclosure to host the subcomponents	8 Sub-racks
OCR Sub-Rack	The sub-rack slots into the rack, and is used to facilitate the splicing of fibres	72
OCR_to_CCJ_Tie Cable	Extends the Segment 3 fibre from the Cable Chamber to the OCR	144 fibres ²⁵
Cable Chamber Joint	Aggregates the fibre cables(s) coming from the Segment 3 and interconnects with the OCR Tie Cable	144 fibres

Source: Cartesian, BT planning rules

3.27 However, in the UBC model we have simplified the list of costs items, and loaded them all to the cost of an OCR Sub-rack. The reasons for doing this is because we do not have data about the utilisation of the existing OCRs at BT's exchanges, therefore we minimise the risk of overestimating the cost by adding a new chassis in each Exchange.

OLT (Optical Line Termination)

3.28 The OLT is used for aggregating the signals from the FTTC subscribers. In the model we are using GPON OLTs for G.Fast and FTTP, and GE OLT for FTTC. The table below shows the OLT sub-parts which are used in the bottom-up model

²⁵ We are aware that BT uses multiple cable types, which capacity varies from 24 fibres to 144 fibres (see Figure 1 in BT, 2016. Response to Ofcom consultation on possible approaches to fibre cost modelling). We do not have information about the actual distribution of these cable types across BT's commercial FTTC network. However, given that the cost of installing the fibre cable far exceeds the cost of acquiring the cable, we consider that an efficient operator would install the biggest cable type from the outset. Therefore, we have assumed that the capacity of a OCR to CCJ tie cable is 144 fibres, rather than a blend of different cable type capacities.

Cartesian: Universal Broadband – Network & Cost Module DocumentationFigure 20. *List of OLT Subcomponents*

Element	Description	Capacity
OLT_Chassis	The housing that hosts the Network Cards and any common equipment cards not listed below (e.g. fan tray, switching module)	<ul style="list-style-type: none"> • 8 OLT Southbound Cards
OLT_Southbound Card	Network Access Card supporting GE ports	<ul style="list-style-type: none"> • 16 x GE ports (GE) • 8 x GPON ports (GPON)
OLT_Northbound Card	Network Access Card supporting GE ports	<ul style="list-style-type: none"> • 1 per OLT]
OLT_to_OCR_Tie Cable	Connects the OLT to the OCR	<ul style="list-style-type: none"> • 10 fibres

Source: Cartesian, BT planning rules

- 3.29 We have adopted the same approach in the UBC model, simplifying the list of OLT costs items to two, a GE OLT Southbound Card and a GPON OLT Southbound Card, for the same reasons as with the OCR.

Exchange Accommodation Costs

- 3.30 All Exchange buildings are assumed to have the following infrastructure:

- Cable Chamber
- Direct Current (DC) power, battery back-up and generator
- Alternating Current (AC) power and power inverter
- Air conditioning
- Security
- Environmental alarms
- Fire suppressant
- Cable management
- Management network

- 3.31 These “Accommodation” costs are not modelled individually on a bottom-up basis. Instead, we have taken the same approach as in the WLA model to estimate an average capital cost per rack of active equipment at the Exchange (i.e. OLT in this case). We are reusing the same figure for the UBC model (updated to FY2017/18).

Other Costs

- 3.32 Following input from BT, the bottom-up model also takes into consideration other costs associated with the Universal Broadband service rollout. The table below summarises them:

Figure 21. *Other NGA Cost Items Used in the Bottom-Up Model*

Element	Description	Data Source
Provisioning Services	Activities required by BT in order to provision, cancel, amend NGA customers. They have been aggregated into Software Configuration, PCP Jumpering, Engineering Premises Visit	BT's Chief Engineer's model

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Planning (DSLAM and Remote Parent)	Cost of planning and designing rollout of DSLAMs and Remote Parent cables.	BT's Chief Engineer's model
OSS/BSS Hardware and Software	Costs of the OSS and BSS platforms in order to support the GEA services, e.g. provisioning, monitoring	Ofcom estimate
Cabinet Interventions	Repair costs driven by faults due to customer installations at the cabinet	BT's Chief Engineer's model
SLG Payments	Payments BT makes to other CPs when it fails to meet the agreed Service Level Guarantees (SLGs).	Ofcom estimate
Cumulo	Business Rate Taxes incremental to GEA services	Ofcom estimates based on VOA and BT data

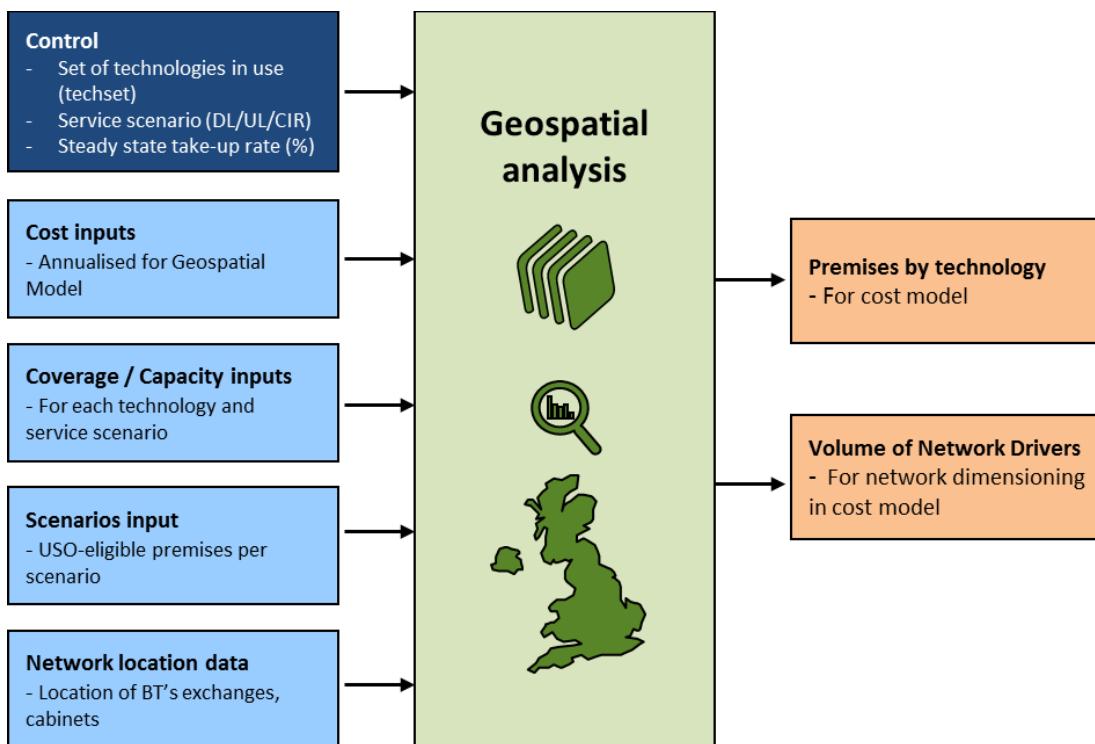
Source: Cartesian

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4 Geospatial Model Implementation and Assumptions

- 4.1 Cartesian developed two models (a Geospatial model and a Network Cost model) to estimate the cost that an efficient operator would incur to provide a universal broadband service. The Geospatial model uses a number of data files, mostly provided by Ofcom, including premises and cabinet location. In Appendix [*] there is a table of sources.
- 4.2 The Geospatial Model uses an analytical approach to calculate the most cost effective mix of technologies for a specified scenario and combination of possible technologies. It provides an output file specifying the number of premises by technology and the volume of network drivers, which is used by the Network Cost Model to calculate the deployment and running costs of the universal broadband service over the specified 12-year period. The figure below shows an overview of the Geospatial Model high level architecture.

Figure 22. *High Level Architecture of Geospatial Model*



Source: Cartesian

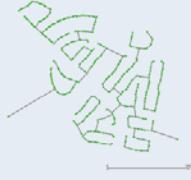
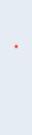
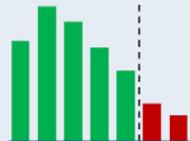
Approach

- 4.3 The Geospatial analysis was structured to follow a decision-making sequence that a fixed network operator could be expected to follow:
- 4.4 *Fixed technologies are the preferred technology.* We prioritise the use of FTTx technologies to re-use as much of the existing fixed infrastructure as possible, given its wide presence across the country.
- 4.5 *FWA is a fall-back technology.* Due to the relatively extensive coverage of FWA and low capacity of this technology, FWA was only used on those premises that are not cost effective to cover with FTTX deployments.

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- 4.6 *Satellite acts as a cost threshold.* After connecting all premises with the cheapest technology set, premises were assigned to satellite if their cost to connect was greater than the annualised cost of a satellite broadband service (including rental, CPE and installation).
- 4.7 For the purposes of the Geospatial model, component costs were treated as follows:
- Detailed cost items were grouped into super components which share a common volume driver.
 - Cost were calculated by summing the tilted annuity²⁶ and the annual Opex, as explained in Ofcom's Annex 8. The geospatial analysis seeks to identify the appropriate mix of technologies to minimise the overall costs, where costs refer to this newly calculated cost unit.
 - Only two main cost drivers – metres and premises – were used to estimate the network dimensioning.
 - Shared costs across technologies were not considered in the geospatial analysis as they were not deemed to impact the choice of technology (e.g. an OCR at the exchange will be connecting fibre cables from technologies including FTTC, FTTP, G.Fast).
- 4.8 Figure 23 shows the overall approach to identify the most appropriate technology mix. In each step of the process, the geospatial analysis selected the technology with the lowest cost per premises. For example, in step two we compare the cost per premises of VDSL with that of LR-VDSL and we keep the technology that has the lowest cost premises. Additional details of each step can be found below.

Figure 23. *Approach to Geospatial Analysis*

	1 Data preparation	2 Cabinet Technologies	3 Dense Clusters	4 Disperse Premises	5 Satellite Substitution
Technologies	<ul style="list-style-type: none"> • All 	<ul style="list-style-type: none"> • VDSL • LR-VDSL (Optional) 	<ul style="list-style-type: none"> • FTTP • G.Fast (Optional) 	<ul style="list-style-type: none"> • FWA (Optional) • FTTP 	<ul style="list-style-type: none"> • Satellite (Optional)
Illustrative Diagram					
High-Level Approach	<ul style="list-style-type: none"> • Receive external files • Consolidate information following Ofcom's guidelines • Ingest consolidated data into the geospatial model 	<ul style="list-style-type: none"> • Identify premises within reach of each cabinet technology • Calculate cost of each cabinet technology • Select the technology with the lowest cost per premise passed 	<ul style="list-style-type: none"> • Identify clusters of premises with high density • Calculate the cost of FTTP and G.Fast deployment for each cluster • Select the technology with the lowest cost per premise passed 	<ul style="list-style-type: none"> • Distribute FWA base stations to serve the remaining premises • Incorporate premises from overlapping clusters if the base station has capacity • Select FWA to serve these premises if it more cost effective 	<ul style="list-style-type: none"> • For each premises, compare the cost of the chosen terrestrial technology with satellite • Substitute with satellite if a satellite subscription is lower cost

Source: Cartesian

²⁶ For more information on tilted annuity, see page 6 of the ITU Expert-Level Training on Network Cost Modelling for Asia and Pacific Countries Level II (http://www.itu.int/ITU-D/finance/work-cost-tariffs/events/tariff-seminars/Bangkok-10/pdf/part_3_cost_accounting_model_valuation.pdf)

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Data Preparation

- 4.9 Section 7 lists the files we received from Ofcom containing information regarding premises, cabinets and exchanges. We consolidated the information and excluded incomplete records. In this respect, there were 3 out of 5,594 exchanges excluded; 7,303 out of 145,120 cabinets excluded²⁷.
- 4.10 Additionally, we were provided with BT's FTTC BDUK future rollout plans²⁸, which we used to estimate those premises which would not be UBC-eligible due to being close enough to the future FTTC cabinets. Figure 24 presents a summary of the premises we have excluded from the analysis for the reasons highlighted above:

Figure 24. *Details of Premises Excluded from Geospatial Analysis*

	Scenario A1	Scenario A2	Scenario B1	Scenario B2	Scenario C1	Scenario C2
Premises Received	1,338,995	3,945,992	2,562,222	4,123,085	3,501,294	5,436,829
Belonging to a Cabinet without Location Data	41,372	73,135	73,135	73,135	73,135	73,135
In BDUK Deployment Plan	55,042	159,522	119,422	165,796	146,866	236,489
Premises to be Analysed	1,242,581	3,713,335	2,369,665	3,884,154	3,281,293	5,127,205

Source: Ofcom, Cartesian

- 4.11 For the Exchange-only Lines (EoL) - we assumed that the premises were connected to a cabinet located at the parent Exchange for the lines.
- 4.12 After finalising the geospatial model, additional information was received identifying premises that will be upgraded to ADSL2+.²⁹ This data was not included in this analysis. In a future analysis, this information could be included as a pre-processing step: those premises within a certain distance to the exchange will no longer be UBC-eligible after their upgrade to ADSL2+.

Cabinet Technologies Module

- 4.13 After ingesting the data, the analysis then follows the analytical sequence outlined in paragraph 4.3. The first stage of this is to determine which UBC-eligible premises can be served by cabinet-based VDSL or LR-VDSL. The coverage of these technologies is estimated using the theoretical maximum copper sub-loop length that would support the performance requirements of the given UBC scenario (see paragraph 3.6 and Figure 5 for more details).
- 4.14 The figure below shows the coverage area of an LR-VDSL cabinet for scenarios A and B, with the covered premises highlighted in green:

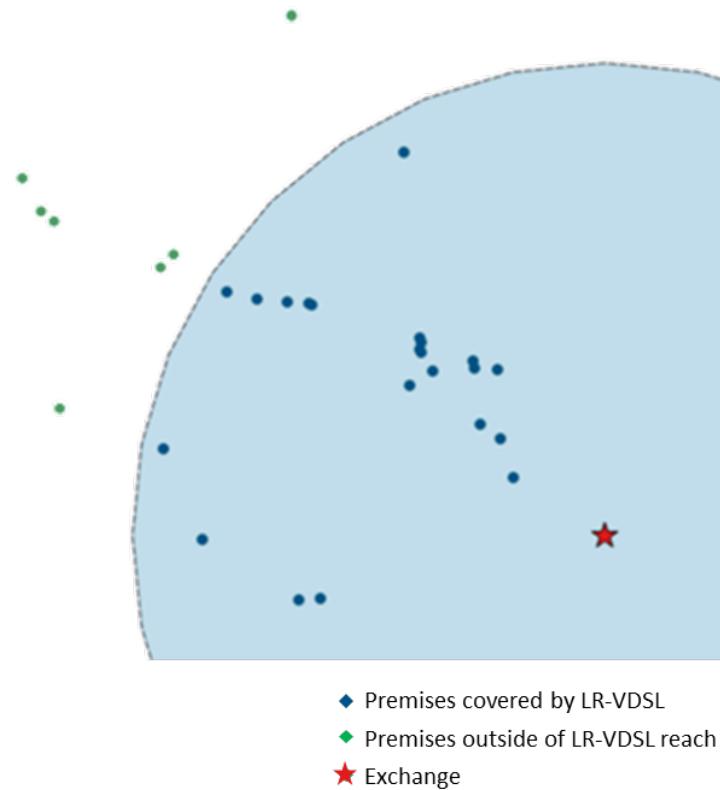
²⁷ This figure includes PCPs, Exchanges and Remote Nodes from BT, and was provided by Ofcom.

²⁸ Openreach regularly publish updates to the GEA FTTC network rollout plan, listing, on a per-cabinet (PCP) basis, the historic and planned timing of FTTC deployments.

²⁹ This relates to the upgrade by BTWholesale from IPstream to WholesaLe Broadband Connect as explained in Ofcom's consultation.

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Figure 25. **Coverage Area of LR-VDSL Cabinet for Scenarios with DL 10 Mbps (3.5km)**



Source: Cartesian

4.15 The model then determines the cost of serving the premises within the coverage area. In calculating the costs, the following principles are applied:

- All ADSL customers in a cabinet adopting LR-VDSL need to migrate to LR-VDSL due to cross-talk; therefore, the cost of these forced migrations will be included.
- Projected spare capacity of current VDSL cabinets was taken into account, using the following methodology:
 - We received the current number of FTTC subscribers in each cabinet; we also used the WLA model to estimate the average FTTC subscriber growth between FY2017/18 and FY2020/21;
 - Adding both figures, we obtained the projected utilisation of the FTTC cabinets by the end of FY2020/21; we then estimated the size of each cabinet: if the projected utilisation was less than 128, a cabinet type 1 was assumed; otherwise a type 2 cabinet;
 - We then used the estimated maximum capacity of the cabinets and the projected utilisation to estimate the future spare capacity of each VDSL cabinet;
 - Finally, we used the projected number of subscribers at each cabinet and the calculated future spare capacity: a new cabinet will be included only if the first figure is larger than the second.
- For existing VDSL cabinets migrating to LR-VDSL it was assumed that there would be no Segment 3 Cabling requirements, given the cabinet is already fibre-enabled.

4.16 Figure 26 presents the principal cost and capacity inputs used by the geospatial analysis for VDSL and LR-VDSL. The table also shows the components from Figure 6 included in each aggregated network element. With the exception of the ADSL migration, input values have been sourced from the NGA Cost

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Model developed by Cartesian to support Ofcom's WLA consultation³⁰. For the UBC analysis, 2017/18 costs are used as the reference (unlike the WLA NGA model, which uses 2015/16 values).

Figure 26. **VDSL and LR-VDSL Costs for Geospatial Model**

Supercomponent	Driver	Maximum Capacity	Annualised Cost (£)	Cost Components Included
Cabinet (Type 1)	Premises (Net Premises ³¹ for LR-VDSL)	128	1,389.5	<ul style="list-style-type: none"> • DSLAM Cabinet • Power Connection • Cabinet Concrete Base • Certification Managed Service • PCP Re-shell and Connectors • Extra faults at PCP/Copper • Duct and Copper PCP to FTTC Cab • Segment 3 Track Joint and Segment 3 Aggregation Node • Segment 3 Fibre Testing
Cabinet (Type 2)	Premises (Net premises for LR-VDSL)	288	1,782.6	
Access Card (Type 1)	Premises	32	83.9	<ul style="list-style-type: none"> • Access Card
Access Card (Type 2)	Premises	48	134.6	
GE Port (Type 1)	Premises	128-80 ³²	0.3	<ul style="list-style-type: none"> • GE Port
GE Port (Type 2)	Premises	288-80	0.3	
Segment 3 Fibre Cabling	Metres		1.6	<ul style="list-style-type: none"> • Fibre cable (48 fibre) • Fibre cable installation • Duct: assumption 20% new build Duct, and 80% existing Duct³³
ADSL Migration (only LR-VDSL)	ADSL Subscribers	1	23.7	<ul style="list-style-type: none"> • CPE • Installation of service by an engineer

Source: Cartesian, Ofcom, BT

Dense Clusters Module

- 4.17 After removing the premises covered by cabinet-based technologies, dense clusters of premises were identified as candidates for FTTP and G.Fast deployment. Clusters are identified using the PostGIS implementation of DBSCAN³⁴ (Density-Based Spatial Clustering of Applications with Noise) with the following parametrisation: a desire distance of 200 metres, and a density of 15 premises³⁵. The technology selection was made based on cost per premises.
- 4.18 The figure below shows a dense cluster of premises (yellow) identified using the DBSCAN algorithm, just outside of the coverage area of a LR-VDSL cabinet (green circle).

³⁰ Wholesale local access market review (31st March 2017): Consultation on the proposed market, market power determinations and remedies.

³¹ Net Premises equals the total number of premises (ADSL subscribers which are forced to be migrated to VDSL, plus the eligible premises for universal broadband service adjusted by the take-up rate) less the spare capacity of the existing FTTC cabinet/exchange.

³² The number of premises that can be served by a GE Port is dependent on the Committed Information Rate of each scenario.

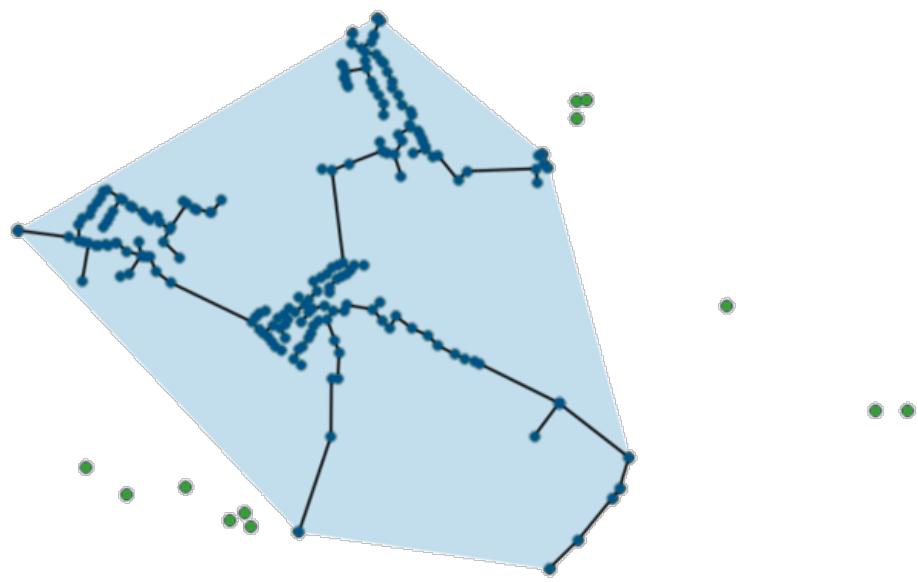
³³ Mix of duct provided by report commissioned by Ofcom, *Estimating the cost of a broadband Universal Service Obligation* (November 2016).

³⁴ Please refer to https://postgis.net/docs/manual-2.3/ST_ClusterDBSCAN.html for PostGIS documentation, to <https://en.wikipedia.org/wiki/DBSCAN>, for a general understanding of how the algorithm works and, <https://www.aaai.org/Papers/KDD/1996/KDD96-037.pdf> for more in-depth understanding of the algorithm.

³⁵ We ran a sensitivity analysis on these parameters in order to ensure that the average distance between premises is around 15 – 20m. From experience, these values ensure that FTTP is cost efficient technology.

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Figure 27. **Dense Cluster (Blue Properties) Identified with DBSCAN**



Source: Cartesian

FTTP

- 4.19 For each dense cluster, the model calculates the Minimum Spanning Tree³⁶ (MST) to estimate the D-Side cabling needed to connect the premises. Additionally, the Segment 3 fibre distance was estimated by taking the minimum radial distance from the premises to their serving cabinet and exchange and adjusting it by a radial-to-route factor [1.3].

G.Fast

- 4.20 For each dense cluster identified using the DBSCAN algorithm, a grid was created based on the maximum reach of copper loop³⁷ length for G.Fast adjusted by a radial-to-route factor [1.3]. Within each of these grids, a G.Fast DSLAM was placed for every 16 subscribers.

FTTP and G.Fast Costs

- 4.21 Figure 28 shows the aggregated, simplified costs and drivers used in the geospatial analysis to estimate the FTTP and G.Fast deployment cost, as well as the subcomponents from Figure 10 and Figure 13 included in each aggregated cost item.

³⁶ An edge-weighted graph is a graph where we associate weights or costs with each edge. A minimum spanning tree (MST) of an edge-weighted graph is a spanning tree whose weight (the sum of the weights of its edges) is no larger than the weight of any other spanning tree. For a general understanding of what the algorithm does, please refer to: https://en.wikipedia.org/wiki/Minimum_spanning_tree. The implementation of the algorithm was done with the igraph R package. For more information regarding the igraph R package please refer to <https://cran.r-project.org/web/packages/igraph/igraph.pdf>

³⁷ See Figure 8

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Figure 28. **FTTP and G.Fast Costs for Geospatial Model**

Supercomponent	Driver	Maximum Capacity	Annualised Cost (£)	Cost components included
Primary Splitter Node	Premises	112	116.6	<ul style="list-style-type: none"> • Primary Splitter Node • FTTP Tube Intercept Joint • Blown Fibre Tube and Unit • Optical Joint • Segment 3 Track Joint, Aggregation Node
Primary Tray	Premises	28	1.6	<ul style="list-style-type: none"> • Primary Tray
Secondary Splitter Node (only FTTP)	Premises	28	82.2	<ul style="list-style-type: none"> • Splitter Distribution Point • FTTP Tube Intercept Joint • Blown Fibre Tube and Unit • Optical Joint
Secondary Tray (only FTTP)	Premises	7	1.6	<ul style="list-style-type: none"> • Secondary Tray
G.Fast DSLAM (only G.Fast)	Premises	16	698.4	<ul style="list-style-type: none"> • DSLAM • Hybrid Enclosure • Power Box • Copper Intercept Point
GPON Port	Premises	28	1.7	<ul style="list-style-type: none"> • GPON port • Segment 3 fibre testing³⁸
D-Side Fibre Cabling	Metres		3.3	<ul style="list-style-type: none"> • Fibre cable 48f, and installation • Duct: assumption 45% new build Duct, 30% existing Duct and 25% existing Pole³⁹
D-Side Fibre Testing	Premises	1	1.4	<ul style="list-style-type: none"> • Fibre Testing
Segment 3 Fibre Cabling	Metres		1.6	<ul style="list-style-type: none"> • Same as for VDSL / LR-VDSL

Source: Cartesian assumptions based on Ofcom and BT data.

Dispersed Premises Module

4.22 After applying the Cabinet Module and the Dense Clusters Module, a number of premises remain unconnected. These geographically dispersed premises were assessed for connection with Fixed-Wireless Access technology (FWA) and FTTP. FWA is optional, so there are two possible ramifications of this approach

FWA versus FTTP

4.23 A convex hull⁴⁰ was created over the unconnected premises and a grid was overlaid, similarly to G.Fast. Within each grid square containing an unconnected premise at least one base station was placed. If the base station had spare capacity, fixed technologies were removed based on the capacity demand

³⁸ We included Segment 3 fibre testing to this aggregated cost as they have the same volume driver: one Segment 3 fibre testing per GPON port, as detailed in Figure 10 and Figure 13.

³⁹ Mix of duct provided by report commissioned by Ofcom, *Estimating the cost of a broadband Universal Service Obligation*.

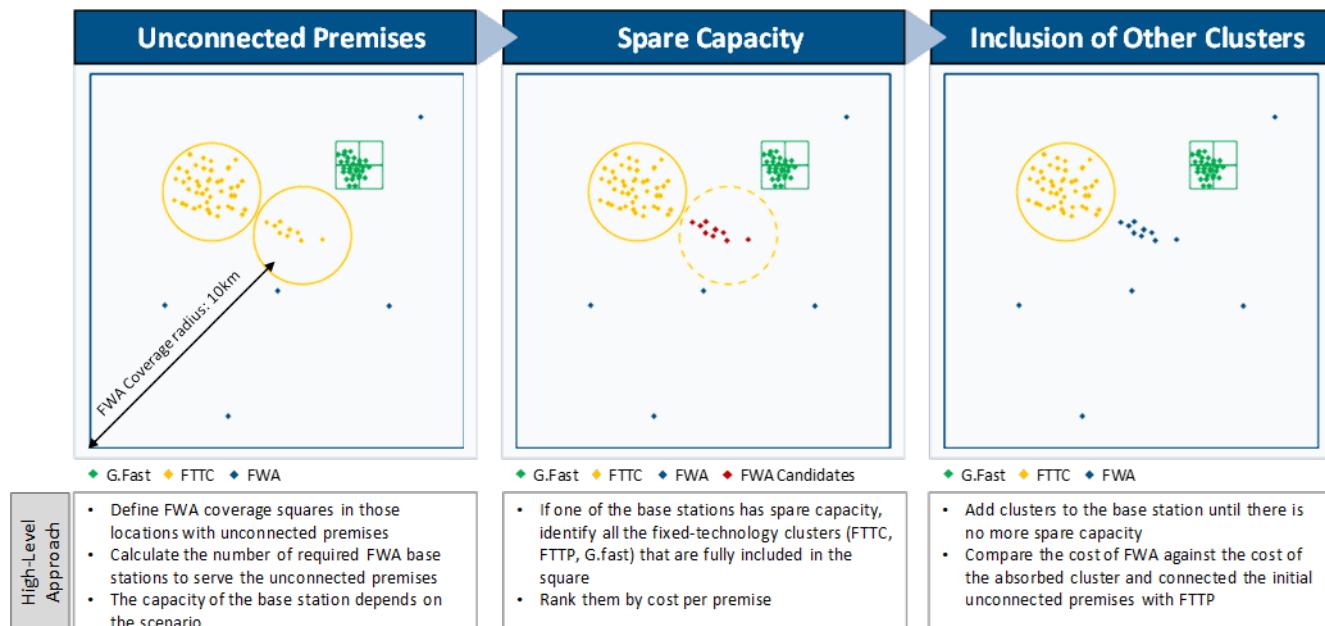
⁴⁰ The convex hull of a set of points is defined as the smallest convex polygon, that encloses all of the points in the set. Convex means that the polygon has no corner that is bent inwards.

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of the premises and the cost per premise until there was no more spare capacity or clusters to be switched to wireless.

- 4.24 In parallel, we calculated the cost of connecting the geographically dispersed premises with FTTP. The technology selection was made by comparing the cost of connecting the premises with fixed technologies versus wireless technology. The figure below summarises the geospatial approach we have developed:

Figure 29. **FWA Algorithm**



Source: Cartesian

- 4.25 Figure 30 show the aggregated costs and drivers used in the geospatial analysis to estimate the deployment cost for FWA (the costs for FTTP are presented above in Figure 28), as well as the subcomponents from Figure 15 included in each aggregated cost item.

Figure 30. **FWA Costs for Geospatial Model**

Supercomponent	Driver	Maximum Capacity	Annualised Cost (£)	Cost Components Included ⁴¹
Base Station	Premises	138-6 ⁴²	27,612.3	<ul style="list-style-type: none"> • FWA site • Active Equipment • Microwave Backhaul
Customer Premise Antenna	Premises	1	47.1	<ul style="list-style-type: none"> • Antenna at Customers Premises

⁴¹ We have used the cost input assumptions and estimations for FWA from the report commissioned by Ofcom, *Estimating the cost of a broadband Universal Service Obligation* (November 2016)

⁴² The number of premises that a Base Station can serve is dependent on the Committed Information Rate and the maximum throughput bandwidth of the technology. These capacity figures assume a coverage per cell of 69 Mbps, as explained in section [*]

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Source: Cartesian

FTTP Only (FWA Switched Off)

- 4.26 If we disable FWA as a technology, the remaining disperse unconnected premises were connected using FTTP. In this case, a two-step process was used to connect them. Firstly, the DBSCAN algorithm was applied with the following parametrisation: an ϵ distance of 500 metres, and a minPremisesFactor of 5 premises⁴³. Secondly, each unconnected premise not belonging to a cluster was considered as an isolated premise, and was therefore connected directly to the nearest cabinet or exchange. In this version of FTTP, premises are connected to the network using the least of the distance to the network and the distance to the nearest dense FTTP cluster.

Satellite Module

- 4.27 On completion of the Dispersed Premises Module, the lowest-cost terrestrial technology option has been selected for each of the UBC premises. The cost per premise is then compared against the annual subscription cost to Satellite broadband service. If the cost of satellite is less than the cost per premise estimated on previous steps, the premises are switched to satellite services. Figure 31 shows the threshold cost used for switching technologies to satellite.

Figure 31. **Satellite Costs for Geospatial Model**

Supercomponent	Driver	Maximum Capacity	Annualised Cost (£)	Cost Components Included ⁴⁴
Satellite Broadband	Premises	1	1,021.0	<ul style="list-style-type: none"> • CPE • One-off installation • Annual subscription

Source: Cartesian

Technologies Available

- 4.28 The geospatial and network cost models can be run for different combinations of technologies. We refer to these combinations of technologies as *techsets*. Some technologies can be turned on or off (such as LR-VDSL, G.Fast, FWA and Satellite), whereas core technologies (VDSL2 and FTTP) are included in all techsets. Ofcom requested seven techsets to be included in the model; see the list in Figure 32.

Figure 32. **Techsets Analysed**

Techset	Technologies Analysed by Scenario
All on	Scenario A & B: VDSL, LR-VDSL, FTTP, G.Fast, FWA, Satellite Scenario C: VDSL, LR-VDSL, FTTP, G.Fast, FWA
LR-VDSL off	Scenario A & B: VDSL, FTTP, G.Fast, FWA, Satellite

⁴³ DBSCAN identifies those premises which have at least 5 MinPremisesFactor in a radius of ϵ , and identifies them as core. Premises not meeting these criteria are labelled as ‘noise’. The algorithm keeps expanding the dense cluster with core properties until the options have been exhausted.

⁴⁴ All commercial broadband satellite offerings come with a monthly data usage cap, which ranges from 10GB to 100GB. This limitation makes satellite broadband inherently not comparable with the other technologies, which do not usually come with a data usage cap. To minimise this impact, we have selected as a benchmark the satellite broadband package with a generous data usage cap (from Avonline Broadband).

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	Scenario C: VDSL, FTTP, G.Fast, FWA
G.Fast off	Scenario A & B: VDSL, LR-VDSL, FTTP, FWA, Satellite Scenario C: VDSL, LR-VDSL, FTTP, FWA
Fixed off	Scenario A & B: VDSL, FTTP, FWA, Satellite Scenario C: VDSL, FTTP, FWA
FWA off	Scenario A & B: VDSL, LR-VDSL, FTTP, G.Fast, Satellite Scenario C: VDSL, LR-VDSL, FTTP, G.Fast
Satellite off	Scenario A - C: VDSL, LR-VDSL, FTTP, G.Fast, FWA
Wireless off	Scenario A - C: VDSL, LR-VDSL, FTTP, G.Fast

Source: Cartesian

Quality Assurance

4.29 In the development of the Geospatial model, several checks were made to assure the outputs were robust and to corroborate that the algorithms behaved as described above. Three types of reviews were made to this end:

- i. Peer review of the scripts – Developers not involved in the creation of the scripts were engaged to review the code.
- ii. Unit testing each module – The modules were tested in isolation. Several check-points were included in the scripts of each module to compare the behaviour of the program against the expected outcome.
- iii. Sanity check of the results – A final analysis of the results for all scenarios and in key technology sets was made to assure the program was performing correctly.

4.30 Sample Geospatial model outputs are presented below. Emphasis is made on how the technology mix changes by scenario and how the availability of technologies affect the final output on scenario B1.

4.31 The figure below shows the average cost per premises across the six scenarios. It is important to note that the costs presented are those used within the Geospatial model decision-making and do not exactly match those in the Cost Model⁴⁵.

⁴⁵ The main differences with the Cost Model are: 1) detailed cost items were grouped into super components which share a common volume driver; 2) cost were calculated by summing the tilted annuity and the annual Opex; 3) only two main cost drivers – metres and premises – were used to estimate the network dimensioning; 3) shared costs across technologies were not considered as they were not deemed to impact the choice of technology and; 4) the cost of wireless technologies (FWA and Satellite) are included.

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Figure 33. *Premises and Cost per Premises by Scenario*

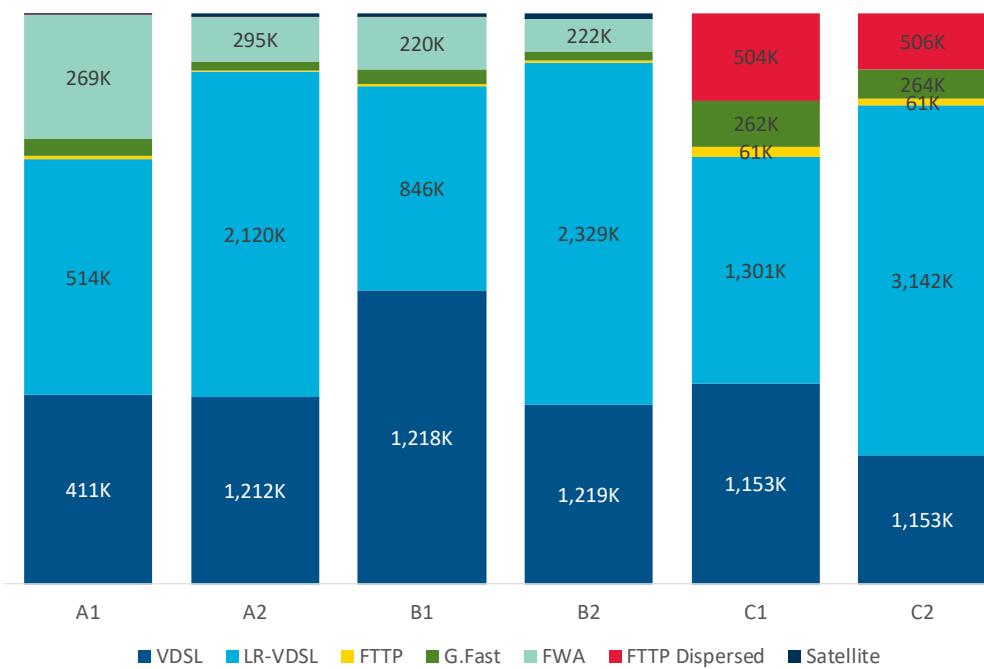


Source: Cartesian

- 4.32 Two effects can be observed. First, scenarios C1 and C2 have a significantly higher cost per premises passed than scenarios A and B. This is mainly due to three reasons: i) FTTC technologies, which are the most cost effective, cover less premises due to the reduced range for these scenarios; ii) UBC performance requirements of the C scenarios are too high to be served with Satellite; iii) the high CIR of the C scenarios limits the number of premises that can be served from an FWA base station.
- 4.33 A second effect can be seen when comparing the outputs for A1 with A2: the cost per premises passed is lower for the second scenario which takes a more conservative view of current broadband speeds and thus includes more premises. The same effect can also be seen between scenarios C1 and C2; however, there is little variation in the cost per premises between B1 and B2. [The increase in the cost per premises in scenarios C1 and C2 versus the others is due to sparse premises being connected with FTTP because of the limited capacity of FWA and the lack of a Satellite option.]
- 4.34 Taking a closer look at the technology mix by scenario, Figure 34 below shows that the majority of the incremental premises in scenario A2 are served with cabinet-based LR-VDSL. Since FTTC has a lower cost per premises than the other technologies, this reduces the average cost in Scenario A2 (and likewise in C2). In the B scenarios, the overall share of FTTC (VDSL2 plus LR-VDSL) does not show much variation. The mix shifts from VDSL2 to LR-VDSL, but as these technologies have similar costs, the average cost per premises is not impacted.

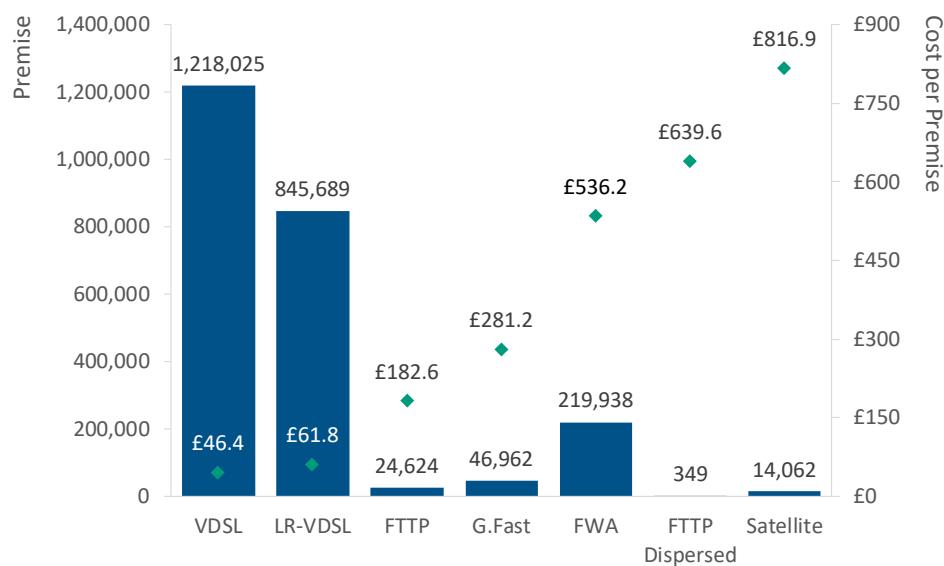
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Figure 34. ***Technology Mix by Scenario***



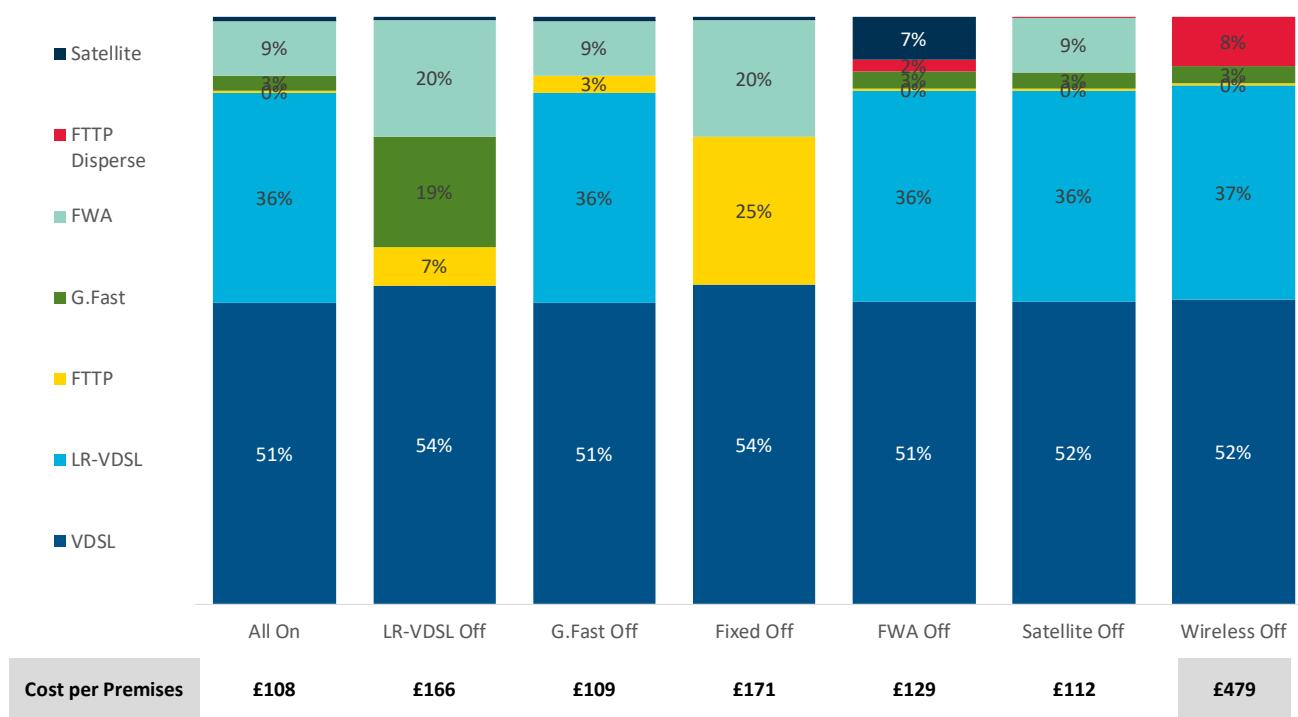
Source: Cartesian

- 4.35 Figure 34 also shows that FWA serves a relatively constant number of premises – around [250 thousand] across the scenarios. This indicates the consistency of the model in identifying remote premises and assigning them to the technology with the highest reach.
- 4.36 Figure 35 shows the breakdown of scenario B1 by technology and the average cost per premises for each technology. The chart shows that most premises (87%) are served using VDSL2 and LR-VDSL which are the lowest cost technologies. FWA is the next most common technology with 9% of premises, which is consistent with its ability to serve premises that are widely distributed. There is also a small role for FTTP and G.Fast in selected clusters of premises that are beyond the reach of cabinet-based technologies. The majority of the remaining, dispersed properties are served by Satellite, which is more cost-effective than FTTP for almost all premises in this category.

Cartesian: Universal Broadband – Network & Cost Module Documentation**Figure 35. Scenario B1: Technology Mix and Cost per Premises**

Source: Cartesian

- 4.37 To further test the model, Cartesian examined a number of scenarios in which selected technologies were removed as options. Figure 36 below shows that the cost per premises is relatively insensitive to the changes in the technologies available, except for when all wireless technologies are removed, and when LR-VDSL is removed. The removal of FWA and Satellite from the technology mix means the remote and dispersed locations need to be connected with more expensive technologies (in particular FTTP), increasing the cost per served premise by over 300%. Removal of LR-VDSL also increases the average costs, but to a lesser extent (51%).

Cartesian: Universal Broadband – Network & Cost Module Documentation**Figure 36. Scenario B1: Technology Mix by Available Technologies**

Source: Cartesian

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5. Network and Cost Modules - Implementation and Assumptions

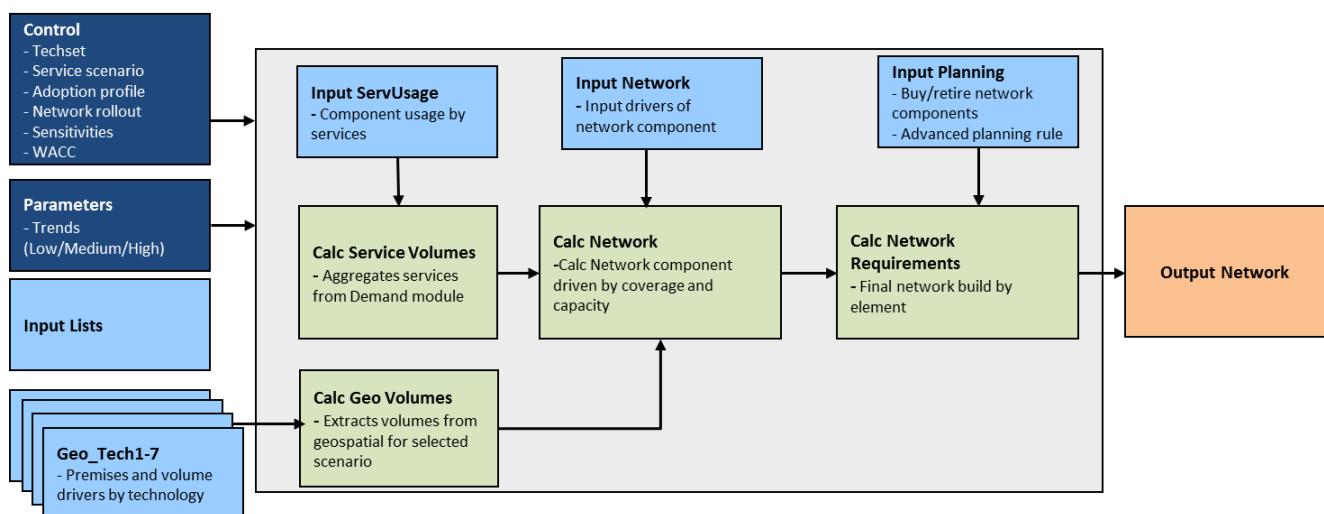
Overview of Network and Cost Modules

- 5.1 As outlined in Figure 1, the outputs from the geospatial analysis are consumed as input data by the Network module. This module uses the Geospatial Analysis results and the Service Demand outputs in order to calculate the incremental volumes of network components to deliver the Universal Broadband service.
- 5.2 The Cost module calculates the capital and operating expenditure required to build and operate the dimensioned network. The outputs from the Cost Module are used by the Cost Recovery module to calculate how costs are recovered over time and across services.
- 5.3 The output of the Network and Cost modules will be used by Ofcom's UBC Cost Recovery module. FWA and Satellite have been excluded from the analysis as per request from Ofcom (refer to section 5 of Ofcom's consultation for the rationale). As an example, if the geospatial analysis determines that 25% of the UBC-eligible premises for a specific scenario should be covered by FWA and Satellite, the Network and Cost modules will only estimate the cost of serving the remaining 75% of premises.

Network Module

- 5.4 The Network module takes the geospatial analysis results and service demand inputs to dimension the network accordingly. An overview of the logic of the network module is shown in the figure below.

Figure 37. **Network Module Overview**



Source: Cartesian

Overview of Network Module Sheets

5.5 Input Sheets

- Control

Shows key parameters which affect the overall model for scenario modelling and sensitivity analysis. These include the network deployment and subscriber adoption profiles over the modelled period, selection of combination of technologies (techset) and scenario, as well as a

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number of sensitivity parameters (e.g. CPI, WACC). The control parameters are taken from Ofcom's UBC Control Module.

- Parameters

Shows the specific parameters for the scenarios and sensitivities selected in Ofcom's UBC Control Module.

- Geo_TechID

There are seven Geo_Tech sheets, with the output volumes from the Geospatial analysis for each techset (see 4.25).

- Input – Network

This sheet contains the dimensioning drivers for each network element, which are provided by the geospatial analysis (via Geo_TechID) or the service volumes.

- Input – ServUsage

Determines which network elements are used by each service in the *Service Usage Factor* matrix. This is used in the Cost Recovery module to calculate the cost of each ancillary service (e.g. Software Change).

- Input – Planning

This sheet includes the asset lives of all the network components and defines the asset replacement purchase rules as well as the advanced planning rules.

5.6 Calculation Sheets

- Calc_GeoVolumes

Returns the volumes from geospatial analysis for the Scenario and techset selected in the Control sheet.

- Calc_ServiceVolumes

Receives the volumes of rentals and ancillary services, calculated in Ofcom's Volumes module.

- Calc – Network

Using the input sheets described above, this sheet calculates the asset count of the Universal broadband network elements.

- Calc – Network Requirements

Using the network element volumes from *Calc_Network*, and the network planning rules from *Input_Planning*, this sheet calculates the total quantity of Universal Broadband network assets that need to be purchased each year.

5.7 Module Output

- Output – Network

This output sheet is a mirror of *Calc – Network Requirement*, and is used as an input by the Cost Module.

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Bandwidth Demand

- 5.8 The Universal Broadband network is dimensioned to support the bandwidth requirements determined by the values of CIR for each scenario e.g. 1.5 Mbps for scenarios B, and 10 Mbps for Scenarios C⁴⁶. The values of CIR are constant for the length of the model.
- 5.9 The Geospatial analysis uses the CIR values to calculate the total bandwidth at the aggregation points (i.e. FTTC Cabinets, Primary Splitter Node and G.Fast DSLAM), which are used to dimension the transmission components of the network, e.g. network cards and ports at these locations.

Dimensioning of ‘Physical’ Network Assets

- 5.10 From a volume driver perspective, we can consider that there are two types of components in the Network module: the ‘Physical’ network assets and the ‘labour and customer-related’ components. We apply a different dimensioning approach to these two component types.
- 5.11 For the ‘Physical’ network assets, we dimension the volumes according to the network deployment profile and taking into account the steady-state subscriber adoption forecast. As an example, when an FTTP network is deployed, the passive splitters are dimensioned to support the steady-state demand forecast to avoid additional site visits to augment capacity in the short-term.
- 5.12 As a result, the steady-state volume drivers of these components have been calculated at the Geospatial analysis. The calculation considers the number of premises for each technology, the end-state take-up rate of 80%⁴⁷, and the capacity of each component. For example, if the Geospatial analysis estimates 140,000 premises to be connected using FTTP, the steady-state number of FTTP subscribers will be 112,000. As the capacity of a PSN is 112 subscribers, we will need a total of 1,000 PSNs.
- 5.13 Knowing the end-state volume of each component across the entire network, we multiply this figure by the network deployment profile each year, in order to determine the asset count that needs to be purchased each year.
- 5.14 We have used this approach for the following components:
- FTTC: all components except for Extra faults at PCP/Copper⁴⁸
 - FTTP and G.Fast: all components except for Segment1 Fibre Testing
 - All components in the local and remote exchange
 - Network Planning activities

Dimensioning of ‘Customer-related’ Components

- 5.15 These components are intrinsically related to the subscriber adoption evolution. The costs are therefore driven from subscriber volumes. The list of components using this approach is as follows:
- Extra faults at PCP/Copper
 - Segment1 fibre⁴⁹

⁴⁶ As Scenarios A do not have a CIR requirement, we have assumed a CIR of 0.5 Mbps in order to dimension the network elements affected by bandwidth requirements (e.g. a FWA site with a capacity of 69Mbps supports $69/0.5 = 138$ subscribers).

⁴⁷ An 80% steady-state take-up rate was determined by Ofcom based on the take-up evolution seen on BDUK.

⁴⁸ For DSLAM Access Cards this represents a simplification, as in practice a CP would be expected to partially equip the DSLAM when initially deployed and add further access cards in response to subscriber growth. The impact of this model simplification is therefore to bring forward the deployment of the additional cards in line with network growth, which leads subscriber growth. However, a CP would be expected to install some extra capacity on day one – to reduce the need for subsequent rework – and the cost of the incremental network cards is small compared to other components (3% of total capex). Hence the overall impact on cost recovery is limited.

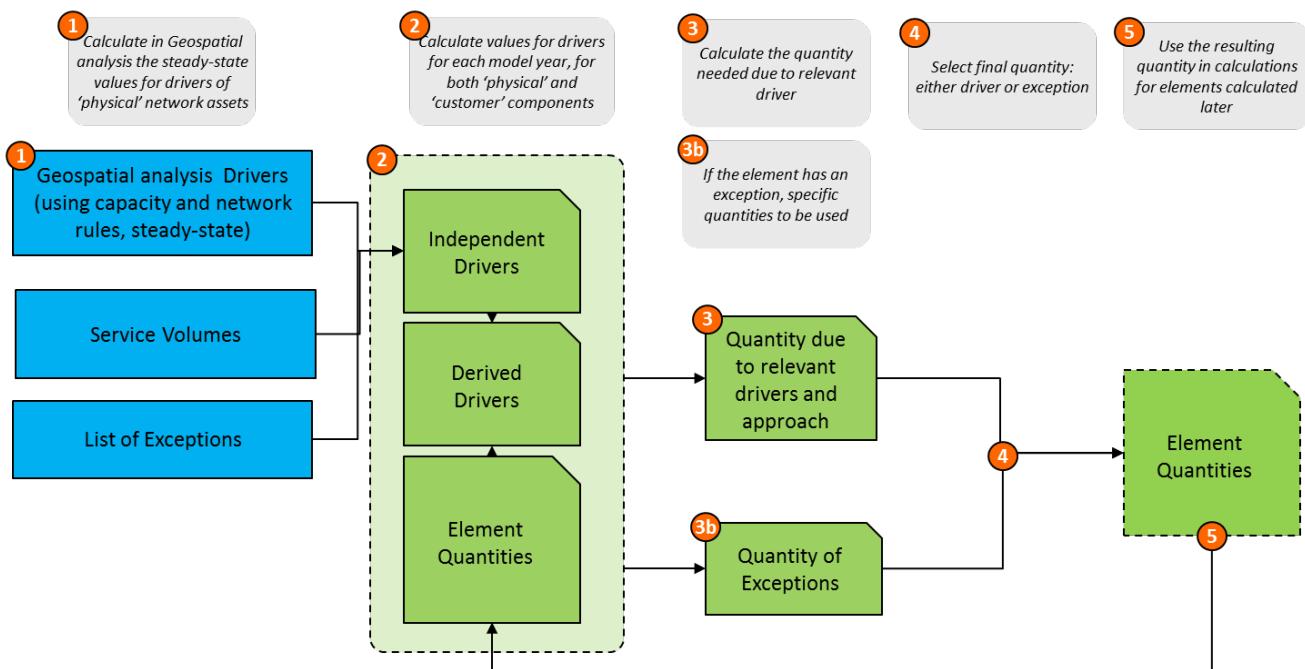
⁴⁹ Includes the installation and testing of the fibre from the Distribution Points to the premises.

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- Ancillary services, including Software configuration, PCP Jumpering activities, and Premise visits
- FTTC and G.Fast Field interventions
- Service Level Guarantee (SLG) Rentals and Connections
- Cumulo rates

- 5.16 The number of subscribers for each technology is calculated by multiplying the steady-state number of premises for each technology (from the geospatial analysis) by the subscriber adoption profile provided by Ofcom in the Control sheet.
- 5.17 The approach to determine the required quantity for each network element in each year is illustrated in Figure 38.⁵⁰

Figure 38. ***Element Dimensioning Approach***



Source: Cartesian

- 5.18 The bottom-up model is also able to accommodate exceptions to the above approach, e.g. Hardware and Software costs for OSS/BSS are treated as exceptions and are independent of the other driver inputs. Care should be taken to ensure that the driver volumes and exceptions are internally consistent when using the model to explore different scenarios.

Calculate the Buy and Retire for Different Elements

- 5.19 Once the bottom-up model has calculated the total number of elements required, it calculates the additional quantities required in each year given advance-planning requirements, the elements

⁵⁰ The calculations of element quantities at step 3 in the diagram are interim results and care must be exercised if analysing these figures as they may appear inconsistent in isolation due to the sequence of calculations. On a standalone basis, only the final results (after calculating the maximum figure) are meaningful.

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purchased for additional capacity and those purchased to replace retired equipment. The bottom-up model also calculates the quantity of network elements retired.

- 5.20 Assets in the network model are retired at the end of their useful lives and replaced if still required. As in real-world operations, there is variation between the useful lives of different network elements in the bottom-up model. We are using the same asset life figures as in the WLA model⁵¹. The table below shows the figures:

Figure 39. *Asset Lifetimes by Equipment Type*⁵²

Equipment Type	Asset Lifetime in Model (Years)
DSLAM	7.1
Street Cabinet	23.4
Copper Cable	16.2
Opto-electronic Equipment	11.3
Rack and Frames	20
Servers & Software	5
Fibre Cable	22.2
Duct	46.8
Optical Passive Equipment	20.8
Depreciation within 1yr	1
OSS Software	10

Source: Cartesian, BT RFS

- 5.21 The bottom-up model is based on an annual assessment, and as such all lead times are rounded to the nearest whole year. As a result, the bottom-up model assumes a planning lead time of one or zero years, depending on the network element. Those elements mostly driven by coverage drivers, which tend to require civil works and planning permission (e.g. fibre cable, FTTC Cabinets), are modelled with a planning lead time of 1 year. Other network elements requiring less planning and lead time for their installation (e.g. access cards) are modelled with a planning lead time of zero years (i.e. less than 6 months).

Cost Module

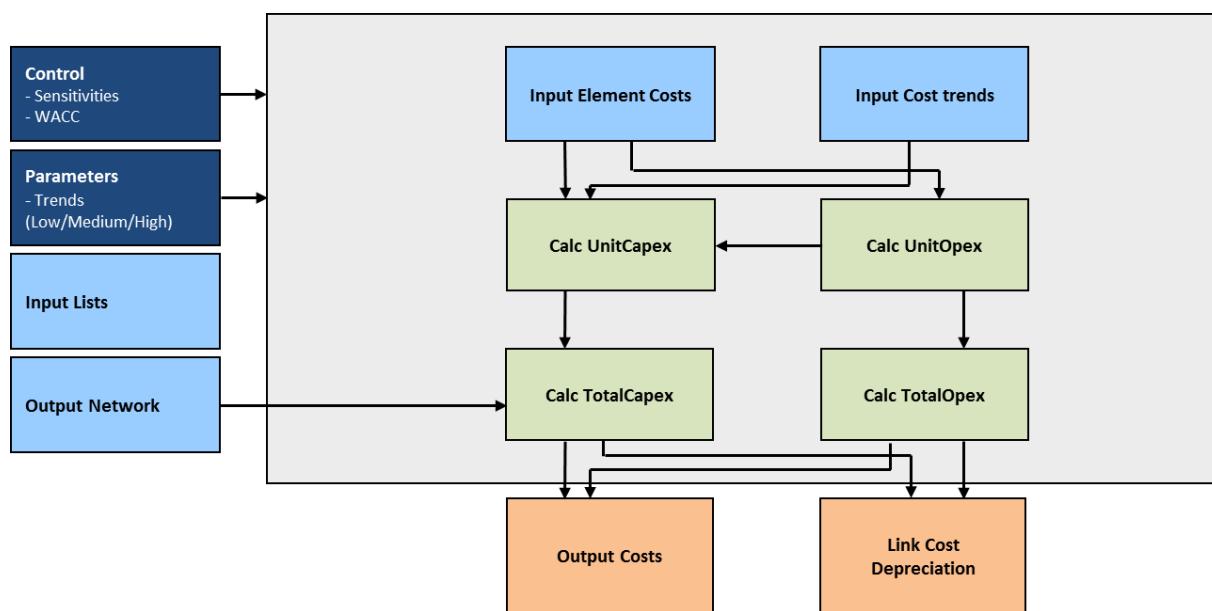
- 5.22 The Cost module takes its inputs from the Network module and produces total network cost estimates. The outputs from this sheet are then used as inputs in the Cost Recovery module. An overview of the cost module logic is shown in Figure 40 below.

⁵¹ BT uses these figures when booking FTTC asset purchases in its Management Accounts, except for Rack and Frames, and OSS Software, which were informed by the 2013 NCC model and Ofcom's own analysis. These asset categories also cover all components of G.Fast and FTTP.

⁵² The figures in this table have been randomised to maintain confidentiality.

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Figure 40. **Cost Module Overview**



Source: Cartesian

Overview of Cost Module Sheets

5.23 Input Sheets

- Control
Shows key parameters which affect the overall model for scenario modelling and sensitivity analysis. The control parameters are taken from Ofcom's UBC Control Module.
- Parameters
Shows the specific parameters for scenarios and sensitivities selected in Ofcom's UBC Control Module.
- Input – Output Network
This sheet contains the total asset count to be purchased each year and is used as an input sheet to calculate the total service costs.
- Input – Element Costs
This sheet details the current unit costs of all the network elements (Capex and Opex) and is used in conjunction with the *Input Cost Trend* sheet to calculate the evolution of Capex and Opex unit costs over time.
- Input – Costs Trends
This sheet contains the projected evolution of costs of the network elements (e.g. cost of active equipment tends to decrease overtime). These inputs are used in conjunction with *Element Costs* sheet to calculate the evolution of Capex and Opex unit costs over time.

5.24 Calculation Sheets

- Calc – UnitCapex
Calculates the unit Capex cost of the network elements, using *Element Costs* and *Cost Trend* as inputs.

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- [Calc – UnitOpex](#)
Calculates the unit Opex cost of the network elements, using *Element Costs*, *Cost Trend* and *UnitCapex* as inputs (the latter is used because some of the Opex cost can be capitalised, depending on the bottom-up model scenario).
- [Calc – TotalCapex](#)
Multiplies the Capex unit cost from *UnitCapex* by the number of network elements to determine the total Capex costs.
- [Calc – TotalOpex](#)
Multiplies the Opex unit cost from *UnitOpex* by the number of network elements to determine the total Opex costs.

5.25 Output Sheets

- [Output – Costs](#)
This output sheet summarises the total incremental Capex and Opex costs incurred to deliver Universal Broadband services. This sheet is used in the Cost Recovery module.
- [Link – Cost Depreciation](#)
This output sheet contains output tables required by the Cost Recovery module for calculating the asset cost depreciation over time.

[Unit Capital Costs](#)

- 5.26 For the Universal Broadband, we re-used the unit costs from the WLA model where possible, but updated to FY 2017/18 using the capex cost trends between 2015/16 and 2017/18. A number of components specific to G.Fast and FTTP were not included in the WLA model (e.g. Primary Splitter Node); for these, we have used cost input data provided by BT.
- 5.27 As with the WLA model, the installation unit costs are included in the unit capital costs. The asset retirement costs have been set to zero, as the model assumes that an asset is retired at the same time it gets replaced (thus effectively assuming zero retirement costs). This is because we would expect an efficient operator to align both tasks in order to minimise costs and to avoid disrupting the service (i.e. the network operator would have to temporarily drop the service in the affected area if it were to separately carry out the retirement and replacement activities).

[Unit Operating Costs](#)

- 5.28 We followed the same approach with regards to the unit operating costs, by reusing the relevant cost inputs from the WLA model. The cost items comprising the unit operating cost by network element are shown in Figure 41.

Figure 41. ***Composition of Unit Operating Costs in the Bottom-Up Model***

Network Element	Technologies	Cost Items	Source
Extra Faults at PCP/Copper	FTTC, G.Fast	• Repair costs	Ofcom (see Section 5 of Ofcom's UBC consultation)
Duct PCP to FTTC Cab	FTTC	• Repair costs, • SMC costs	WLA model
Copper PCP to Cabinet	FTTC	• Repair costs,	WLA model

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		<ul style="list-style-type: none"> • SMC cost 	
CAB_Power Connection	FTTC	<ul style="list-style-type: none"> • Disaster recovery 	WLA model
CAB_Civils (Concrete Base)	FTTC	<ul style="list-style-type: none"> • RCD maintenance • SMC costs • Disaster recovery 	WLA model
CAB_Certification Managed Service	FTTC	<ul style="list-style-type: none"> • Electricity meter reading • Electricity meter maintenance 	WLA model
DSLAM Cabinet	FTTC	<ul style="list-style-type: none"> • Maintenance • Repair costs • SMC costs • Disaster recovery • Battery replacement 	WLA model
DSLAM Access Card	FTTC	<ul style="list-style-type: none"> • Warranty fees • Repair costs • SMC costs • Disaster recovery 	WLA model
DSLAM GE Port	FTTC	<ul style="list-style-type: none"> • Repair costs • SMC cost 	WLA model
Fibre Cable	FTTC, FTTP, G.Fast	<ul style="list-style-type: none"> • Fault repair costs • SMC costs 	WLA model, assumed the same figure for fibre of all technologies in all segments
Ducts and Poles	FTTC, FTTP, G.Fast	<ul style="list-style-type: none"> • Maintenance 	Estimating the cost of a broadband Universal Service Obligation, report commissioned by Ofcom
G.Fast DSLAM	G.Fast	<ul style="list-style-type: none"> • Maintenance • Repair costs • SMC costs • Disaster recovery • Battery replacement 	Assumed the same opex / capex ratio as with the FTTC DSLAM
G.Fast Power Box	G.Fast	<ul style="list-style-type: none"> • Disaster recovery 	Assumed the same opex / capex ratio as with the FTTC Power Connection
G.Fast Copper Interception Joint	G.Fast	<ul style="list-style-type: none"> • Repair costs • SMC cost 	Assumed the same opex / capex ratio as with the PCP -FTTC Copper
GE OLT Southbound Card	FTTC	<ul style="list-style-type: none"> • Warranty fees • Repair costs • SMC costs • Accommodation costs • Electricity 	WLA model
GPON OLT Southbound Card	G.Fast, FTTP	<ul style="list-style-type: none"> • Warranty fees • Repair costs • SMC costs • Accommodation costs • Electricity 	Assumed the same unit cost as GE OLT southbound card
GPON Port	FTTP, G.Fast	<ul style="list-style-type: none"> • Repair costs • SMC cost 	Assumed the same unit cost as DSLAM GE port
OSSBSS_Software	LR-VDSL	<ul style="list-style-type: none"> • OSS/BSS operating costs 	Ofcom (see Section 5 of Ofcom's UBC consultation)

Cartesian: Universal Broadband – Network & Cost Module Documentation

Software Configuration	All	<ul style="list-style-type: none"> • SMC costs 	WLA model
Engineer PCP Jumpering	All	<ul style="list-style-type: none"> • Transport and fuel • Labour costs (including travel) 	WLA model
Engineer Premise Visit	All	<ul style="list-style-type: none"> • Transport and fuel • Faceplate • Wires • Labour costs (including travel) 	WLA model
Field Interventions	FTTC, G.Fast	<ul style="list-style-type: none"> • Repair costs arising from customer installations 	WLA model
SLG Payments	All	<ul style="list-style-type: none"> • SLG payments to telecoms providers 	Ofcom (see Section 5 of Ofcom's UBC consultation)
Cumulo	All	<ul style="list-style-type: none"> • Cumulo 	WLA model

Source: Cartesian

- 5.29 With regards to FTTP, we have purposely not allocated opex costs to the splitters, as we consider that they require considerably less time and effort to operate and maintain them, e.g. PON ensures no faults due to power supply issues.
- 5.30 Similarly, we have not included a Field Intervention cost item for FTTP, as we assume that as it is a brand-new technology installed in greenfield areas. In comparison, G.Fast and FTTC reuse existing copper lines which can be very old, and connected to a PCP with a large number of cables , thus maximising the chances of making mistakes.
- 5.31 We have used the equivalent average power per FTTC Cabinet that was calculated and included in the WLA model. We assumed that the G.Fast DSLAMs consume the same power as an FTTC Cabinet. The cost of Power consumed at the exchange is included in the cost of the OLT Southbound Cards.

Element Unit Costs Trends

- 5.32 The bottom-up model calculates the unit costs (both capital and operational) of each network element over the life of the network.
- 5.33 We have used the relevant cost trends from the WLA model. From 2017/18, they were modelled as linear trends. When similar components had a similar cost trend, we grouped them into a trend category. The new cost trends not included in the WLA model are ADSL Migration, Splitter nodes and Ports⁵³. See Figure 42 for the list of cost trend categories (capital costs) in the bottom-up model.

⁵³ We sourced them from BT, except for the Splitter Nodes trend, which we obtained from Ofcom.

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Figure 42. *Linear Cost Trends by Category in Bottom-Up Model (Capital Costs)*⁵⁴

Trend Category	Cost Trend
ADSL Migration	1.1%
Aggregated Fibre Cable	-3.3%
Cumulo	N/A
DSLAM Type 1 Access Card	-1.7%
DSLAM Type 1 Cabinet	0.0%
DSLAM Type 2 Access Card	-1.6%
DSLAM Type 2 Cabinet	0.0%
Duct	1.6%
Extra Fault Repairs	N/A
Fibre Testing	0.0%
Labour	3.1%
OLT Chassis	-3.3%
OSSBSS	0.0%
PCP Connectors	0.0%
Planning	2.9%
Port	0.0%
Power Works and Services	3.1%
Racks and Space	0.16%
Remote Parent Planning	0.0%
Repairs	N/A
Splitter Nodes	0.0%
Track Joint	0.17%

Source: Cartesian

- 5.34 The bottom-up model uses the Consumer Price Index (CPI) to convert the nominal values for Capex and Opex to real 2017/18 values. For FY 2017/18 to FY 2020/21 we use CPI forecasts from the Office for Budget Responsibility (OBR)⁵⁵. Forward-looking CPI for the period FY 2020/21 to FY 2027/28 is held at 2.0%, as per OBR's forecast for 2020.
- 5.35 For the majority of network elements, we use Ofcom's pay and non-pay inflation estimates, presented in Table A15.8 of Annex 15 of the 2017 WLA consultation, to inform the Opex trend assumptions in the model. The bottom-up model includes a Capex and Opex trend for Labour to allow for installation costs to be capitalised and retirement costs to be trended for each network element.

⁵⁴ Please note that the numbers in this table have been randomised to maintain confidentiality.

⁵⁵ OBR's Economic and fiscal outlook, September 2016.

Cartesian: Universal Broadband – Network & Cost Module Documentation

Calculation of Total Costs and Module Outputs

5.36 The total annual capital expenditure for each network element is calculated as follows:

- The product of that year's unit capex figures (including equipment and labour costs) and the number of network elements purchased in that year.

5.37 The total annual operating expenditure is calculated as follows:

- The product of that year's unit Opex figures and the number of network elements in operation during that year.

5.38 The total network Capex and Opex provide inputs to the Cost Recovery module. In addition to the total cost outputs, the element unit Capex and Opex trends, and element quantity outputs from the cost module are also used by the Cost Recovery module. Finally, the Service Usage factors from the Network module are also used to allocate the costs of network element output to network services.

Cartesian: Universal Broadband – Network & Cost Module Documentation**6. Glossary**

Abbreviation	Definition
4G	Fourth-generation
5G	Fifth-generation
AC	Alternating Current
ADSL	Asymmetric Digital Subscriber Line
BDUK	Broadband Delivery United Kingdom
BSS	Business Support Systems
BT	British Telecommunications plc
Capex	Capital Expenditure
CCJ	Cable Chamber Joint
CGA	Current Generation Access
CIR	Committed Information Rate
CJ	Cable Joint
CLI	Customer Lead In
CP	Communications Provider
CPE	Customer Premises Equipment
CPI	Consumer Price Index
CSP	Customer Splicing Point
CuRe	Copper Rearrangement
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
DC	Direct Current
DL	Download
D-side	Distribution side
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
eNodeB	Evolved Node B
EoL	Exchange only Line
E-side	Exchange side
FTTC	Fibre To The Cabinet
FTTdp	Fibre To The distribution point
FTTP	Fibre To The Premise
FTTx	Fibre To The x (x being any possible fibre topology)
FWA	Fixed Wireless Access
FY	Financial Year
GE	Gigabit Ethernet
GEA	Generic Ethernet Access
GHz	Gigahertz
GPON	Gigabit Passive Optical Networks

Cartesian: Universal Broadband – Network & Cost Module Documentation

HH	Households
Km	Kilometres
L2S, L2 Switch	Layer 2 Switch
LLU	Local Loop Unbundling
LR-VDSL	Long Range Very high bit-rate Digital Subscriber Line
LTE	Long-Term Evolution
Mbps	Megabits per second
MNO	Mobile Network Operator
MSAN	Multi-Service Access Nodes
MST	Minimum Spanning Tree
NCC	Network Charge Control
NGA	Next Generation Access
NTE	Network Termination Equipment
NTE	Network Terminating Equipment
OBR	Office for Budget Responsibility
OCR	Optical Consolidation Rack
ODF	Optical Distribution Frame
OLT	Optical Line Termination
ONS	Office for National Statistics
ONT	Optical Network Termination
Opex	Operational Expenditure
OSS	Operations Support Systems
PCP	Primary Connection Point
PIA	Physical Infrastructure Access
PON	Passive Optical Network
PSD	Power Spectral Density
PSN	Primary Splitter Node
PTP	Point To Point
RCD	Residual Current Device
RFS	Regulatory Financial Statements
RU	Rack Unit
SEP	Superfast Extension Programme
SFP	Small Form-factor Pluggable
SLA	Service Level Agreement
SLG	Service Level Guarantee
SLU	Sub-Loop Unbundling
SMC	Service Management Centre
SMP	Significant Market Power
SSN	Secondary Splitter Node
STIN	Suppliers' Trial Information Note

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Techset	Technology Set (combination of available technologies)
UBC	Universal Broadband Commitment
UL	Upload
UPS	Uninterruptible Power Supply
USO	Universal Service Obligation
VDSL2	Very high bit-rate Digital Subscriber Line 2
VLAN	Virtual Local Area Network
VOA	Valuation Office Agency
WFAEL	Wholesale Fixed Analogue Exchange Lines
Wi-Fi	Trademarked phrase for IEEE 802.11x standard
WiMax	Worldwide Interoperability for Microwave Access
WLA	Wholesale Local Access
WLACC	Wholesale Local Access Charge Control
WLAMR	Wholesale Local Access Market Review
WLR	Wholesale Line Rental

Cartesian: Universal Broadband – Network & Cost Module Documentation

7. Data Sources

Source	Description
Connected Nations 2016	Dataset produced by the Ofcom Connected Nations team which captures all the unique telephone lines (Openreach specific) that don't meet the Universal Service Obligation requirements in terms of Download speed or Upload speed. This dataset associates the unique telephone line identifier with premises location and with PCP and Exchange.
BT Cabinet Location to Exchange Mapping	Information provided by BT to the Connected Nations team as part of the v2 tranche. This dataset has for each PCP unique identifier: the type of PCP (FTTC enabled or not), the location of the PCP and, the exchange they are connected to.
BT Exchange Location	Information provided by BT to the Connected Nations team as part of the v2 tranche. This dataset has the location of each Exchange unique identifier.
BT PCP-Exchange Mapping	Due to initial problems with population of the PCP and Exchange fields in the Connected Nations 2016 datasets (in the v2 tranche), the Connected Nations team provided a BT-authored file listing all the UPRN and its PCP-Exchange relationship.
BT FTTC Deployment Report	Openreach regularly publish updates to the GEA FTTC network rollout plan listing, on a per-cabinet (PCP) basis, the historic and planned timing of FTTC deployments.
BT PCP Mapping Report	Openreach regularly publish a dataset defining which street cabinets serve a given postcode, how many postcodes are served by a given cabinet, whether EoL are present at a cabinet, and lines breakdown by postcode.
WLA Charge Control FTTC Data	This data identifies aspects of the GEA FTTC network rollout to-date, and is a dataset provided by Openreach in response to Q10 of tranche 1 of the 23rd s.135 request for the WLA-CC. Additionally, this dataset contains for each PCP, its location, its copper exchange location and, its fibre exchange location.
BT Active FTTC Lines per Cabinet	This dataset, provided by Ofcom from BT, contains the number of FTTC active lines connected to each cabinet by CP.
BT Active MPF-SMPF Lines per Exchange	This dataset, provided by Ofcom from BT, contains the number of active MPF and SMPF lines per exchange by CP.
UK Postcodes (Code-Point Open)	Information freely available from Ordnance Survey with the location of all the postcodes in Great Britain.
Cost Model Data Sources	We used cost inputs from the WLA model (which had mostly used data from BT's Engineering Model) for those network components used in FTTC deployments. For FTTP and G.Fast-specific items, we used BT's FTTP and FTTRN modelling assumptions. For FWA, we used the cost inputs included in Ofcom's previous USO report. We sourced Satellite broadband service costs from a market scan of publicly available data.

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