ANALYSIS OF THREE'S CONGESTION MODELLING

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Non-Confidential

CONTENTS

EXECUTIVE SUMMARY

This report provides an overview of Three's analysis of forecast congestion in its network in the absence of additional spectrum. In particular, it provides a high level explanation of:

- The conceptual approach to modelling;
- Three's key assumptions with regards to future demand and capacity growth and the robustness of these assumptions; and
- The resulting impact on estimated levels of congestion that Three's network may suffer as a result and the end-user impact.

Three's analysis compares supply and demand at a granular level: consisting of the areas served by individual cells in the current 1800 MHz 4G network, which covers the areas with highest traffic density in the network. Where forecast demand exceeds a threshold of effective supply the analysis assumes that the network will be congested, i.e. end users will perceive a notable reduction in their quality of service.

The demand forecast at an area level assumes throughput in each cell grows at the same rate as Three's internal assumptions of overall network traffic growth. This in turn is based on assumptions on the rate of growth of data usage per subscriber and customer growth, in the absence of any capacity constraints. The assumptions on the growth in data usage per subscriber are more conservative than forecasts from other industry experts.

The capacity forecast at an area level depends on two factors:

- Technical enhancements which allow increased capacity from existing investments through increased spectral efficiency; and
- Investments in capacity enhancements, initially deploying additional spectrum on existing sites followed by the deployment of more sites (as a proxy for the range of densification solutions which could be deployed).

The assumptions on the rate at which Three can add additional capacity appears to be optimistic taking account of the difficulties of gaining access to existing sites and of acquiring and provisioning new sites. To the extent that Three cannot meet this rate of growth, the forecast level of congestion will understate the actual level of congestion.

In the absence of additional spectrum and taking account of an optimistic view of the rate of capacity growth (from capacity enhancements that can be rolled out on sites and increases in spectral efficiency from existing investments), the analysis shows that [✂-Results of the analysis by Frontier]

1 CONCEPTUAL APPROACH

Congestion modelling is challenging

Congestion on mobile networks occurs when the available network resources in a given area are insufficient to provide an acceptable level of service, given the demand required ('offered') by subscribers in that area. Modelling congestion is challenging for number of reasons:

- The very heterogeneous distribution of demand across the network by area and by time of day, reflecting variations in the location and usage of subscribers over time;
- The effective capacity in a given area/cell varies significantly over the network (and to a lesser degree over time) and is to a degree dependent on demand; and;
- The relationship between supply, demand and users' perceived network performance is complex.

However, despite these challenges, a good understanding of the relationship between demand, supply and congestion is essential to efficiently managing a mobile network in the short and long term. Three routinely conducts congestion modelling in order to forecast the level of congestion on its network under a range of different scenarios in order to support its overall strategy. This modelling feeds into both its commercial strategy and network strategy investment plans.

The congestion modelling focusses on the RAN

Given the relative importance of the radio access network (RAN) in terms of the proportion of network investment and the physical constraints on adding RAN capacity (i.e. spectrum and physical sites), the congestion modelling focusses on the RAN.

Using the current RAN performance as a starting point, Three has built a congestion model to:

- Anticipate future network performance;
- Identify potential congestion problems on the network;
- Identify the likely demand that the network can support and therefore derive customer acquisition and service strategies; and
- Plan future network investment and spectral deployment to ensure that consumers continue to receive a high-level service.

Given the commercial importance of accurately determining a strategic and commercial investment plan derived from a network-based approach, Three has a strong incentive to accurately forecast future network demand and capacity. As such Three has invested considerable resources and time in determining a robust and reasonable model of future network performance, which reflects its best-estimates of how these metrics will evolve over time.

The model forecasts based on a disaggregated area level

Three models congestion on a disaggregated area level basis reflecting the non-fungibility of traffic between cells on a site, i.e. if one area is congested it is not possible to divert the mobile traffic to a second area to relieve the issue. The areas used are based on the number of cells in Three's network in the base year, which is the lowest level of disaggregation for which robust data on the distribution of demand is available[1]. As the network evolves over time, for example due to densification of the network, including the addition of 'small cells', the actual cells in the network will differ from those in the base year. The model takes account of this densification by making assumptions about capacity in these areas which includes the impact of densification.

The modelling is based on forecasts of future supply and demand in these areas based on the level of supply and demand at a cell level in a base period, capturing the distribution of demand and variability in capacity across the network. By comparing forecast capacity to forecast demand in the area corresponding to existing cells the model determines whether any given area will be congested and hence the overall level of congestion across the network.

The analysis considers the 3G and 4G networks together

Both supply and demand is split over the 3G and 4G networks. Capacity is not fungible over the short term, i.e. dynamically within the network to take account of differing levels of utilisation on the different technologies. This means that one of the layers could be congested even though there is spare capacity overall. As such considering 3G and 4G capacity as a single pool will be conservative, i.e. will tend to understate congestion.

[✂-Possible future options.][2].

A throughput based approach

In order to compare supply and demand, these must be expressed in similar terms. The model expresses demand based on the unconstrained aggregate demand, i.e. demand in the absence of congestion[3] within a given area as a throughput in Mbps during the busy hour. The available capacity in the area is then expressed as a maximum achievable throughput in Mbps.

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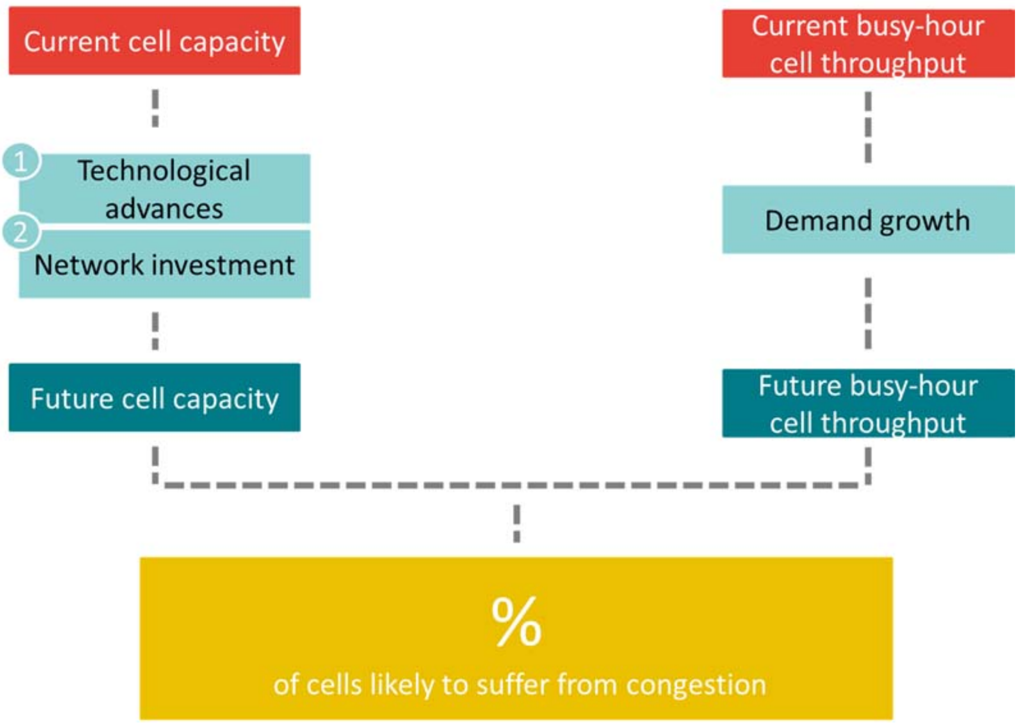
1 [✂-Option prevented by terms of Three's network share arrangements.]

2 [✂]

3 If there is congestion some offered demand will be blocked and the achieved throughput will be lower than the unconstrained demand.

Three forecasts capacity and unconstrained demand (measured as throughput in Mbps) at a base year cell level to estimate whether capacity will be sufficient to cope with future demand as shown in the diagram below. If unconstrained future demand is expected to exceed the supply capability of a cell (based upon a utilisation threshold) Three marks a cell as "congested". Given uncertainties over the longer term, in particular the potential impact of 5G technologies from 2020 onwards, the focus of Three's analysis is on the next five years, i.e. up to 2021.

Figure 1 Three's approach to estimating congestion

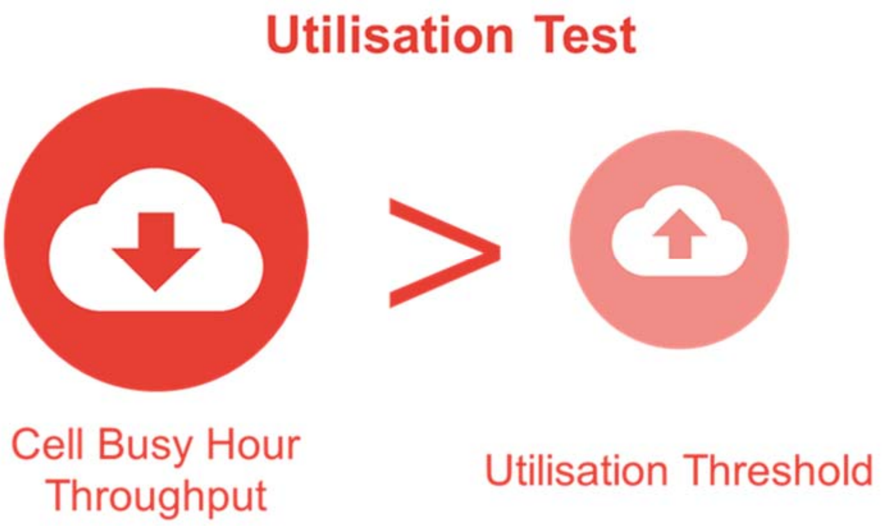


Source: Frontier Economics based upon input from Three

The analysis in this paper reflects the case where Three does not acquire additional spectrum

In order to understand the impact of not acquiring additional spectrum in the upcoming PSSR auction, Three has conducted an analysis based on this congestion modelling which shows the forecasted level of congestion in the network in this scenario. This report outlines this approach.

Figure 2 Threshold test for identifying congestion on Three's network.



Source: Frontier Economics

Input assumptions

The input assumptions to the congestion model are:

- the base year data used as a basis for the forecast supply and demand;
- the forecast of maximum throughput capacity on each base year cell area;
- the forecast of demand on each base year cell area; and
- the comparison of capacity and demand in each area against a threshold (based on the base year data) to estimate the number of congested areas.

Each of the components of the model is described in more detail below. It should be noted that Three has used conservative assumptions throughout its congestion model, and the congestion forecast numbers shown below are likely to be under-estimates.

2 BASE YEAR DATA

As noted above, the congestion model uses base year data at a cell level as a basis from which to forecast capacity and demand at a disaggregated level. This data is also used to determine the congestion threshold.

2.1 Cell level data collected by Three

[✂-Three’s views on what consumers value and how it collects cell level data.]

The data collected includes:

- Cell configuration data including information on current spectral deployment.
- A number of technical performance metrics measuring both cell level demand and capacity and end-user experience;
- The aggregate busy hour demand from all users within the cell, i.e. total downlink throughput in Mbps;
- The available capacity in the cell to serve customers, which reflects the technical performance metrics[4]; and
- The average user experience in the busy hour, i.e. the mean throughput per user[5].

2.2 Cell sample

The forecast is based on a subset of [✂-number] sites, and hence cells, in Three’s network – those sites that currently have 4G spectrum in 1800 MHz band installed, as at December 2016. [✂-Sectorisation of Three’s LTE sites.]

The sample was restricted to these sites in order to allow a full data set to be collected on which to identify supply and demand.

As a result Three has not modelled congestion on sites which do not currently have 1800 MHz 4G spectrum deployed, which represent additional [✂-number] cells. If these were expected to become congested in future years, the model would understate the level of congestion and is therefore conservative.

However, the degree of under-forecasting of congestion is likely to be relatively small. To illustrate this point, we understand from Three that before it commenced 4G roll out in 2014 it identified the top 6,000 busiest sites in its network. Of these 6,000 sites, by the end of 2016, [✂-number] remain as 3G only. This verifies that the 4G roll out programme has addressed most of the 3G congested sites and also illustrates the difficulty in upgrading sites, even where there is a strong business case to carry out these upgrades. This suggests that the current approach of

4 Measured as average nGBR downlink cell capacity in Mbps

5 Measured as average nGBR downlink end-user IP throughput in Mbps

focusing only on 4G sites is likely to provide robust estimates of the level of congestion in high-traffic areas.

Figure 3 [✂-Table showing numbers of busiest sites not upgraded to LTE.]

Source: [✂]

3 AREA LEVEL CAPACITY FORECAST

Three measures cell capacity using throughput capacity, i.e. a technical estimate of the maximum throughput that a cell is able to carry in Mbps. Below we (i) set out the current throughput capacity of Three's network, (ii) describe the technological developments and network investments that are likely to allow Three to increase the throughput capacity that can be extracted from the available spectrum in the future; and (iii) describe how these technological developments will impact Three's throughput capacity in the future.

3.1 Three's base year capacity

Cell capacity with a similar configuration varies depending on a range of factors including the size of the cell, the amount of 'clutter' in the cell and the distribution of customers around the cell.

Cell capacity can be determined based on the spectrum and technology deployed on that cell and the 'typical' performance achieved by a cell with these characteristics or an 'actual' basis, using the cell level data on throughput per cell, taking into account the radio conditions pertaining in that cell.

Three [✂-Three's view of likely future developments.] has conservatively set the baseline for cell's capacity as the higher of:

- Typical capacity given Three's LTE spectral deployments as described below; and
- Actual cell capacity achieved as recorded by Three's RAN data for the 4G network *plus* typical capacity of a cell for the 3G network[6].

This assumes that areas with relatively low performance can be "brought up" to a typical performance, while those areas which show above typical performance on the 4G network will maintain this performance.

3.1.1 Typical performance

The capacity of a cell is a function of spectrum deployed on that cell and the spectral efficiency achieved by the radio equipment (i.e. how much capacity a network produces for a given increment of spectrum). Three currently holds access to spectrum in four different bands (800 MHz, 1400 MHz 1800 MHz and 2100 MHz), which are deployed as shown in the table below:

Figure 4 [✂]

Source: [✂]

[6] Actual capacity is not available for the 3G network

[✂-Information on how Three configures its network.]

Figure 5 [✂]

[✂]

Source: [✂]

[✂]

Figure 6 [✂]

Source: Frontier Economics based upon Three's congestion model

3.1.2 Actual throughput

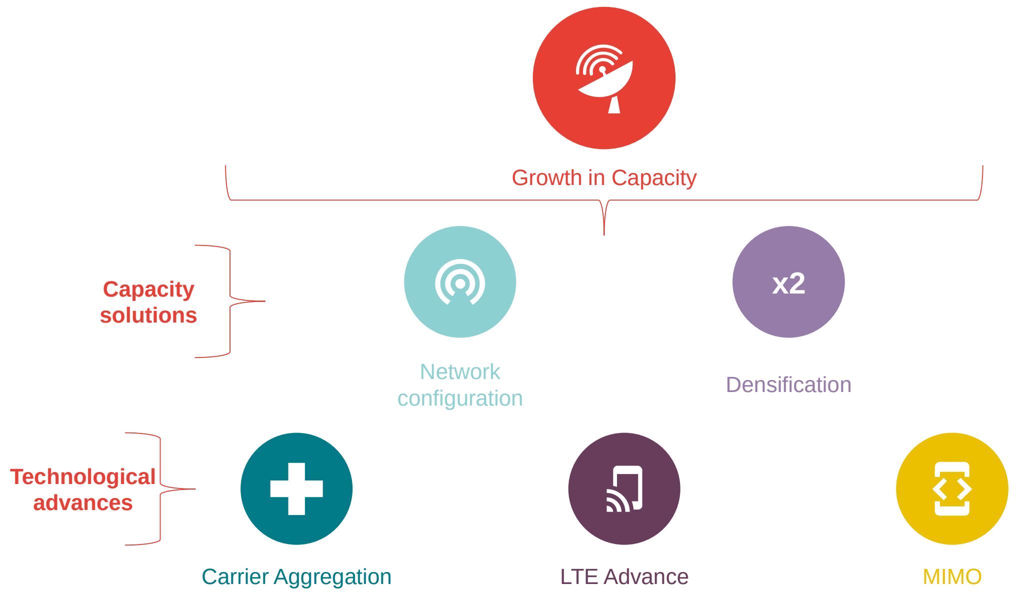
In addition to the network-level spectral efficiency achieved, Three's network data also reports cell-level estimates of capacity achieved on the 4G network. An individual cell can achieve higher or lower levels of downlink throughput capacity depending upon the geography, topography and customer distribution around that site.

As noted above, data on actual throughput is only used where the measured 4G capacity exceeds the typical 4G capacity above.

3.2 Future Capacity Growth

Having determined a conservative starting point for cell capacity using the method set out above, Three next models expected future capacity gains in line with the following five anticipated developments.

Figure 7 Sources of Capacity Growth on Three’s Network



Source: Frontier Economics Based Upon Three’s Congestion Model

3.2.1 Capacity solutions

In addition to spectral efficiency gains arising from technological developments, Three’s congestion model accounts for gains in future supply owing to two investments by the business:

- [✂-Two anticipated business investments.]
- [✂]

The model assumes that once a cell becomes congested a ‘capacity’ solution’ is implemented on this cell in the following year to attempt to alleviate the congestion. Under the scenario where Three gains no more spectrum in the PSSR Auction, two types of capacity solution are modelled:

1. [✂-One of the capacity solutions.]; and
2. Providing additional cells, fully deploying existing spectrum as a proxy for densification.

As the lead time to deploy additional spectrum on existing sites is less than the lead time to provision new sites, the model assumes that when a site first reaches congestion the first step will be to deploy more spectrum on existing sites, with new cells deployed following this.

The model assumes that when a cell becomes congested, a capacity solution will be deployed, if available, in the following year. This lag, rather than a capacity solution being applied immediately that a cell is congested or to pre-empt future congestion, reflects the time to implement capacity solutions once congestion is identified.

In addition the model assumes that only one capacity solution can be deployed on a given cell in each year, i.e. it is not practical to simultaneously both deploy additional spectrum on a cell and densify the network in the area covered by the cell[7].

Deploying all 4G spectrum

- [✂-Three's spectrum plans.]

Densification

Once the additional spectrum is deployed, the form in which additional cells are added to the network is not explicitly specified but may be:

- An additional macro-site, effectively splitting the cell;
- Roll out of small cells using existing spectrum; or
- Solutions such as in building systems.

The actual solution applied will depend on the specific characteristics of the area.

The capacity of an additional macro-cell has been used as the benchmark for the capacity relief that one of these solutions could bring. However, any additional macro-site splitting the cell will not double the effective capacity due to a combination of greater interference and suboptimal siting of the site (due to lack of availability of suitable sites). As such Three has assumed that each capacity solution will provide incremental capacity equivalent to 75% of the capacity delivered by a standalone macro-site.

3.2.2 Technological advances

Three is anticipating three key sources of future spectral efficiency growth[8]:

- Carrier aggregation;
- LTE Advanced; and
- MIMO.

These are applied to the base line capacity, including any capacity solutions. These are described in more detail below.

[7] Based on the rate of roll out of 4G on Three's high traffic sites, this assumption looks optimistic, i.e. that the resulting congestion forecast is conservative.

[8] All these capacity gains rely upon widespread consumer adoption of devices carrying these features. As such Three has scaled down the capacity gains by factors accounting for likely device penetration.

Carrier aggregation.

Carrier aggregation allows subscribers to simultaneously access frequencies in different spectrum bands at a given site, which not only increases the speeds that can be achieved but also enables further capacity efficiencies because resources can be allocated more efficiently.

[✂-Three's plans for carrier aggregation and expected consequences of the same.]

LTE Advanced

LTE Advanced is an improved mobile communication standard enhancing upon LTE technologies. [✂-Three's plans for implementation of LTE Advanced.] LTE Advanced brings in features such as interference management, optimisation of resource blocks and modulation.

LTE Advanced gains have been estimated by Three's RAN experts based on laboratory tests and take into consideration the availability of devices to support these features.

Figure 8 [✂-Gains for Three from implementation of LTE Advanced.]

[✂]

Source: Frontier Economics Based Upon Three's Congestion Model

MIMO (multiple input, multiple output)

[✂-Three's plans for implementing MIMO and associated gains.]

Figure 9 [✂]

[✂]

Source: Frontier Economics Based Upon Three's Congestion Model

3.2.3 Future Capacity at a Cell and Network Level

Cell Level

Given the technological developments expanded upon above, Three estimates that the maximum level of capacity that it will be able to achieve on each macro-cell (i.e. with spectrum fully deployed) will increase in the next five years, in line with the table below[9].

Figure 10 [✂-Predicted impact on Three's cell level capacity of planned steps.]

[✂]

Source: Frontier Economics Based Upon Three's Congestion Model

Network Level

Combining both the cell-level capacity growth along with densification Three estimates that capacity on its 4G high-traffic network will increase by [✂-number] in the next decade, after accounting for both capacity solution deployment and densification, as seen in the graph below:

Figure 11 [✂-Chart showing capacity growth across Three's network.]

[✂]

Source: Frontier Economics Based Upon Three's Congestion Model

[9] Note no significant increase in spectral efficiency is forecast of 3G.

4 AREA LEVEL DEMAND FORECAST

4.1 Current cell-level demand

The demand side of Three's model starts with cell-level busy-hour throughput from December 2016 (combined from Three's 3G and 4G networks).

Three has not included voice traffic in this model, given its negligible capacity requirements on a modern mobile network.

Three's metric of busy-hour throughput is derived from RAN observations averaging throughput (in Mbps) from the three busiest hours in the week. In order to remove outliers, Three has averaged busy-hour throughput on week 50 of 2016..

4.2 Forecasting demand at an area level

While in reality, demand growth varies on an area by area basis (for example, a new local housing development can cause demand in a particular area to far outstrip national demand growth), Three believes that at a broad level it is a reasonable modelling simplification to assume that demand for each area will grow in line with a national basis, therefore maintaining the current relativities in demand between areas. This assumption will overstate the demand growth in some areas and understate the demand growth in other areas. To a large degree these should cancel out as long as the overall distribution of traffic across areas is similar (even if there is some movement within this distribution).

From a congestion modelling viewpoint, this would be problematic only if there were to be some correlation between the rate of growth and the current level of traffic in an area, e.g. if demand growth in areas currently served by low traffic cells will significantly outstrip demand growth in areas currently served by high traffic cells. Three has no a-priori reason to believe there will be such a correlation.

Figure 12 Demand Side of Three's Congestion Model

Source: Frontier Economics Based on Three's Network Model

4.3 Three's network demand forecast

Three's demand growth is based upon a disaggregated estimate of subscriber base growth (derived from Three's commercial marketing department) and per-user demand growth (derived from Three's networking team). Three estimates that per-user growth will be [✂-number] per annum over the next five years.

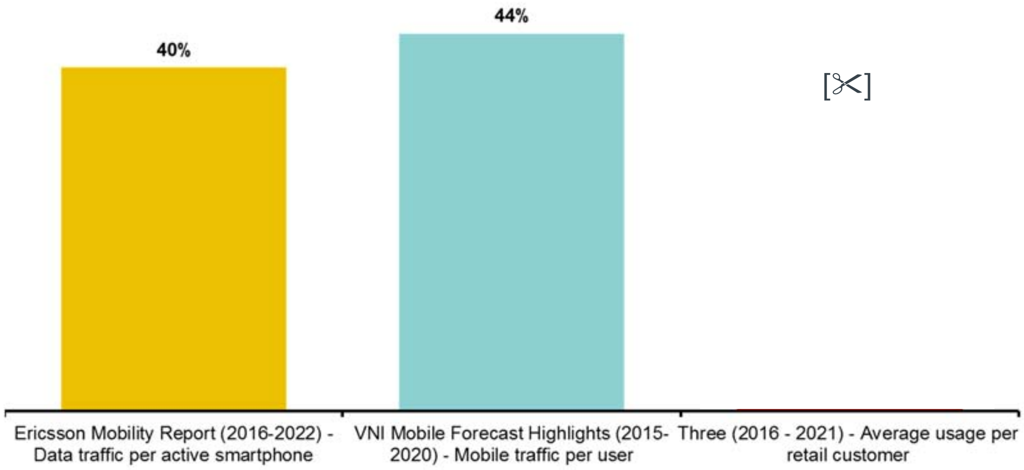
Three makes regular updates to its future data throughput forecast, which is then used as the basis for capacity management. [✂-Data on past growth.]

Figure 13 [✂]

Source: [✂]

Three has also compared its demand forecasts against other industry experts to ensure that it is in line with other forecasts.

Figure 14 Three’s demand growth projections are conservative relative to industry experts



Source: Frontier Economics.

For instance, the Ericsson Mobility Report (November 2016)[10] estimates that the average smartphone will carry 22 GB/month of data by 2022 up from 2.7 GB/month today. That growth in traffic will be driven by increasing usage video and social networking on smartphones by consumers.

22

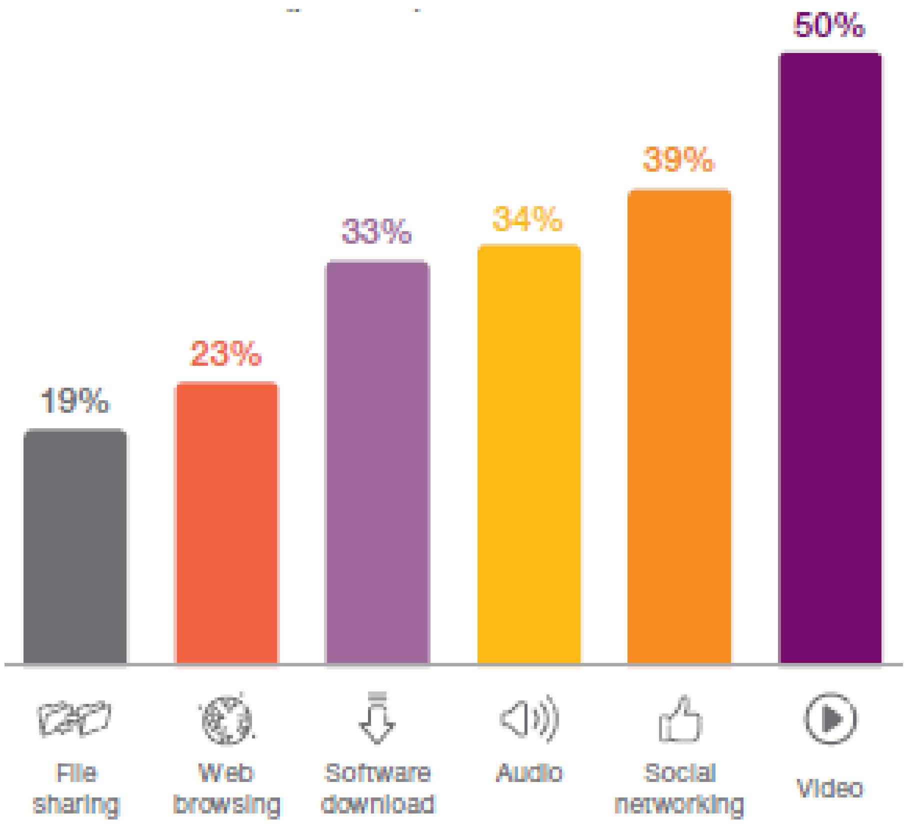
GB/month

Average data traffic per smartphone in Western Europe in 2022

(Ericsson Mobility Report, November 2016)

[10] https://www.ericsson.com/mobility-report

Figure 15 Mobile traffic by application category CAGR 2016-2022 (percent)



Source: Ericsson Mobility Report, November 2016

5 DETERMINING CONGESTION

Network models typically assume that user experience will degrade before traffic reaches the full design capacity of a network component, i.e. before utilisation reaches 100%. This is the case in mobile networks, given that in a working network effective cell capacity will never reach the best case theoretical 'design capacity', due to imperfect radio conditions.

Three's congestion model is based upon cell-level utilisation (as measured by throughput demand divided by actual or average cell capacity in the busy-hour). Based upon extensive analysis of Three's LTE network in 2016[11], it has identified a strong causal relationship between high levels of utilisation on a cell and poor end-user average throughput (i.e. below [✂]Mbps), which impacts upon mobile browsing experience.

Three's model considers a cell to be congested once traffic on that cell has exceeded 95% of the capacity of that cell. This threshold has been derived to ensure that the model captures a large majority of the sites experiencing user speeds of less than [✂]Mbps as seen in the chart below. Three's RAN data averages cell utilisation over the three busiest hours of the week. As such, this approach is likely to understate true congestion as there will be moments during each of these busy hours where cell utilisation is closer to 100% and performance will significantly degrade, even if on average performance is acceptable.

Figure 16 Correlation Between Utilisation Rate and Speed on Three's LTE network

[✂]

Source: Frontier Economics Analysis of Three's LTE network data for weeks

The very high level of utilisation observed is a function of:

- the algorithm used to determine the cell capacity which is clearly an accurate estimate of the actual available capacity when the cell is near congestion; and
- The fact that the 4G network delivers a high quality of service at relatively high levels of utilisation by allocating radio resources intelligently amongst active users.

This means that the model is not highly sensitive to this assumption. The assumption is also relatively conservative, being based on a relatively high level of utilisation before a cell is considered congested compared to benchmarks typically used in network planning.

[11] Three analysed data from Week 50 2015; Week 10 2016; Week 20 2016; Week 30 2016 and Week 31 2016.

6 KEY RESULTS

6.1 Congestion forecast

[✂-Discussion of results.]

Figure 17 [✂]

[✂]

Source: [✂]

[✂]

Figure 18 [✂]

[✂]

Source: [✂]

6.2 Overall network growth rates

[✂-Discussion of results.]

Figure 19 **[✂]**

[✂]

Source: [✂]

[✂]

Figure 20 [✂]

[✂]

Source: [✂]

7 CONCLUSION

[✂-Conclusions]

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