Analysis on the Evolution of Mobile Network Characteristics from NetBravo Dataset

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ABSTRACT

The rise of smart devices and the continuous increase of wireless data traffic usage triggered the development of technologies and infrastructures. This research analyses crowd-sourced open data provided by NetBravo from 2016 to 2021 in Europe to reveal how network features like speed, coverage, and channel occupancy improved. Also, this research compares different types of network connections (Wi-Fi and cellular) and different technology (Wi-Fi 2.4GHz/5GHz and cellular 2G/3G/4G) to find out similarities, differences and performance characteristics for each of them. Lastly, the data provides geospatial information that allows to make a country-wise analysis of network characteristics. Moreover, the research provides a different perspective that can be used by the European Commission, as well as other European governments and Mobile Network Operators, to track the progress towards their network performance goals. The best performing technology is cellular 4G, having twice as high download speed and 1.6x times the upload speed of the next best-performing technology. Also, the results have revealed that 75% of Wi-Fi measurements fail to reach the -80dBm threshold for basic connectivity. Among countries, The Netherlands has the highest average download speed with 24.7 Mbps and the highest average upload speed with 12.4 Mbps.

Keywords

Mobile Signal Strength, Big Data, Geospatial Location, NetBravo, Wi-Fi, Cellular Network, Network Speed Performance

1. INTRODUCTION

Mobile network coverage and speed performances are constantly improving to fulfill the needs of users. New technologies like 5G are under development to handle the huge amount of mobile traffic [5]. Reliable internet is crucial for businesses since it allows companies to keep an edge over competitors in their respective industries such as transportation, trading companies, news media, web hosting or service providers. Also, emergency services heavily rely on good coverage when it comes to fast and successful interventions [3]. On the other hand, more and more users rely on fast internet connection and good coverage for day-by-day activities such as driving, conducting transactions or interacting with others.

Understanding the performance of communication networks is essential for various parties such as mobile network operators (MNOs), European governments and the European Commission. For MNOs, it is important to have a clear overview of the current infrastructure to ensure the availability and quality of services. Collecting data on the signal strength or internet speed and analyzing it can reveal areas that have poor network coverage and need improvements.

As for countries in Europe, providing internet access to citizens and businesses is a priority. Technological advance swiftly changes the home and working environment. IoT devices are one example. Because of their efficiency and applicability on a large scale in domains such as healthcare, energy conservation or transportation, these devices will impact how business operate. Moreover, in combination with 5G, they will improve Quality of Service (QoS) and effective utilization of channels [16]. To make everything possible, it is important that MNOs are capable of providing appropriate network performances to support these technologies. Network data analysis is necessary to identify what is the current state of development of network infrastructure for a country. It could help the government understand what is the progress in providing reliable internet in wide areas.

On the other hand, the increasing need for connectivity and the transition of many activities from a physical to an online environment might have required a fast improvement of network characteristics to support the needs of users [12]. Therefore, network operators might have deployed new infrastructure to help with in higher network demand for coverage and capacity. However, the improvement of network performances vary across European countries since each country adopted different policies when it comes to upgrading network infrastructure. An analysis of network data from across Europe can provide an insight to the current network capabilities of different countries.

There are mainly two methods to acquire information regarding network performance: drive tests [11] and crowd-sourcing platforms [7]. Drive tests require special devices to measure signal strength and involve driving through the same region multiple times to take samples. The data provided is of high quality due to the technology used, but the whole process is time-consuming, expensive, and not scalable for large areas. This is why platforms that involve gathering network characteristics from wide geographical areas adopt the crowd-sourcing approach. It relies on users to install an application on their mobile devices that will take samples of the signal strength at random intervals

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of time. Multiple factors affect the perceived signal quality on a mobile device (e.g. line of sight, manufacturer, distance to the cell tower, tree cover density and their imperviousness, etc.) [9], meaning the data is of lower quality in this case.

To keep track of network performance and to ensure that the current infrastructure is capable of providing high quality services for the users, the European Commission (EC) launched a crowd-sourced project named NetBravo [13] to gather network data from across Europe. Features like latency, upload, and download performance of user's Internet connection, as well as technology used, Wi-Fi 2.4GHz/5GHz and cellular 2G/3G/4G, are available for the public. Also, signal strength measurements are provided. The information comes in monthly releases at different resolutions (i.e. 100 meters or 1 kilometer), contains the geographical position and how many measurements were taken. The data is projected on the European Grid (European Petroleum Survey Group [EPSG]:3035).

At this moment, the usage of crowd-sourced big data in network performance analysis is limited. The majority of research focuses on improvements from a technological point of view, not performance-wise. Also, other research focuses on a global perspective, not European, and provides an overview for only one type of connection, either Wi-Fi or cellular. This may leave no possibilities for a comparison between them. Moreover, there are no studies that target the network performance from a NetBravo perspective. An additional look at a different data set might provide useful insights for the European Commission, as well as other European governments and Mobile Network Operators which will help on the progress towards their network performance goals.

1.1 Research Goals

This research aims to analyze the data provided by NetBravo from 2016 to 2021 to provide insights on how network performance changed over this period of time. Moreover, a comparison in terms of performance, speed and signal strength, for different types of network connections (Wi-Fi and cellular) and different technologies (2.4GHz/ 5GHz for Wi-Fi and 2G/3G/4G for cellular) will be provided. Lastly, since a delimitation on countries for the data set provided is possible, the same comparisons mentioned above will be applied to individual countries across Europe. Therefore, the research will be divided into two parts: creating a general overview and a country-wise overview of the network performance. Having that in mind, the purpose of this paper can be translated into providing answers to the following research questions:

- **RQ 1.1** How did mobile network performances change from 2016 to 2021 considering speed and signal strength across Europe?
- **RQ 1.2** What are the differences between Wi-Fi and cellular connections in terms of speed and signal strength?
- **RQ 1.3** Which technology is currently delivering the best overall performance?
- **RQ 2** How does network performance differ across countries in Europe?

Section 2 presents related work on the evolution of mobile networks and the motivation behind this research. After that, **Section 3** gives an insight into the structure and features of the available network data. **Section 4** will discuss the methodology and frameworks that were used to conduct the analysis. Afterwards, the results and a comparison with other research will be displayed in **Section 5**. In the end, **Section 6** discusses the findings of this research and **Section 7** reveals the conclusions and limitations of the current analysis.

2. RELATED WORK

Fracarro et al. used NetBravo data set in their research [9]. The authors have combined the data with geo-spatial information regarding the environment such as weather, tree cover density, imperviousness, altitude, or network infrastructure to train and test an uncertainty-aware artificial neural network. The goal of the project was to estimate the network signal strength across the UK and find which features had the most significant impact on the measurements. They trained the model by minimizing Root Mean Squared Error (RMSE) and computed the Mean Absolute Error (MAE).

In another study, Ferreira et al. [6] measured the signal strength across two predefined routes in an urban area in Rio de Janeiro. The goal is to predict the signal strength using the Cascade Knife Edge (CKE) and Delta-Bullington methods of the International Telecommunication Union-Radiocommunication (ITU-R). It was found that CKE had better adjustments for the data provided and further used to train and test an artificial neural network (ANN). In the end, the hybrid application (CKE/ANN) had a better performance in predicting the signal strength than stand-alone applications. This research highlighting the reasons why a couple of methods can be used to predict the signal strength.

Viswanathan and Weldon [15] provided a good overview of the evolution of mobile communication and how key innovations and new technologies contribute to major performance improvements. The research presents a timeline of innovations starting from the first analog cellular systems to the newest technologies like the 4G Long Term Evolution (LTE) system. Consequently, a list of 11 features that had a major impact on the performance of the mobile networks is discussed. In the end, there is speculation on elements, such as spectrum, spectral efficiency, spatial efficiency, and system efficiency, that will be deterministic for 5G technologies. This research is considered since some of the improvements described might be seen in the analysis of data from NetBravo.

Astely et al. [2] conducted another research that focuses on the technological improvements, specifically for LTE. The authors provide an overview of how key characteristics such as spectrum efficiency, radio-network architecture or support of division duplex (FDD) and time-division duplex (TDD) will increase peak rates and decrease radio-network delay. They compared LTE FDD with a reference FDD system that was using more conventional techniques. The results illustrate differences in spectrum efficiency regarding downlink and uplink.

3. NETBRAVO DATASET

3.1 Data aggregates

As stated before, the data used in this research is the NetBravo Open Dataset [8]. The data is split in three big categories:

- Broadband Speed test measurements including cellular technologies from 2G to 4G and Wi-Fi at 2.4GHz

Table 1. **Overview of special attributes contained in measurement files**

File	Grid Data	Download	Upload	Ping	Strength	Std Dev	Frequency	Security
broadband	✓	✓	✓	✓	X	X	X	X
Wi-Fi signal	✓	X	X	X	✓	✓	✓	✓
cellular signal	✓	X	X	X	✓	✓	X	X

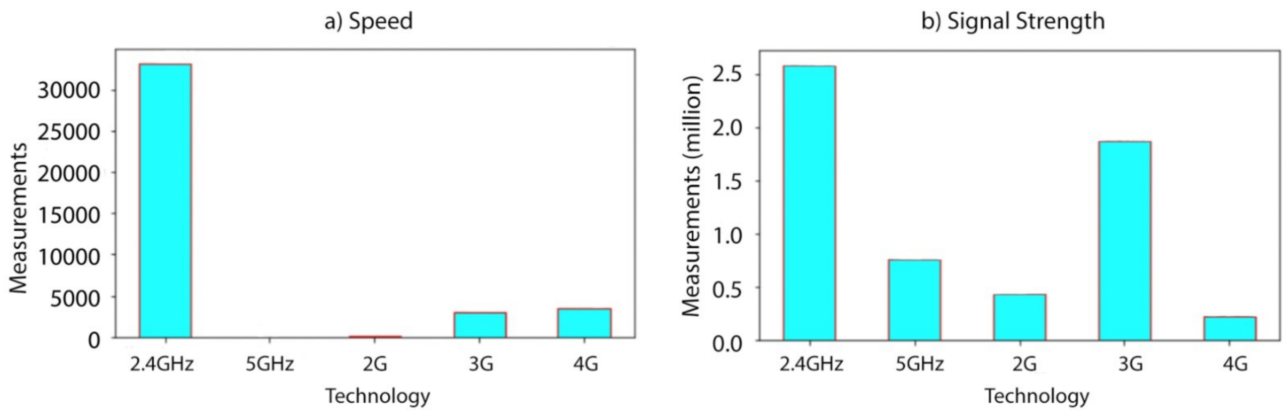

Figure 1. Number of speed measurements based on technology

and 5GHz bands

- cellular Signal Strength measurements
- Wi-Fi Signal Strength measurements .

Also, the data is composed of five different file formats: .prj, .shp, .shx, .csv and .dbf. Following the same order, they represent the shape file project, the geometry file, the geometry index file, the aggregated NetBravo file, respectively the attribute database file.

Lastly, the data is projected to a space grid according to the European Grid (European Petroleum Survey Group [EPSG]:3035) [4]. The data aggregates are projected to two different grid resolutions: 100m and 1km.

The full data gathered across Europe is available in every format file and it is released monthly together with new measurements taken. As further analysis proved, the data provided from NetBravo is identical from the middle of 2017 until the current moment of writing. This proved to be an inconvenience since it denied the possibility of analyzing the evolution of network performance for the past few years (**RQ 1.1**), reducing the effective data set to 2016-2017.

For the purpose of this research and for all research questions, all three types of measurements have been used - Broad band, cellular, Wi-Fi - but only .csv and .shp files - since python is providing good compatibility and manipulation for this type of data sets. Lastly, we choose the 100m grid resolution because it provides the same overview of network performance as the 1km grid resolution, but it offers more points of measurement for different countries.

3.2 Data format

Depending on the type of measurement, the format of the data is different among the three types of aggregates. All aggregates share the following attributes:

- Code of the grid cell according to the reference system
- X coordinate on the cell grid (latitude)
- Y coordinate on the cell grid (longitude)
- Type of the connection used (Wi-Fi/cellular)
- Technology of the connection used (2.4GHz/5GHz for Wi-Fi or 2G/3G/4G for cellular)
- Number of measurements in the grid .

In addition, broadband speed test measurements include the *download speed, upload speed* and *ping.* cellular and Wi-Fi include *signal strength* and *standard deviation* for each measurements. Moreover, Wi-Fi measurements also contain the *frequency of the channel* and the *security type* (open/closed). For the first part of the research, all of the features mentioned above were used apart from the coordinate system. The latter was necessary for the division of the data provided into data frames corresponding to each country to answer **RQ 2**. *Table* 1 presents the distribution of special attributes among data files.

3.3 Data distribution

Since an analysis based on the type of connection and technology used is one of the study purposes for this research, we report the data distribution for speed test measurements and signal strength measurements. As *Figure* 1 shows, a weak point in the data set is that the low amount of speed measurement for Wi-Fi 5GHz and cellular 2G will not give a proper overview on the general performance of these technologies. On the other hand, Wi-Fi 2.4GHz and cellular 4G are the most commonly used in the speed performance data set. As for the signal strength, all the technologies have enough data points for an accurate representation of current network capabilities

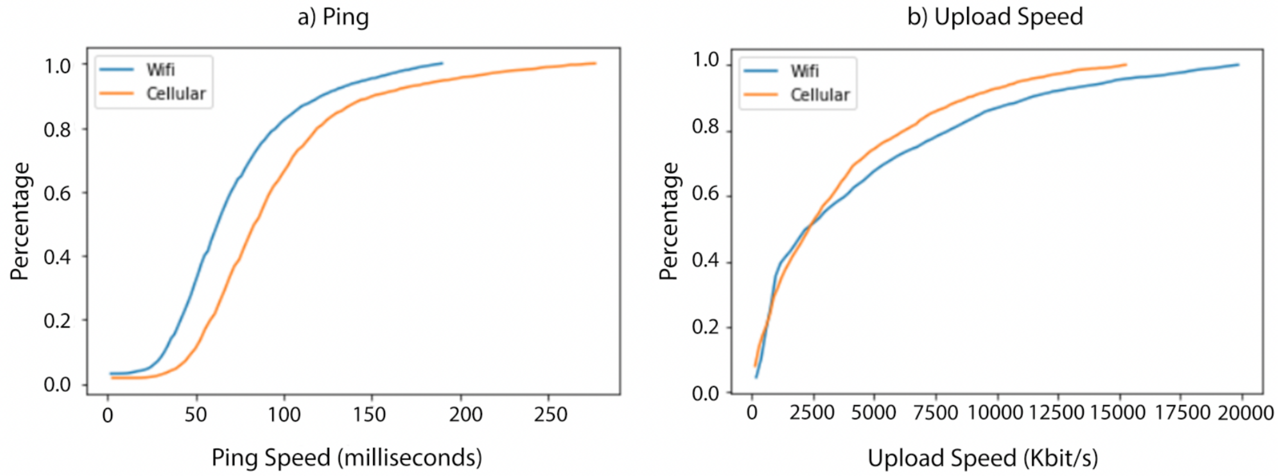

Figure 2. Distribution of upload speed measurements and ping for Wi-Fi and cellular

across Europe. In total, the data set consists of 39,743 measurements for speed test and 5,889,108 measurements for the signal strength.

4. METHODOLOGY

4.1 Frameworks

For the research, *python* and *anaconda platform* have been chosen due to high speed performances, flexibility regarding data visualization and manipulation, but also access to analytic libraries. Among the libraries used, the most notable ones are *numpy* and *pandas* for data manipulation, *seaborn* and *matplotlib* for data vizualisation and *geopandas, shapely* and *fiona* for working with geospatial data and projections on the grid coordinate system. Geopandas library had conflicts with the Windows OS and a virtual machine running Ubuntu was necessary to run it in the end.

4.2 Implementation

There are two main points of focus for the general performance test: speed and signal strength.

For the speed test measurements, we split the data set into different data frames corresponding to Wi-Fi and cellular measurements. The purpose is to find differences and similarities between these types of connection, whether one provides higher average speed or lower average ping. As a further step, the two data frames have been split again based on the technology used to see if newer technologies are able to provide better overall performances. Moreover to view the general acceptance and usability among mobile devices utilized. A total of 7 data frames have been computed in the end, two of them corresponding to Wi-Fi and cellular connections and the other five corresponding to each type of technology used - 2.4GHz/5GHz for Wi-Fi and 2G/3G/4G for cellular. The only available attributes for analysis are download, upload and ping. For each one of them, a weighted average between all the measured values and the number of measurements for each point have been computed alongside basic statistic measurements such as minimum, maximum, median, standard deviation, 25^{th} percentile and 75^{th} percentile. The outliers have been excluded using the 1.5 IQR rule.

For the signal strength measurements, the data already comes in two different files corresponding to Wi-Fi and cellular. For cellular, the data has been divided into different technologies and basic statistic measurements have been conducted for the values of signal strength. On the other hand, the Wi-Fi data has been divided into data frames for each frequency of the signal to verify channel occupancy. A total of 7 frequencies have been selected from the data set based on the number of measurements - 2412MHz, 2437MHz, 2452MHz, 2462MHz, 2472MHz, 5180MHz, 5220MHz. Outliers were removed based on the same 1.5 IQR rule.

The second part of the research focuses on evaluating network performances in different countries across Europe, so it is necessary to split the data accordingly. The .shp files provided have a special attribute besides the others in .csv files, namely *geometry*. This field contains a geometric description of the entry in the table based on the grid reference system used. The X and Y coordinates create a point or a polygon that consists only of that point. In this sense, the shape of each country can be viewed as a polygon or multi-polygon composed from multiple points. This research uses a .shp file containing Europe borders used by the Universitas Tartuensis (Estonia) for an online course about geospatial analysis [14]. The geometric description of each country was in a different coordinate reference system that uses longitute and latitute, therefore it was necessary to project it on the EPSG:3035 grid system to correspond with the data. After that, every point corresponding to the X and Y coordinates in the data set has been checked if it is within any of the polygons representing countries. The data frame has been divided accordingly and speed and signal strength analysis was conducted for different countries. Due to the reduced number of speed measurements, only countries with more that 500 data points were selected. Considering signal strength, countries with more that 30000 data points were selected. In the end, the top 12 countries regarding the number of measurements were selected for both test measurements.

5. RESULTS

As the data set was initially split into Wi-Fi and cellular, experiments illustrate that cellular connections have a slight edge when it comes to download speed, but nothing worth revealing. Moreover, there is not much distinction between the lowest 50 percentage of the measurements for both connections when it comes to upload speed. As *Figure 2* reveals, when it comes to the highest 50 percentage, Wi-Fi connections demonstrate better performance. Also,

Table 2. Statistic measurements for broadband speed test

	Wi-Fi			cellular		
Percentile	Download(Mbps)	Upload(Mbps)	Ping(ms)	Download(Mbps)	Upload(Mbps)	Ping(ms)
25th	3.6	0.8	48	3.4	0.8	67
50th	8.5	2.8	67	9.1	2.7	93
75th	18.6	8.4	105	20.5	6.6	151

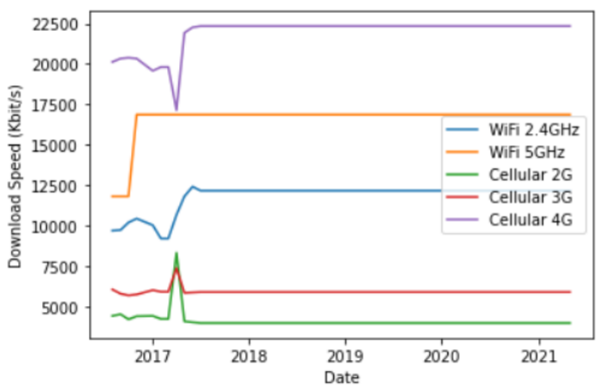

Figure 3. Download speed for different technologies in time

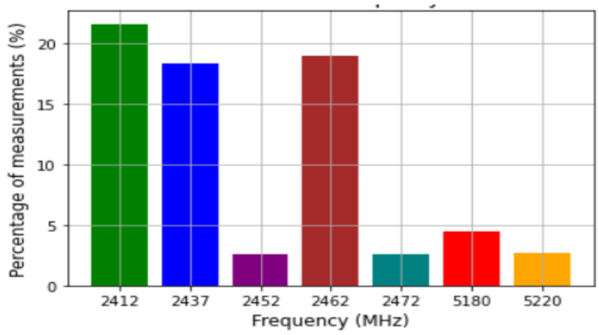

Figure 4. Distribution of Wi-Fi data into channels

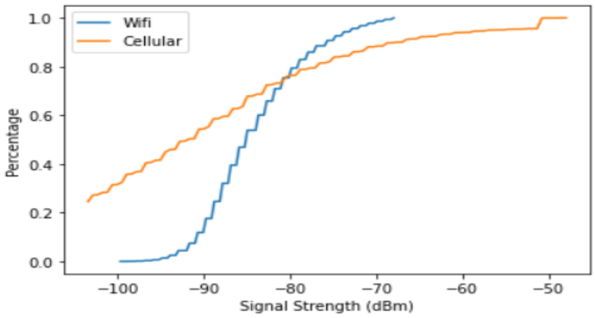

Figure 5. Distribution of Wi-FI and cellular data for signal strength

in terms of ping, there is no doubt that Wi-Fi has better results. Actual values of the statistic measurements can be found in *Table 2*. An explanation for the ping difference would be that all technologies for cellular connections (2G/3G/4G) have been taken into consideration. As explained in [10], a 2G mobile connection can have a latency in the range of 300-1000 ms, while the latency for a 3G connection can be anywhere in between 100-500 ms. Only 4G connection drops below 100ms, but still LTE technologies have additional latencies to deal with compared to Wi-Fi. These latencies are: Control Plane latency, User Plane latency, Core network latency and Internet Routing latency [10].

Furthermore, comparing different types of technologies does not yield any notable result considering the same connection type. Newer technologies tend to perform better than previous ones. Because of the low number of measurements for Wi-Fi 5GHz and the overall poor quality of the data set provided, the only interesting aspect is the difference between cellular 4G and Wi-Fi at 2.4GHz in terms of download speed. As *Figure 3* illustrates, in 2016-2017, 4G download speed fluctuated between 17500-22500(Kbit/s) on average, which is more than 50% higher than Wi-Fi 2.4GHz. One of the aspects that can influence the result is the limitation of the performance for Wi-Fi networks due to the congestion caused by the overcrowded usage of spectrum band. To further investigate this assumption, an evaluation of the channel occupancy has been conducted. The results displayed in *Figure 4* reveal that the most used channels are 1 (2412MHz), 11(2462MHz) and 6(2437MHz) with 21.58%, 18.92%, respectively 18.26% of the measurements using these channels, all the others falling below 5%. Considering the fact that only these 3 channels do not interfere with each other and Wi-Fi routers automatically select one of them upon initial setup, most devices operate on these channels at the same time which can lead to poor performance results compared to LTE networks.

One last aspect to discuss is the comparison between the two type of connections with regard to the signal strength performance. Wi-Fi is a local area network (LAN) that has been designed to provide high speed performance within a short-range (cca. 100m), whereas cellular networks have to provide connection typically in a larger area. Therefore, it is expected that Wi-Fi signal strength value is contained in a smaller range than cellular. Moreover, 4G infrastructure is considered to be more stable than Wi-Fi because of the transmission medium (copper or optical fibre) and also because the control of frequency for cellular networks is centralized, which makes interferences less likely to occur. The experiment conducted used 689992 measurements for Wi-Fi and 166340 for cellular. It is worth mentioning that outliers have been excluded from the data set for both connection types. The result revealed that Wi-Fi signal strength stays inside a 34dBm range, from -102dBm to -68dBm, while cellular ranges from -107dBm to -48dBm. For Wi-Fi, typically a signal strength better than -80dBm in required for basic connectivity, while for 3G the threshold is at -100dBm, respectively -112dBm for 4G. Also, it is worth mentioning that the signal strength received depends on the hardware of the mobile device used. The distribution of the data shown in *Figure 5* reveals that exactly 75% of the Wi-Fi measurements fail to pass the -80dBm target, whereas only 32% are below -100dBm for all cellular measurements.

Now, moving onto the country-based analysis, the results in *Figure 6* demonstrate that northern countries, and de-

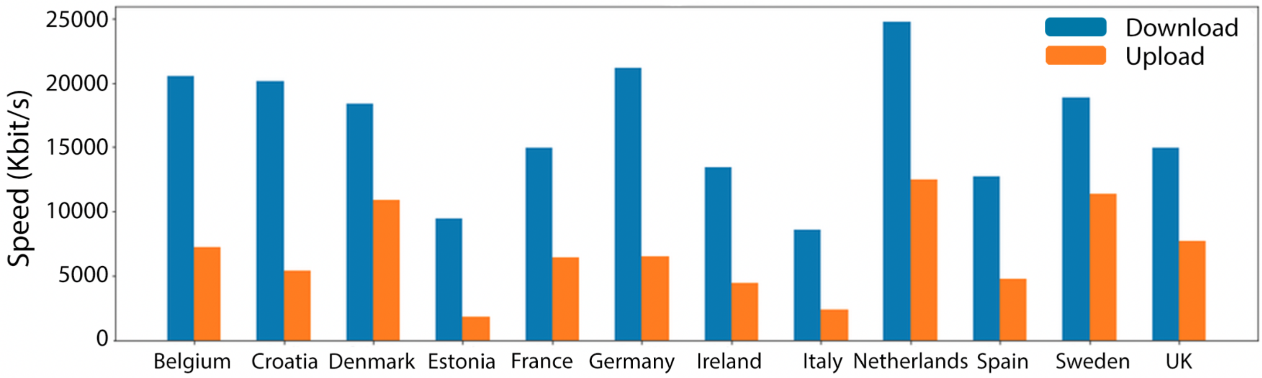

Figure 6. Speed performances for different European countries

Table 3. Signal strength performance for different European countries

Country	Cellular(dBm)	Wi-Fi(dBm)	Open Wi-Fi(dBm)	Closed Wi-Fi(dBm)
Austria	-92.36	-79.89	-75.47	-80.85
Belgium	-98	-82.21	-81.29	-82.51
Croatia	-90.11	-83.93	-79.69	-84.33
France	-94.27	-81.63	-81.55	-81.66
Germany	-88.97	82.51	-81.00	-82.84
Greece	-80.39	-81.19	-78.71	-81.77
Ireland	-87.79	-81.28	-79.04	-81.73
Italy	-94.01	-82.92	-80.84	-83.37
Netherlands	-95.28	-81.67	-81.01	-81.79
Serbia	-93.59	-82.81	-79.65	-83.42
Spain	-90.42	-81.73	-79.45	-82.09
UK	-92.45	-80.11	-79.72	80.23

veloped countries in general, excel in overall speed measurements, with Netherlands having the best performances with an average download speed of 24.7 Mbps and upload speed of 12.4 Mbps for all types of connections. Denmark and Sweden also have high download speed, 18.3 Mbps and respectively 18.8 Mbps, which is lower than the averages of Germany, Belgium or Croatia, but the upload speed exceeds other European countries. The experiment conclusions align with the statistics from OECD regarding ICT access and usage by households and individuals [1]. Countries with a higher number of users and percentage of population that constantly utilize internet and communication technologies tend to have better network improvement policies and as a result, better performance. On the other hand, there are differences with regard to signal strength performance. In this case, the top 12 countries based on the number of measurements are within 4dBm radius from each other when it comes to Wi-Fi signal strength. All the averages orbit around the -80dBm mark for usable connectivity. On the other hand, there are variations of the cellular signal strength across these countries, but all the averages land in the -98dBm and -80dBm range. Full results can be seen in *Table 3*.

Regarding the difference in download speed between Wi-Fi and cellular networks for different countries, there is no clear pattern emerging from the data set. *Figure 7* shows that Netherlands, Germany and Belgium are the best performing countries when it comes to Wi-Fi connections, having an average download speed of 25.2 Mbps, 22.4 Mbps, respectively 20.5 Mbps. Also, these countries have better performance on Wi-Fi connection than on cellular connection. Experiments provided similar results for upload speed regarding countries with best performance. On the other end of the comparison, Croatia, Italy, France and Spain have faster cellular connection. Croatia's download speed for this type of connection is 59% higher than its Wi-Fi capabilities. Another research on crowd-sourced data from OpenSignal was performed by Fogg [8], but the experiments conducted yield different results for the countries analyzed in this research. For all the countries with higher cellular speed mentioned above, apart from Croatia, the data set used by Fogg proved the contrary. The gap between the Wi-Fi performance and cellular performance can depend on multiple factors such as the power of fixed networks, since Wi-Fi relies on it to provide Internet connection, or a more developed network infrastructure since it is an indicator of investment power of MNO. For further analysis, *Figure 8* displays the distribution of measurements for different cellular technologies. Again, Sweden (88.65%), Netherlands (77.34%) and Croatia (76.52%) are among the top countries when it comes to 4G usage for mobile devices data used by this research. Now, looking at the cellular performance in terms of speed (Figure 7) and the distribution of measurements based on technology used (Figure 8), it is clear that countries able to provide better 4G coverage have better network performance results.

Some other interesting results concern the distribution of signal strength measurements and the difference in signal strength for open Wi-Fi against closed Wi-Fi. When talking about Wi-Fi signal strength, the experiments illustrate that 75% of all the measurement for every country lie within the range of -83dBm and -77dBm, but medians are at most 2dBm apart from each other. On the other hand, *Figure 9* shows that cellular measurements are distributed more widely and are much dependent on the country. Con-

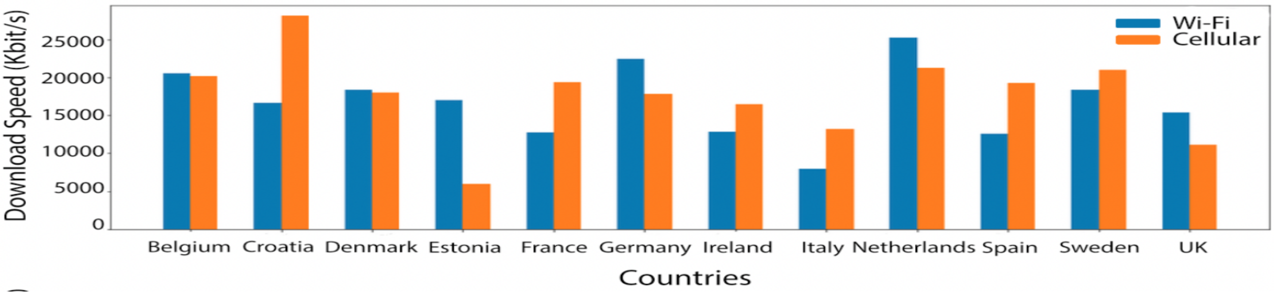

Figure 7. Download speed of Wi-Fi and cellular networks for different European countries

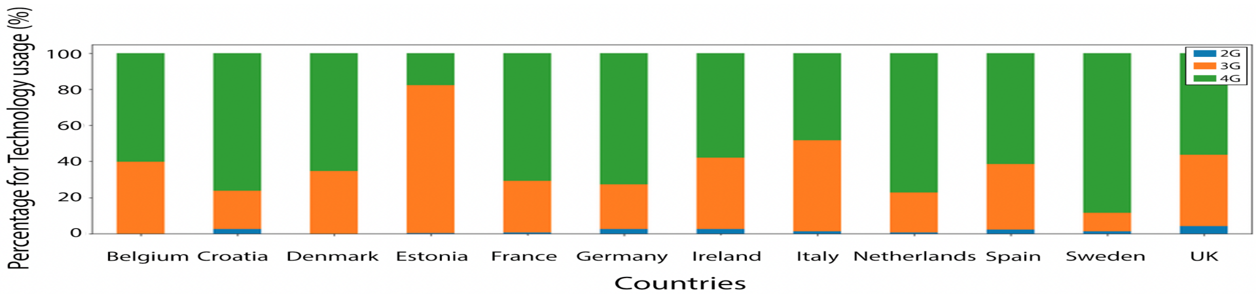

Figure 8. Distribution of cellular data into technology usage

sidering the security type of Wi-Fi connections, *Table 3* reveals that open Wi-Fi performs better than its counterpart in all of the cases, but there is a maximum of 5dBm difference in the worst case. It is a surprising result considering that closed Wi-Fi usually has a limited number of devices connected at the same time, whereas open Wi-Fi is deployed in public spaces where everyone can connect. It is worth mentioning that around 73% to 92% of the data provided is based on closed connections, so only a small percentage of data is collected from open connections. A total of 457768 measurements for open Wi-Fi and 2011422 measurements for closed Wi-Fi have been used.

6. DISCUSSION

Based on the results of the experiments conducted, a discussion with regard to the research questions is relevant. Note that not all of the results presented in this section have a visualisation. Instead, we utilized the actual results to create the figures displayed since we considered they provide a more representative visualisation for the research goals. References of available figures will appear whenever an observation corresponds to one of them.

That being said, for **RQ 1.1**, the data showed in *Figure 3* illustrates that Wi-Fi 2.4GHz experienced a 25.53% increase in download speed from August 2016 until July 2017, whereas cellular 4G growth was only 11.02%. As for upload speed, Wi-Fi 2.4GHz gained 26.83% increase in upload speed, whereas cellular 4G improved by 11.03%. In terms of ping, Wi-Fi 2.4GHz experienced a drop of 56.32% and 4G suffered a 27% increase. As for the signal strength, there are no notable differences for Wi-Fi connections, both of them having around -83dBm on average during this period. On the other hand, the signal strength for cellular technologies increased by 2.1dBm, 3.37dBm and 8.04dBm for 2G, 3G, respectively 4G, which might indicate an improvement in the infrastructure. The final values, in the same order, are: -90.79dBm, -91.49dBm, -90.53dBm.

For **RQ 1.2**, the experiments have showed that cellular 4G is delivering better speed performances on average than Wi-Fi 2.4GHz, followed by 3G. As can be seen in *Figure 2*, an important aspect is that Wi-Fi technologies reached higher upload speed than cellular, even though the average is lower. Not the same can be said about ping, where 26% of the Wi-Fi measurements had lower than 50ms, whereas only 10% of the cellular measurements reached this threshold. The results illustrate that 75% of the Wi-Fi measurements fail to pass the -80dBm target for basic connectivity, whereas only 32% of the measurements are below -100dBm threshold for all cellular measurements.

For **RQ 1.3**, the data set proved that cellular 4G is providing the best speed features, with twice as much download speed than the next best-performing technology and 1.6x the upload speed. Also, considering the average signal strength of -90.53dBm for 4G technology, it can be said that it provides very good signal in general.

Lastly, for **RQ 2**, the speed performance for all connections heavily depend on the country of speaking. As presented in *Figure 6*, northern countries like Netherlands, Sweden and Denmark, illustrate the best performance, followed by other highly developed countries like Germany, France or Belgium. Among these countries, some of them have faster Wi-Fi connection, whereas others rely on faster cellular connection, as presented in *Figure 7*, so there is no correlation between the overall speed performance and the faster type of connection. However, comparing the results displayed in *Figure 7* and *Figure 8*, countries with better cellular 4G coverage and infrastructure have better network performance. Talking about signal strength, all the countries studied in this research are within a 4dBm range of each other for Wi-Fi connections, all of them having around -80dBm on average. On the other hand, cellular signal strength varies in a wider range, -98dBm and -78dBm as it can be seen in *Figure 9*.

7. CONCLUSIONS & FUTURE WORK

In this paper, we investigate the crowd-sourced data set from NetBravo and present a general overview of network

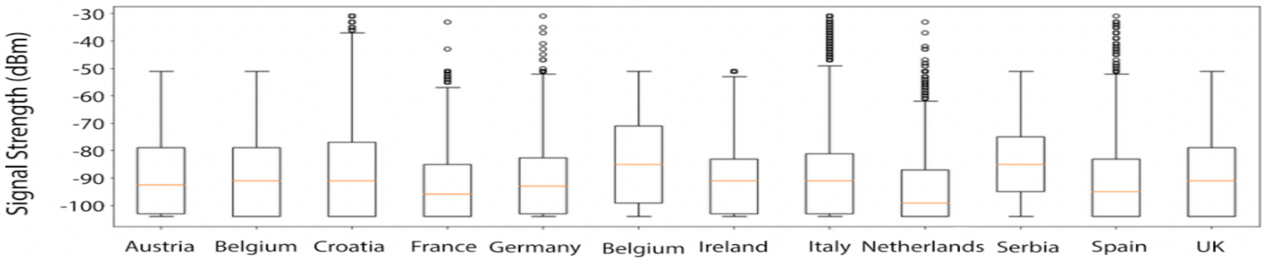

Figure 9. Distribution of cellular data for different countries

performance, as well as a country-wise overview. We evaluate the speed performance in terms of download, upload and ping. In addition to signal strength, we consider features like frequency and security type for Wi-Fi connections.

For the general overview, our findings show an improvement in both download and upload speed for both type of connections, with Wi-Fi connections experiencing a higher gain percentage-wise than cellular connections. On the other hand, when it comes to ping, Wi-Fi achieved better results, whereas cellular performance dropped over time. With regard to signal strength, there are no changes in the performance of Wi-Fi connections, whereas there is a slight improvement for cellular connections. Overall, the results reveal that cellular 4G has the highest download speed and upload speed among all other technologies, both cellular and Wi-Fi.

When it comes to the country-wise analysis, results suggest that northern countries alongside other highly developed countries achieve better network performance. The usage of newer technologies and better coverage leads to better results. Also, open Wi-Fi connections performed better than closed Wi-Fi connections in all of the countries studied, but it is necessary to keep in mind that signal strength received depends on factors such as the hardware of the mobile device used. Crowd-sourced data is influenced by these kind of factors, therefore different data sets might yield different results.

One of the main goals of this research was to provide a temporal analysis of the data to reveal the evolution of the network performance in the past years. NetBravo data set narrowed down this possibility to only 2016-2017 since all the releases after the middle of 2017 have no additional measurements. Also, the low amount of speed measurements for Wi-Fi 5GHz, cellular 2G and cellular 3G are insufficient to provide relevant information for these technologies. Having these limitations in mind, a future improvement of the current research would be to perform the analysis again once additional information from NetBravo is available.

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