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## Conference Paper

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# **An exploratory network analysis of mobile broadband provider's infrastructure relationships in Tamil Nadu, India.**

**Draft Please do not quote.**

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Keywords: India, Tamil Nadu, Chennai, Mobile Broadband, Rural Broadband, ICT4D, Internet connectivity, Centrality, Networks, Complexity.

## **Abstract**

This study analyses the emergent network features of the upstream connectivity structure of three mobile broadband providers in the area included between the cities of Kancheepuram and Chennai in Tamil Nadu, India, from an original end-users perspective. This perspective is based on using a large dataset, collected by the authors, in February 2015, generated by the crowdsourcing-based Portolan Network Sensing Application on Android devices. The key feature of these data is that they are user generated and reflect mobility, as they were sourced from smartphones along the route between Chennai and Kancheepuram, rather than being based on stationary operators masts. Internet Service Providers traditionally rely on Border Gateway Protocols (BGP) for interconnecting purposes. Adding an end-user perspective to the existing BGP routing tables reveals a more complete picture of the underlying topology for the studied mobile broadband providers. The data were then used to conduct an Internet Periphery Analysis, pointing towards the roles of existing traffic peering agreements among the Internet Service Providers, and focussing on the role played by International Exchange Points (IXPs) key electronic infrastructures in the region. The analysis identifies the emergence of possible bottlenecks affecting upstream competition and the key role played by IXPs in providing a more widely distributed network access structure. This paper proposes to further study the usage of settlement free peering in fair competition and the preconditions of Quality of Service and service pricing in the Indian Mobile Broadband Market.

## **1. Introduction**

Mobile broadband Internet is considered to be a highly relevant factor for the development of the Indian economy. Mobile broadband subscriptions are serving vast amounts of the urban population with rising numbers for rural areas. Besides this growth, upstream connectivity features are mainly analysed through an Internet Service Provider Perspective. By using an original end-user perspective, this article aims to provide further insight for studying three Chennai and Tamil Nadu mobile broadband providers by using a complex network Internet Periphery Analysis. This approach sheds light on potentially important roles of specific Internet Service Providers, the roles of existing traffic peering agreements and the underlying topological infrastructures of the studied networks.

## **2. Local ICT Infrastructure and Connectivity in India**

### **2.1 Overview**

An overview of India's telecom indicators shows the relevance of mobile cellular and mobile broadband Internet for the country. World Bank data for example show that, in 2014, the Indian population had 2 fixed telephone subscriptions per 100 inhabitants (2 per 100 in 2013) while in the same time, mobile cellular subscriptions reached 74 per 100 inhabitants (71 per 100 in 2013), (World Bank, 2016a and 2016b). At the same time, the percentage of individuals using the Internet rose from 0.53% in 2000, 2.39% in 2005, to 7.5% in 2010 and a staggering 18% in 2015 (ITU, 2015). Not surprisingly, one may associate this growth in Internet users to the diffusion of smartphones. The Indian smartphone market grew by 17.1% in Q2 2016 compared to the previous quarter (IDC, 2016). According to The Telecom Regulatory Authority of India, the wireless subscriber base reached 1,033.63 million at the end of March 2016, representing a monthly growth rate of 0.68%. Broadband subscribers reached 149.75 million in March 2016, representing a monthly growth

rate of 3.37%. Furthermore, the Telecom Regulatory Authority of India, TRAI (2016b), notes an important difference between the growth of wireless subscriptions in urban and rural areas. While urban areas show a monthly growth rate of 0.21 per-cent in March 2016, then urban one is 1.31 per-cent. Table 1 provides a helpful overview of Internet subscribers by segment and technology.

Particulars	Indian Broadband Subscribers in million	Monthly growth rate in the month of March 2016
Wired subscribers	16.98	1.38%
Mobile device users (phones & dongles)	132.24	3.64%
Fixed Wireless subscribers (Wi-Fi, Wi-Max, P2P Radio & VSAT)	0.52	2.36%
Total	149.75	3.37%

Table 1: Segment-wise Broadband subscriber base in March 2016, Source: Elaborated by the authors using TRAI (2016b).

This fast growth in mobile broadband adoption might have come at the cost of low Quality of Service (QoS) as Service Providers need to supply specific infrastructure upgrades to absorb newly registering end-users. Radio waves spectrums, e.g. are highly desirable by Service Providers but stay governmentally blocked for defence usages, resulting in too many users per unit of available spectrum. An Open Letter of the GSM Association stated that this spectrum crisis could threaten India's Digital Vision. According to Akamai's quarterly State of the Internet report, see information in Table 2, India's average connection speeds reached 2.4Mbps, representing a year on year growth of 22% but second to the last in the APAC region rank (Akamai, 2015).

In terms of average peak connection, India ranks 116<sup>th</sup> place with an average peak Mbps of 18.7, compared to China with 23.1 Mbps, Philippines with 25.3 Mbps, Indonesia with 31.0 Mbps and Sri Lanka with 33.5 Mbps (Akamai, 2015).

Global Rank Connection Speed	Country / Region	Q2 2015 Average Mbps	Percentage of Quarter on Quarter Change	Percentage of Year on Year Change
1	South Korea	23.1	-2.1	-11
2	Hong Kong	17.0	1.5	1.3
3	Japan	16.4	7.8	7.4
14	Singapore	12.7	6.8	22
26	Taiwan	10.6	1.1	6.5
42	Thailand	8.6	17	28
43	New Zealand	8.4	0.8	18
46	Australia	7.8	4.8	8
65	Sri Lanka	5.3	10	50
70	Malaysia	5.0	18	17
92	China	3.4	-7.1	-8.6
95	Vietnam	3.3	3	29
101	Philippines	3.1	13	23
115	India	2.3	11	-24
117	Indonesia	2.2	5.8	22

Table 2: APAC region connection speeds, Source: Elaborated by the authors using Akamai (2015).

## 2.2 Mobile Connectivity

The Indian Telecommunications Sector emerged in 1851, when the British Government set the first Kalkotta telephone landlines in operation. In 1881, telegraph facilities were opened to the public, resulting in the merger of telephone services with the postal system two years later (Baruah and Baruah, 2014).

The first Indian GSM cellular call took place on 31 July 1995. Ever since, Mobile Telephony in India faced a rapid growth over the last 20 years while connectivity paired with collapsing communication costs lead to a massive productivity multiplier in the Indian economy (Kramer, Jenkins and Katz, 2007). Not surprisingly, the Department of Telecommunications at the Indian Ministry of Communications & Information Technology considers telecom services as important tool for socio-economic development (Gov-IN, 2015). This phenomenal growth was driven by the government, state-owned companies and most importantly the private sector, resulting in a focus on mobile cellular connectivity, rather than landline telephony connections or public call offices. The rapid transformation started with the announcement of policy reforms with the National Telecom Policy (NTP) in 1994. These reforms included objectives such as availability of telephone on demand, provisioning of services at reasonable prices, competitiveness and initiatives to attract Foreign Direct Investment (FDI) as well as the ease of local telecom equipment manufacturing regulations. The policy reviewed in 1999 (NTP1999) resulted in the opening of National long distance and International long distance services to private operators, Private telecom licensing on revenue sharing basis and direct interconnectivity and sharing of the network with other telecom operators within the same telecom service areas, (TRAI, 1999).

The Indian Department of Telecommunications established these telecom service areas for the purpose of regulating unified access and cellular mobile service licensing. These licensing apply for wired and mobile telephony connections as being organized in 22 ranked (A,B,C, and Metro) localised areas. Then, the Ministry of Communications & Information Technology harmonized the nomenclatures of the telecom service areas in 2007, (Gov-IN, 2007). Overall this results in a reduced competitive environment with only a few service providing agents per telecom service area.

According to Icompare (2016), both the state of Tamil Nadu and the city of Chennai are served by four 3G Mobile Broadband service providers being Aircel, Bharti Airtel, BSNL and Vodafone. All of these service providers are offering 3G USB Modem Plans, 3G Mobile Wi-Fi Plans, 3G SIM Plans and 3G Tablet Plans while their service provider base varies considerably, see Table 3.

3G Service Provider	Wireless Subscriber Base in March 2016 (in millions) Tamil Nadu (inclusive Chennai)	Total Indian Wireless Subscriber Base in March 2016 (in millions)
<b>1.1.1 Aircel</b>	17.24	72.65
<b>1.1.2 Bharti Airtel</b>	21.59	97.68
<b>1.1.3 BSNL</b>	8.75	72.25
Vodafone	15.53	96.44

Table 3: Wireless Subscriber Base in Tamil Nadu, Source: Elaborated by the authors using using TRAI (2016b) data.

Looking at both the providers postpaid 3G SIM card subscription prices reveals interesting differences in service pricing. These service prices however, do not differentiate between the state of Tamil Nadu and the city of Chennai. While Vodafone and Bharti Airtel show a similar pricing of 250INR per 1 GB data and 450INR for 2GB data, (both for 30 days), Aircel shows slightly lower prices with 198INR for 1GB data and 399 for 2GB data, respectively. Interestingly BSNL offers their broadband services for considerably lower prices of 129INR for 1GB data and 225 for 2GB of data.

3G Service Provider	Price in Indian Rupees (IND) for 1GB of Data (30 days validity)	Price in Indian Rupees (IND) for 2GB of Data (30 days validity)
Aircel	198	399
Bharti Airtel	250	450
BSNL	125	225
Vodafone	250	450

Table 4: Tamil Nadu (except Chennai) 3G Provider comparison, Source: Elaborated by the authors using Icompare (2016).

### 2.3 Internet Connectivity & Internationality

The Internet communication infrastructure as a whole can be seen as a network of networks. It therefore consists of hardware components and a system of software layers that interconnect geographically distributed computer networks using the TCP/IP Internet protocol suite for linking all devices being connected to the Internet. Connectivity between those networks is established by a different set of Internet Service Providers (ISPs). The Internet architecture itself can be represented using a set of three tiers, or layers of networks.

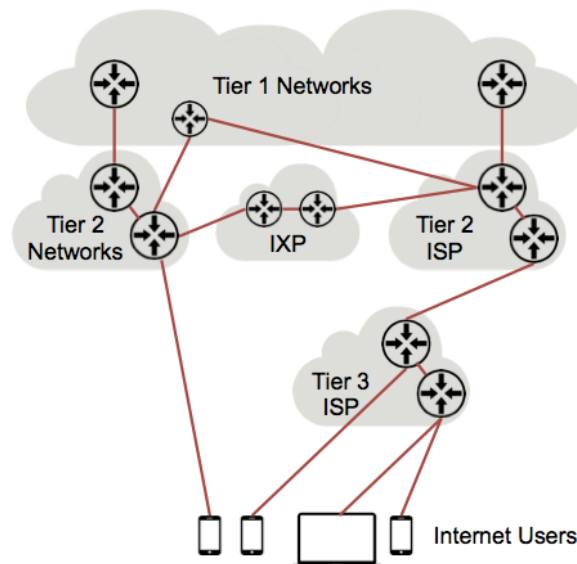


Figure 1: Network Tiers in Internet Protocol Networks, Source: Elaborated by the authors.

As depicted in Figure 1, Tier 1 networks represent Internet Protocol Networks that are participating in settlement-free interconnection between routers, meaning that neither the sending- nor the receiving peering network but their respective customers are paying for traffic exchange. Those customers are Tier 2 networks, being Internet Service Providers (ISPs) that are peering with other networks while also being in the need of purchasing Internet Protocol (IP) transit for their engagement in reaching the entire Internet. Tier 3 networks as 'lowest layer' are Internet Service providers that are solely purchasing IP transit from other networks. When an end-user is using an Internet connection, e.g. for retrieving information from a specific content provider, the connectivity between the individual networks is established through either a tier 2 or 3 Internet Service Provider (ISP), in return of an end-user subscription fee. ISPs then send the data packages through the Internet, whereas every Tier2 or Tier3 ISP delivers traffic via those Tier 1 upstream transit providers at a cost.

Traffic-routing in the Internet is organised with clearly defined routing policies of Autonomous Systems (ASes), whereas an AS represents a collection of connected Internet Protocol (IP) routing prefixes that are

under the control of one or more network operators on behalf of a single entity or domain (Hawkinson and Bates, 1996). Any organisation may run these Border Gateway Protocols (BGPs), which are a standardized exterior gateway protocols designed to exchange routing information between gateway hosts (each with its own router) in an autonomous system<sup>1</sup>. This exchange is usually organised with the help of the so-called BGP routing tables. Therefore, a BGP routing table contains a list of known routers in the respective autonomous system i.e. the addresses a host can reach as well as an associated cost metric with the path to each router. In this way, the best available route is chosen. Autonomous Systems are identified by using private Autonomous System numbers (ASNs) to an Internet Service Provider (ISP). An Internet Service Provider has hence a number of officially registered and unique Autonomous System Numbers (ASNs). These AS-Numbers may then identify each network on the Internet.

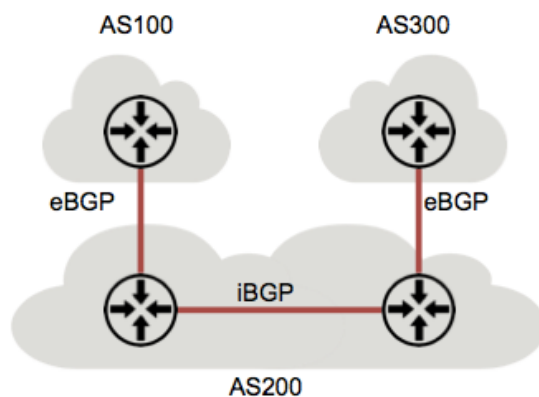


Figure 2: AS-Number identification, Source: Elaborated by the authors.

As of September 2015, there are currently 1,345 Autonomous System Numbers associated to Indian organisations (Hurricane Electric, 2015a), whereas the top ASNs in terms of routing adjacencies, or neighbouring IPv4 or IPv6 addresses for peering purposes, are Bharti Airtel Ltd, having 1,032 adjacencies, Tata Communications (formerly VSNL) having 433 adjacencies, Reliance Communications having 251 adjacencies and Vodafone India Ltd with 196 adjacencies.. The following Table 3 provides a short overview of India's 20 biggest Autonomous Systems with their IPv4 and IPv6 adjacencies.

#	ASN	Name	Adjacencies v4	Routes v4	Adjacencies v6	Routes v6
1	AS9498	Bharti Airtel Ltd	1,032	13,085	147	471
2	AS4755	Tata Communications (formerly VSNL)	433	2,064	64	177
3	AS18101	Reliance Communications Ltd	251	1,031	24	77
4	AS55410	Vodafone India Limited	196	1,988	24	57
5	AS9583	Sify Ltd	167	1,728	67	77
6	AS45820	Tata Teleservices ISP AS	85	353	7	27
7	AS9730	Bharti Telesonic Ltd	76	572	0	0
8	AS133229	Host Palace Internet Services	58	10	32	1
9	AS132410	Reliance Jio INFOCOMM Ltd	50	38	38	11

<sup>1</sup> This became possible following the adoption of the IETF Request For Change #1930.  
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10	AS10201	Dishnet Wireless Limited. Broadband Wireless	47	413	2	2
11	AS9829	BSNL (Bharat Sanchar Nigam Ltd)	31	1,880	9	36
12	AS55824	NKN Core Network	27	234	12	42
13	AS55644	Idea Cellular Limited	26	634	6	11
14	AS10029	Spectranet	22	485	4	14
15	AS17439	Netmagic Datacenter Mumbai	20	341	7	10
16	AS17762	Tata Teleservices Maharashtra Ltd.	19	499	3	4
17	AS17903	Cognizant Technology Solutions India Pvt Ltd.	18	99	0	0
18	AS45194	Syscon Infoway Pvt. Ltd.	16	279	4	2
19	AS45117	Ishan's Network	16	108	0	0
20	AS24029	NICI (IXP)	15	6	0	0

Table 5: Top 20 Indian ASN ranked by IPv4 Adjacencies Source: Elaborated by the authors using Hurricane Electric (2015a)

In terms of total number of Autonomous System Numbers (ASN) worldwide, India is ranked 11<sup>th</sup> place among those 236 countries having ASNs. India hosts, according to the Hurricane Electric BGP World Report, 1,345 ASNs and is therefore ranked place 11, right after Romania with 1,742 and Canada with 1,826 ASNs, respectively. The following Table 6 provides a short overview of the top 11 countries, ranked by number of ASNs.

Rank	Country	CC	ASNs
1	United States	US	24,631
2	Russian Federation	RU	5,897
3	Brazil	BR	3,597
4	United Kingdom	GB	2,383
5	Ukraine	UA	2,231
6	Poland	PL	2,211
7	Germany	DE	2,035
8	Australia	AU	1,919
9	Canada	CA	1,826
10	Romania	RO	1,742
11	India	IN	1,345

Table 6: ASN World Ranking 1-11, Source: Elaborated by the authors using Hurricane Electric (2016b).

The International Telecommunications Union (ITU) stated in an Internet Society Report, see Jenson (2008) that Internet Exchange (IXP) points are crucial elements of the Internet infrastructure, connecting networks to exchange traffic with one another. Therefore country-based Internet Service Provider (ISP) connections to any single IXP create an enormous potential for technical and economic benefits for any local Internet community (Jensen, 2008). Especially direct links to one of the Indian IXP's points of presence could be of high economic value since those direct links may reduce the number of steps of any internationally targeted connection while in the same time the connecting provider has the potential to save upstream transit costs. NIXI, the Indian Internet Exchange Point (IXP) currently has 7 locations with Chennai being one of them.

Three more locations are about to follow soon. NIXI Chennai is considered to directly peer with Spectranet, Vodafone India Ltd., and Tata Communications (formerly VSNL).

<b>National Internet Exchange of India (AS24029)</b>	<b>Connected Networks (ASNs)</b>	<b>This articles ASN Sources, supposed to be directly linked to NIXI</b>
NIXI Ahmedabad	1	-
NIXI Bangalore	6	AS10029
NIXI Chennai	21	AS10029, AS55410, AS4755
NIXI Hyderabad	5	-
NIXI Kolkata	10	AS4755
NIXI Mumbai	36	AS10029, AS55410, AS4755, AS23682
NIXI Delhi (NOIDA)	26	AS10029, AS55410, AS4755
NIXI Guwahati	No peering yet.	-
NIXI Mohali	No peering yet	-
NIXI Lucknow	No peering yet	-

Table 7: Source: Elaborated by the authors on NIXI (2015) information.

### 3. Methodology

#### 3.1 Introduction

This article explores the fine-grained upstream connectivity structure of a chosen set of Chennai and Tamil Nadu mobile broadband operators. Exploring these relevant (mobile broadband) connectivity metrics results in a crowd-sourced and direct Internet Periphery analysis that helps capturing network structural properties as being used in a preliminary pilot experiment on a Bhutanese mobile broadband market incumbent by Giovannetti and Sigloch (2014). The benefits of measuring the Internet network structure from the Internet edges (end-user perspective) using mobile monitoring nodes versus the Internet core (ISP perspective), such as the identification of ISP upstream connectivity bottlenecks, has been greatly discussed in Faggiani et al. (2012). Those results may in the future also be used to better understand local costs and accessibility of Internet-related services.

#### 3.2 Experiment

This experiment is making use of primary upstream connectivity data collected by using > Version 4.1 Android smartphones running the Portolan Network Sensing Architecture, see Portolan Project (2015), as background-sensing application. Each smartphone was thus acting as a unique mobile network monitoring node while being connected to a set of three mobile broadband providers SIM cards being Aircel, Bharti Airtel and Vodafone. Portolan thus uses the smartphone monitoring nodes to send traceroutes, discovering the paths taken between the source and an a priori randomly chosen set of target destinations for any triggered data package. The application also provided quality metrics such as the maximum throughput estimation along an Internet path as well as cellular network protocol (GSM, UMTS) coverage and received signal strengths indicators (RSSI) along any hop between a traceroutes' source and chosen destination.

The data generating experiment generated a sequence of traceroutes starting from Chennai (Madras), India. All further measurements were then taken along the route towards Kancheepuram in the rural area of Tamil Nadu, India. The experiment therefore captures mobility rather than just measurements based on stationary mobile operators masts.

As per Paris traceroutes network diagnosis, see Paris Traceroute (2016), any traceroute recorded the round-trip time (RTT) of data packages received from each successive vertex hop along the route, or path, through the Internet. The sum of the mean times in each hop therefore indicates the total time spent to establish a complete connection between a given source and destination of a traceroute. A traceroute proceeds to the



next hop unless all of the three data packages sent by the Portolan application are lost more than twice. At this step, the connection is considered as being lost and the respective traceroute is no longer being evaluated. Paris traceroutes are considered to be the most reliable way of testing routes between any source and destination, as they are capturing true router topologies when a router balances traffic load (on packet header fields) across two paths via alternative ones (Augustin et al., 2007 and Viger et al., 2008).

The total amount of collected traceroute data of this experiment corresponds to 731,200 hops, or single IPv4 address steps. These steps are separated into 57,122 unique traceroutes with each traceroute having a multitude of hops. Only 15,639 of these traceroutes, however, are associable to the three mobile broadband connected Android smartphones of this experiment. This represents a total amount of 57,089 hops, or 7.8% of the observations. The other 41,438 traceroutes were collected in local Wi-Fi networks during resting or day-time hours. The total collected traceroute metadata is then separated into the three Mobile Broadband SIM providers. By doing so, the traceroute metadata collection gathered 30,633 hops for the smartphone being connected to Vodafone, 21,707 hops for the smartphone being connected to a Bharti Airtel and 4,749 hops for the smartphone being connected to Aircel.

### 3.3 Network Metrics and IP-Mapping

The recorded Paris traceroutes provide a number of traversed IPv4 – address nodes along the path from a traceroutes' source to an *a priori* chosen destination as well as a number of edges, representing any hop from source to the next hop in a traceroute whereas each following hop becomes the next steps' source. Those hops are representing dedicated interconnections for any observed provider. A graph can therefore be represented as being  $G = G(V, E)$ , where vertices  $V$  represent IP addresses traversed by the collected traceroutes and the edges,  $E$  as being the pairs  $\{\{u, v\} | u, v \in V\}$  linked through a direct hop within one traceroute. The generated directed IP traceroutes graph can therefore be denoted as  $G_{IP}$ .

After the data generation experiment, we proceeded to map the observed IP vertices belonging to the graph  $G_{IP}$ , to their associated Autonomous System (AS) by using the Maxmind GeoIP2 database (Maxmind, 2015). Since each AS represents a grouping of IP networks operated by one or more network operator(s), one needs to check whether or not an IP address belongs to an IP address range of an AS. Transforming all IP hop observations, or vertices  $V$ , of  $G_{IP}$  into integer values is therefore a prerequisite, since the GeoIP2 database exclusively offers IP-ASN matching based on IP integer information. This transformation follows three subsequent steps:

1. Determine each dotted String value (e.g. 192.168.1.2) for each of the collected IPv4 addresses,
2. Transform the dotted String values into their respective four Octets,  $O_1, O_2, O_3,$  and  $O_4$  and
3. Calculate as follows:

$$O_1 * 256^3 + O_2 * 256^2 + O_3 * 256 + O_4$$

The mapping result is a directed graph at ASN granularity, denoted as being  $G_{ASN}$ . One may easily see the difference of granularity between

$$G_{IP} = G_{IP}(V_{IP}, E_{IP}) \text{ and } G_{ASN} = G_{ASN}(V_{ASN}, E_{ASN})$$

Each edge  $E$  in  $G_{IP}$  and  $G_{ASN}$  has an ordering to its vertices  $V_{IP}$ , and  $V_{ASN}$ , so that its direct edges  $\{u, v\}$  read from tail  $u$  (outgoing IP or ASN) to head  $v$  (incoming IP or ASN). The graphs  $G_{IP}$  and  $G_{ASN}$  are then embedded into a two dimensional Euclidean space, and its generated visualisation helps to understand the essential structure of Indian upstream mobile connectivity, irrespectively of the mobile broadband provider. The network visualisation for  $G_{IP}$  and  $G_{ASN}$  are generated using the Open Source complex network visualisation tool Gephi, licensed under the GNU General Public License (GPL) v3, see Gephi (2008). Since the visualisation of the graphs  $G_{IP}$  and  $G_{ASN}$  were applied at IP router and ASN level granularity, whereas any ASN may inhibit a multitude of those traceroute-captured IP routers, we can deduce that using the visualisation at IP router level offers a higher granularity, whereas the visualisation of  $G_{ASN}$  reveals first structural indications. Lastly,  $G_{ASN}$  is being separated into the aforementioned provider-based sub-graphs.

The objective of this experiment was to explore the emerging statistical network properties of the chosen mobile broadband provider's upstream connectivity. The following complex and social network metrics being used in this experiment are discussed below:

### 3.4 Graph diameter and Node Centrality

The graph diameter is representing the longest possible distance (shortest path) for connecting any two points, such as source and destination, in a general graph  $G$  therefore representing the largest maximum number of hops that any given information package flow can pass through in the observed network. Longer, or greater, network diameters are therefore likely to have a negative impact on a mobile broadband provider's Quality of Service (QoS), whereas shorter network diameters indicate a positive impact on a mobile broadband provider's QoS. One may therefore start to capture the elementary properties of the connectivity for each traceroute by stating it's Adjacency Matrix (or sometimes neighbourhood matrix),  $A^t = [a_{ij}^t]$ , where

$$a_{ij}^t = \begin{cases} 1, & \text{if } \{i, j\} \in E, \\ 0, & \text{otherwise} \end{cases}$$

So that  $a_{ij}^t$  is non-zero for those entries whose row-columns indices correspond to vertices joined by a direct edge in the network  $G$  generated by the observed traceroutes and zeros for those that are not. Due to the directed nature of the observed traceroutes, one may differentiate between the number of edges pointing towards a certain vertex, the vertex in-degree  $d_v^{in}$  and the number of edges pointing away from a vertex towards the next or final one, the vertex out-degree  $d_v^{out}$ .

The denotation of the Adjacency Matrix hence allows us to express the in-degree  $d_j^{in}$ , and out-degree,  $d_i^{out}$  as being the connectivity of each vertex in a given traceroute  $t$  from the total number of observed traceroutes  $T$ , being  $t \in T$  as

$$d_i^{out} = \sum_j a_{ij}^t \quad \text{and} \quad d_j^{in} = \sum_i a_{ij}^t$$

This experiment covered 57122 unique traceroutes, whereas each traceroute may be denoted by an Adjacency Matrix,  $A^t$ . The sum of all traceroute's Adjacency Matrices, one per observed traceroute,  $t$ , for all  $t \in T$  is a weighted network, or final matrix  $A$ , whereas  $A = \sum_{t \in T} A^t$ . The elements  $A_{ij}$  of the matrix  $A$  are non-negative numbers, showing how many times a given connections has been observed between two IP addresses or ASN numbers in the set of all traceroutes,  $T$ , equivalent to the sum of binary observations  $A_{ij}^t$  for all possible traceroutes being  $t \in T$ . From the final matrix  $A = \sum_{t \in T} A^t$ , one may derive the corresponding weighted in- and out-degrees of the observed networks, being:

$$d_i^{out} = \sum_{t \in T} \sum_j a_{ij}^t \quad \text{and} \quad d_j^{in} = \sum_{t \in T} \sum_i a_{ij}^t$$

The weighted degree of any vertex is given by the sum of the vertex' in- and out-degrees, being

$$d_i = d_i^{in} + d_i^{out}$$

### 3.5 Path Lengths, Network transitivity and Centrality

The path length  $L_p$  of a path  $p$  helps to quantify the structural properties of any graph  $G$  by measuring typical separations between two vertices as global property. Assuming an undirected graph  $G$ , one can denote the path length as being a sequence of vertices such as:

$$L_p = (v_1, v_2, \dots, v_n) \in V$$

where  $v_p$  is adjacent to  $v_{p+1}$  for  $1 \leq p < n$ . Therefore the path  $L_p$ , ranging from  $v_1$  to  $v_n$  has the length of  $n$ . Shorter path lengths being used as connectivity metrics are considered to facilitate quick transfer of information and are therefore valuable indicators for reducing upstream connectivity costs.

The average path length,  $Lavg_G$ , is given by the number of all vertices,  $V$ , in a graph  $G$ . For an unweighted graph  $G$ , one may denote the shortest distance between two vertices,  $v_1$  and  $v_2$  as being  $d(v_1, v_2)$ , where  $v_1$  and  $v_2 \in V$ . Assuming that the vertex  $v_2$  cannot be reached from vertex  $v_1$ , our average path length  $Lavg_G$  can be denoted as being:

$$Lavg_G = \frac{1}{V \cdot (V - 1)} \cdot \sum_{i \neq j} d(v_i, v_j)$$

The clustering coefficient,  $Coeff_i$  or the networks transitivity (Boccaletti et al., 2006), of each vertex,  $v_i$ , is the ratio between existing edges,  $e_i$  amongst all other vertices,  $V$  being connected to the same mobile broadband provider  $i$ , over the maximum number of potential interconnections. The network transitivity therefore captures mutual interconnections of direct neighbour-vertices of any vertex  $v_i$ , whereas  $v_i \in V$ , and thus measures the probability that any peers of a vertex are connected between themselves (Watts & Strogatz, 1998), which is mostly important for Autonomous System nodes and the interconnection of the set of AS nodes and their neighbours. The average clustering coefficient,  $AvgCoeff_i$  places a stronger value on low-degree vertices.

The last set of metrics focuses on capturing the centrality of the vertices  $V$  in an observed network  $G$ . This measurement is of crucial importance since it may help to identify situations where a certain vertex, belonging to a specific organisation, plays a central role in the connectivity of another network, which is useful to discover network bottlenecks and those providers with an essential facility, having a clear effect on market powers (D'Ignazio and Giovannetti, 2006). One may therefore use the network centrality to reveal those providers playing a crucial role.

Closeness Centrality quantifies the importance of a vertex based on the inverse of the average distance between a node and all the other nodes of a network (Freeman, 1978; Wassermann, Faust, and Jacobucci 1994). One may therefore denote Closeness Centrality as being:

$$C_C(p) = \frac{1}{\sum_{i \in V} s_{i,j}(p)}$$

where  $s_{i,j}(p)$  representing the shortest path connecting  $i$  and  $j$  in a given path  $p$ .

Betweenness Centrality used to capture a degree of unavoidability of a given node, showing the proportion of times that a node appears on the shortest paths between any other two nodes, or how many pairs of nodes would have to go through a certain node in order to reach one another in a minimum number of hops (Freeman, 1977). One can therefore denote Betweenness Centrality by:

$$C_B(p) = \sum_{i \neq j} s_{ij}(p) / s_{ij}$$

where  $s_{ij}(p)$  represents the number of shortest paths connecting  $i$  and  $j$ , passing through  $p$  and  $s_{ij}$  being the total number of shortest paths.

## 4. Preliminary results of the exploratory Network-Structural Experiment

### 4.1 Structural Network Overview at IPv4-address and ASN level

When exploring the total set of 57,122 observed unique traceroutes (including Wi-Fi connections) as a directed graph  $G_{IP}$ , as described above, then  $G_{IP}$  consist of 89,828 vertices, representing IP addresses and 152,689 edges linking those vertices (repetition of linkages between vertices included). This results in a complete set of 731,200 hop observations. After mapping the IPv4 addresses to their associated Autonomous

System Numbers reveals  $G_{ASN}$ , whereas  $G_{ASN}$  is consisting of 25,223 vertices and 60,877 linking edges (repetition of linkages between vertices included). This shows well that each vertex representing an ASN number potentially contains a multitude of the total of 89,828 IP addresses. Interestingly, when comparing these findings to the Hurricane Electric (2015a) dataset,  $G_{ASN}$  covers 48.28% of all BGP observed Autonomous Systems with IPv4 announcements. Despite the low number of total observations, this shows a sense of completeness, a positive sign for the chosen data collection method with the Portolan application. Table 8 below is therefore visualising the difference between  $G_{IP}$  and  $G_{ASN}$  by using the concentric layout by Mohan (2013), whereas each  $n$  hop is visualised by the  $n$ 'th circle starting from the center of the graph. This representation shows a sense of hierarchy for the ASN connections in  $G_{ASN}$ . The linkages seem to be tighter for  $G_{IP}$  since each  $n$ 'th circle represents the number of hops away from a chosen IPv4 or ASN root vertex. While the authors may not draw any conclusive insights from this precarious representation, further analysis reveal the here indicated hierarchical differences.

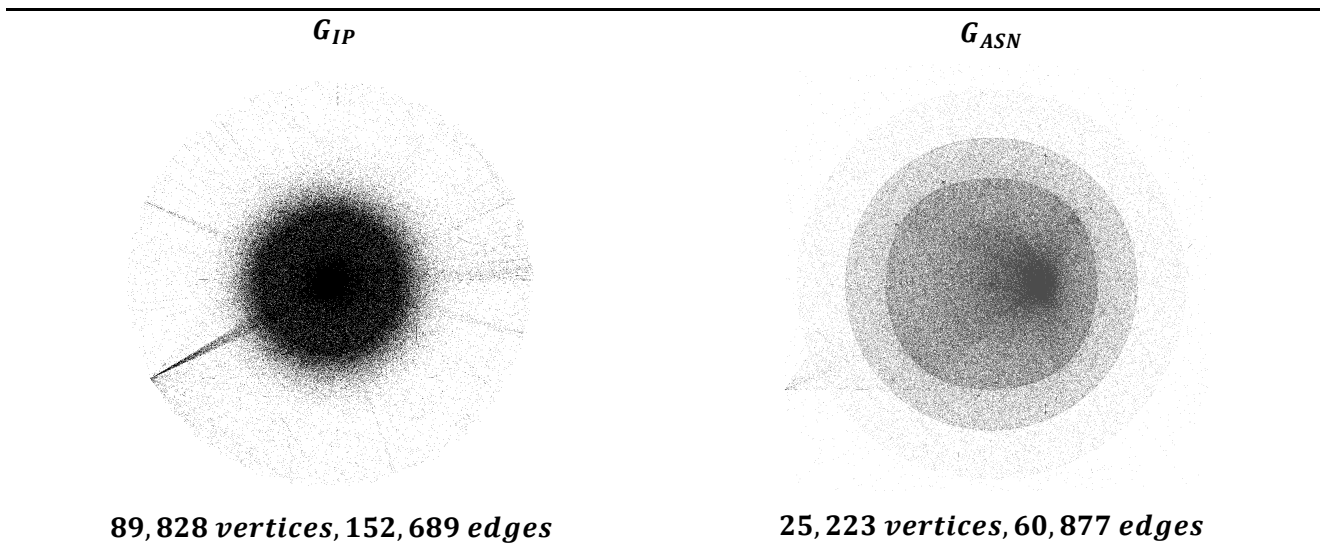


Table 8: Comparison of the graphs capturing IP-addresses (left) and ASN (right), Source: elaborated by the authors using the concentric graph visualization layout of Mohan (2013) using Gephi (2008).

Comparing the network metrics between the graphs  $G_{IP}$  and  $G_{ASN}$  with Table 9 reveals first interesting initial differences in any of the stated network metrics. Not surprisingly are Autonomous Systems more often linked than IPv4-addresses (based on Average Degree, Average Weighted Degree). This shows the nature of IP network grouping in Autonomous Systems. Interestingly, we can see a much shorter Network Diameter for  $G_{IP}$  than for  $G_{ASN}$  as well as a larger Average Path Length. This means that the distance between any pair of IPv4 connections is far greater than those of AS connections. This furthermore indicates a large number of potential inhouse-AS interconnections between IP addresses, as those hops are not directly visible at this level of granularity. However, we will re-assess the network diameter at a later stage of this experiment in order to reveal the mobile broadband operator-based Quality of Service statements.

As one may see from the values for the clustering coefficients, vertices in  $G_{ASN}$  have a higher frequency of link-triangles, which indicates a higher frequency of linkages, or relationships, between neighbouring Autonomous Systems compared to neighbouring IPv4-addresses. This makes sense considering the nature of an AS in potentially accommodating IPv4-address ranges and therefore multiple IPv4 addresses. The same holds true looking at the average clustering coefficient, which places a higher value on the strength of relationships or edges between vertices. We can therefore conclude that ASN relationships are of higher strength than relationships between IPv4-addresses. This again captures well the nature of Autonomous Systems. ASes are therefore tighter connected together than IPv4 addresses in general and tend to be bound to one-another, whereas the AS neighbours of one another are on average tighter connected.

Graph	Average Degree	Average Weighted Degree	Network Diameter	Average Path Length	Clustering Coefficient	Average Clustering Coefficient
$G_{ASN}$	2.414	28.989	14	4.902	0.321	0.403
$G_{IP}$	1.7	8.14	50	15.137	0.037	0.039

Table 9: Comparison of Network metrics between  $G_{IP}$  and  $G_{ASN}$ , Source: elaborated by the authors.

## 4.2 Connectivity, Centrality and Clustering of Providers

The next methodological step reveals a set of graphs, containing those ASN-mapped traceroutes of  $G_{ASN}$ , which started at the chosen mobile broadband provider as being marked in bold. The set of graphs is therefore limited and contains the sub-graphs of the 12 source ASN providers reported in Table 10.

Graph per Source ASN	AS Name	Number of observed hops*	Hops in percentage of $G_{ASN}$ observations	Number of Vertices (repeated)	# Edges
$G_{10029}$	Spectranet	556043	76.05	23466	54149
$G_{55410}$	Vodafone India Ltd.	51985	7.11	3898	8667
$G_{38266}$	<b>Vodafone Essar Ltd.</b>	<b>30633</b>	<b>4.19</b>	<b>1513</b>	<b>3627</b>
$G_{4755}$	Tatacomm, Tata Communications, formerly VSNL	27781	3.80	1855	4238
$G_{24560}$	<b>Bharti Airtel Ltd.</b>	<b>21707</b>	<b>2.97</b>	<b>1823</b>	<b>4227</b>
$G_{9829}$	BSNL Bharat Sanchar Nigam Ltd	20037	2.74	1351	3181
$G_{23682}$	Broadband Pacenet Pvt Ltd.	10567	1.45	748	1848
$G_{55831}$	<b>Aircel Ltd.</b>	<b>4749</b>	<b>0.61</b>	<b>522</b>	<b>1144</b>
$G_{45271}$	Idea Cellular Ltd.	3862	0.50	409	963
$G_{56247}$	PT Quasar Jaringan Mandiri	2521	0.35	267	635
$G_{45609}$	Bharti Airtel Ltd. (Mobility AS)	956	0.10	180	388
$G_{18101}$	Reliance Communications India	359	0.05	69	146
* hops include source and destination					

Table 10: Source ASN Graph overview, Source: elaborated by the authors.

Most of the 731,200 traceroute hops therefore occurred starting from Spectranet (556,043 hops, 76.05%), followed by other Wi-Fi connections starting from Vodafone India Ltd. with 51,985 hops (7.11%), Tata Communications (formerly VSNL) with 27,781 hops (3.80%), BSNL Bharat Sanchar Nigam Ltd with 20,037 hops (2.74%), Pacenet Pvt. Ltd. with 10,567 hops (1.45%), Idea Cellular Ltd., 3,862 hops (0.50%) PT Quasar with 2,521 hops (0.35%) and Reliance Communications India with 359 hops (0.05%).

The observed mobile cellular connections account for approximately 7.8% of total traceroute connections gathered in this experiment with 30,633 hops starting from Vodafone Essar Ltd. (4.19%), 21,707 hops starting from Bharti Airtel Ltd. (2.97%) and 4,749 ones from Aircel Ltd. (0.61%), respectively. The network analytical results to those Internet Service Providers with a low number of hop observations need to be interpreted with greater caution as the experiment does not necessarily cover the real every-day hop-usage between ASes.

Interestingly, PT Quasar Jaringan Mandiri is, according to the Hurricane Electric BGP routing tables, an Indonesian Provider, which has not been visible since 28 May 2015, (Hurricane Electric, 2015a). It is therefore most likely, that the connected source provider is an IP Network that is simply associated to AS56247 in Indonesia, rather than being connected to a local Autonomous System.

Placing the respective networks, starting at the above-specified AS, into a two – dimensional Euclidean space reveals the first network-structural differences. For completeness purposes, the center of each graph in the concentric layout by Mohan (2013) is the respective network’s AS with most out-degree connections. Table 12 provides an overview of the generated graph visualisations, whereas the naming for each respective graph is denoted as  $G_x$  being source ASN in network , e.g.  $G_{45609}$  represents the graph for all connections starting at Bharti Airtel Limited. Interestingly, we can clearly see differences in the number of  $n$ ’th circles of the respective graphes, see Table 11, where  $n$  represents the number of hops away from the root, or here Core-AS (most out-degree connections). In this sense,  $G_{10029}$ , Spectranet seems to have 5 hops away from the root, whereas  $G_{55410}$  Vodafone India Ltd. has 8 hops away from the root. Table 12 on the following page provides a short overview of this observation as being a subjective graph interpretation whereas the graphs of our three mobile broadband providers,  $G_{38266}$ , Vodafone Essar Ltd.,  $G_{24560}$  Bharti Airtel Ltd. and  $G_{55831}$  Aircel Ltd. are again marked with an asterisk.

Again, based on the concentric layout of Mohen (2013), we can already determine a connection-based difference between traceroutes generated with either Wi-Fi or mobile cellular connections. Wi-Fi based traceroutes represent 674,111 hops with an average of 4.67  $n$ ’th circles or hops to reach a final destination (assumption that traceroutes observed in graphs with a lower number of hops such as  $G_{18101}$  are representable) compared to 57,089 hops starting from cellular-connection with an average of 5.67  $n$ ’th circles or hops to reach a final destination. We can therefore assume that any average cellular connection needs approximately one hop, or connection step, more to reach the final destination. This increased connection is potentially reducing the perceived Quality-of-Service from an end-user perspective.

$G_{ASN}$	$G_{10029}$	$G_{55410}$	$G_{38266}$	$G_{4755}$	$G_{24560}$	$G_{9829}$	$G_{23682}$	$G_{55831}$	$G_{45271}$	$G_{56247}$	$G_{45609}$	$G_{18101}$
Number of $n$ ’th circles	5	8	<b>5</b>	6	<b>7</b>	5	3	<b>5</b>	5	4	3	3
Number of hops	556043	51985	<b>30633</b>	27781	<b>21707</b>	20037	10567	<b>4749</b>	3862	2521	956	359

Table 11: Graph interpretation,  $n$ ’th circles of Mohan (2013) concentric layout, Source: elaborated by the authors.

Table 12 on the following page shows the graphical representations for all of the Autonomous Systems observed for  $G_{ASN}$ . Based on this representation, we can clearly identify differences for the networks of Vodafone Essar Ltd., Bharti Airtel Ltd., and Aircel Ltd.. Bharti Airtel Ltd. Is showing the highest number of  $n$ ’th circles with 7, followed by Vodafone Essar Ltd. With 5 and Aircel Ltd. with 3. We can therefore assume that, based on the simple graphical analysis, Aircel Ltd. should have more efficient connections. The following analysis will closely analyse at this assumptions.

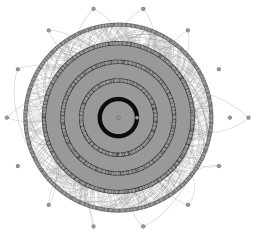
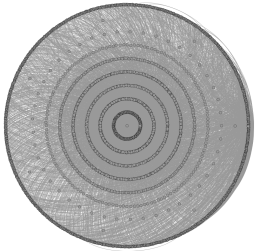
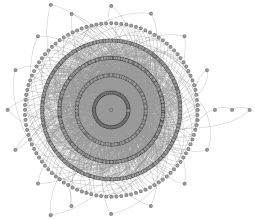
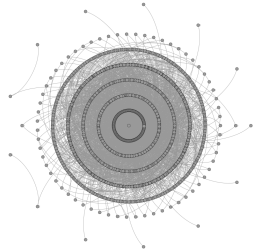
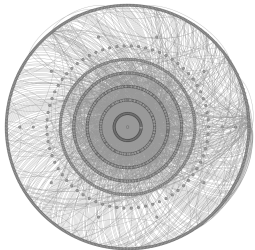
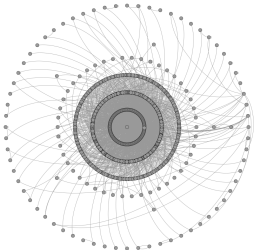
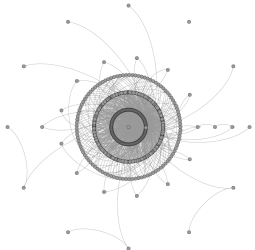
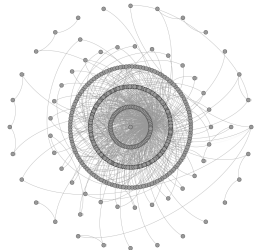

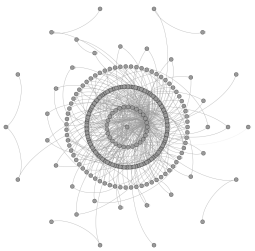
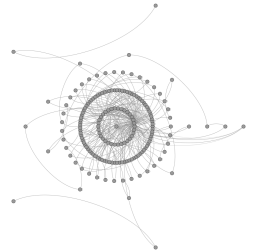
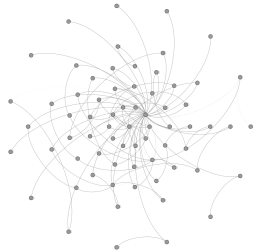
$G_{10029}$	$G_{55410}$	$G_{38266}^*$	$G_{4755}$
			
<i>Spectranet</i>	<i>Vodafone India Ltd.</i>	<i>Vodafone Essar Ltd.</i>	<i>Tatacomm, formerly VSNL</i>
$G_{24560}^*$	$G_{9829}$	$G_{23682}$	$G_{55831}^*$
			
<i>Bharti Airtel Ltd.</i>	<i>BSNL Ltd.</i>	<i>Pacenet Pvt. Ltd.</i>	<i>Airtel Ltd.</i>
$G_{45271}$	$G_{56247}$	$G_{45609}$	$G_{18101}$
			
<i>Idea Cellular Ltd.</i>	<i>PT Quasar Jaringan Mandiri</i>	<i>Bharti Airtel Ltd. (Mobility AS)</i>	<i>Reliance Communications Ltd.</i>

Table 12: Graph Visualisations for those connections, starting at an a priori specified Indian ASN, Source: elaborated by the authors on using Gephi (2008).

ASN / Nr of BGP Peer	AS10029	AS55410	<b>AS38266</b>	AS4755	<b>AS24560</b>	AS9829	AS23682	<b>AS55831</b>	AS45271	AS56247	AS45609	AS18101
ASName	Spectranet	Vodafone India Ltd.	<b>Vodafone Essar Ltd.</b>	Tata Communications (former VSNL)	<b>Bharti Airtel Ltd.</b>	BSNL Bharat Sanchar Nigam Ltd	Broadband Pacenet Pvt Ltd.	<b>Aircel Ltd.</b>	Idea Cellular Ltd.	PT Quasar Jaringan Mandiri	Bharti Airtel Ltd.	Reliance Communications Ltd
#1 Peer v4	AS55410*	AS1273	<b>AS55410*</b>	AS6453	<b>AS9498</b>	AS9498	AS9498	<b>AS55713</b>	AS55644	AS23947	AS9498	AS15412
Country												
Percentage	25%	23%	<b>100%</b>	31%	<b>83%</b>	29%	24%	<b>86%</b>	100%	97%	68%	36%
#2 Peer v4	AS10201	AS3491	N/A	AS2914	<b>AS45514</b>	AS4755*	AS55410*	<b>AS9498</b>	N/A	AS58486	AS24560*	AS24029
Country												
Percentage	16%	16%		11%	<b>17%</b>	12%	22%	<b>14%</b>		3%	32%	14%
#3 Peer v4	AS4755*	AS3356	N/A	AS24029	<b>AS45609*</b>	AS6762	AS9730	N/A	N/A	N/A	N/A	AS55410*
Country												
Percentage	16%	15%		9%	N/A	9%	20%					13%
#4 Peer v4	AS45820	AS9498	N/A	AS55879	<b>AS132981</b>	AS6453	AS18101*	N/A	N/A	N/A	N/A	AS55879
Country												
Percentage	11%	12%		6%	N/A	9%	18%					7%
#5 Peer v4	AS133757	AS3209	N/A	AS45820	<b>AS38571</b>	AS1299	AS17917	N/A	N/A	N/A	N/A	AS9885
Country												
Percentage	11%	5%		6%	N/A	9%	15%					2%

Table 13: BGP – IPv4 Peers of the analysed ASNs, Source: elaborated by the authors on Hurricane Electric BGP Peering data, Hurricane Electric (2015b).



Table 13 represents the most peered national and international Autonomous Systems for those Autonomous Systems being studied in this exploratory analysis. Those ASes being marked in bold represent this studies' mobile broadband providers Vodafone Essar Ltd., Bharti Airtel Ltd., and Aircel Ltd. When exploring the in Table 13 mentioned BGP IPv4 Peers of the analysed Autonomous System Numbers being subject of this experiment, one can clearly differentiate between those ASNs mainly peering with national counterparts (see Table 13, marked with an asterisk) such as Spectranet, Vodafone Essar Ltd., Bharti Airtel Ltd., BSNL, Broadband Pacenet Pvt. Ltd., Aircel Ltd., Idea Cellular Ltd., and those, that are not such as Vodafone India Ltd., Tata Communications, PT Quasar and Reliance Communications Ltd..

Interestingly and as being stated in the following table, some of the observed ASes peer between each other, or ASes that belong to the same organisation. The observed ASes significantly peered, according to the BGP IPv4 routing table in Table 13, to the following other national ASes as well: Bharti Airtel Ltd., Bharti Telesonic Ltd., Quadrant Televentures Ltd., The Indian International Exchange Point NIXI, PT Centra Global Investama, Bharti Airtel Telemedia Services, Tata Teleservices ISP, Idea Cellular Ltd., Dishnet Wirless and Smartlink Broadband Services Pvt. Ltd., whereas only 2 out of the 12 ASNs in this study are significantly peering to the national IXP, NIXI namely Tata Communications with 9%, Reliance Communications Ltd. with 14%. None of the three mobile broadband providers Vodafone Essar Ltd., Bharti Airtel Ltd., and Aircel Ltd. show signs of peering to the Internet Exchange Point NIXI.

The following Table 14 provides an overview of the core vertex being used in the concentric layout with those ASes of the three mobile-broadband providers being again marked in bold. Those Core-ASAs that represent a network themselves are marked with an asterisk, which is the case for Pacenet with most connections through themselves and PT Quasar, Bharti Airtel Ltd., and Reliance Communications Ltd., all having most out-degrees through Reliance Communications Ltd.

$G_{ASN}$	$G_{10029}$	$G_{55410}$	$G_{38266}$	$G_{4755}$	$G_{24560}$	$G_{9829}$	$G_{23682}$	$G_{55831}$	$G_{45271}$	$G_{56247}$	$G_{45609}$	$G_{18101}$
Core-AS $d_{ASN}^{out}$	AS174	AS174	<b>AS174</b>	AS3356	<b>AS174</b>	AS6453	AS23682*	<b>AS6453</b>	AS1273	AS18101*	AS18101*	AS18101*
Out-Degree	1899	353	<b>157</b>	171	<b>159</b>	152	203	<b>79</b>	48	30	30	11

Table 14: Graph-associated Core-AS and their Out-Degrees, Source: elaborated by the authors.

The Wi-Fi based AS traceroutes,  $d_{ASN}^{out_{Wi-Fi}}$  have an average out-degree of 321.89, without Spectranet the average out-degree,  $d_{ASN}^{out_{Wi-Fi, sans AS10029}}$  is considerably lower, being 124.75. In comparison, the mobile cellular based AS traceroutes,  $d_{ASN}^{out_{mobile}}$  have an average out-degree of 131.67 meaning the outgoing connectivity of an the respective ASes core Autonomous System.

Interestingly the most out-degree, as being connections going out from an AS-node for Spectranet, Vodafone India Ltd., Vodafone Essar Ltd., and Bharti Airtel Ltd. is Cogent Communications (United States). Cogent Communications is therefore a crucial partner to potentially peer connections further, whereas the most-connected IPv4 Peers for Cogent Communications are Level 3 Communications (United States, 13%), Telia Sonera AB (Sweden, 9%), and Tinet SpA (Germany, 5%), indicating an importance of internationalisation of connections.

Exploring the associated AS-Numbers' maximum in-degree for each respective graph is revealing the lack of Quality of Service (QoS) in the Indian networks, see Table 15. For each graph  $G_x$  being source ASN in network, where  $G_x$  being source ASN in network  $\in G_{ASN}$ , #N/A is the highest in-degree associated ASN:

$G_{ASN}$	$G_{10029}$	$G_{55410}$	$G_{38266}$	$G_{4755}$	$G_{24560}$	$G_{9829}$	$G_{23682}$	$G_{55831}$	$G_{45271}$	$G_{56247}$	$G_{45609}$	$G_{18101}$
Max $d_{ASN}^{in}$	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
In-Degree $d_{ASN}^{in}$	21489	3043	<b>1191</b>	1433	<b>1477</b>	1043	643	<b>361</b>	277	204	204	53
as % of total $d_{ASN}^{in}$	39.68	35.11	<b>32.84</b>	33.81	<b>34.94</b>	32.79	34.79	<b>31.56</b>	28.76	32.13	32.13	36.30

Table 15: Max in-degree ASN and percentage of total in-degrees for each graph, Source: elaborated by the authors.

As per the rules for Portolan measurements, see Portolan Project (2015), #N/A is reached, when the data packets sent through the Network Sensing Application, are lost twice while transmitting. If this is the case, then the traceroute for an associated traceroute identifier stops collecting information and a new traceroute with a new identifier would start. Hence, data packets, or connectivity, in the networks of  $G_{ASN}$  is lost between 28.76 – 39.68% of the time, indicating a very low Quality of Service (QoS). Mapping failures from IP-addresses to ASN via Maxmind (2015) have to be taken into consideration. If the Maxmind (2015) GeoIP2 database is complete, whose check is out of scope for this exploratory analysis, then #N/A only corresponds to loss of connectivity.

Calculating the graph associated network measurements for the aforementioned graphs of  $G_{ASN, mobile-broadband}$  by using the open-source network analysis and visualization software package Gephi (2008) reveals the results stated in Table 16 whereas those network measurements for the complete set of graphs,  $G_{ASN}$  can be found in the appendix.

ASN Graph Identifier	Autonomous System Name	Average Degree	Average Weighted Degree	Network Diameter	Graph Density	Clustering Coefficient	Average Clustering Coefficient	Average Path Length
$G_{38266}$	Vodafone Essar Ltd.	2.397	20.247	12	0.002	0.170	0.257	4.563
$G_{24560}$	Bharti Airtel Ltd.	2.319	11.907	10	0.001	0.160	0.242	4.129
$G_{55831}$	Aircel Ltd.	2.192	9.098	6	0.004	0.105	0.167	2.423

Table 16: Graph-associated Network Measurements (mobile-cellular), Source: elaborated by the authors using Gephi (2008).

Unsurprisingly we only have a small difference in Average Degree between the three different mobile broadband providers, as being the sum of both incoming and outgoing edges. This means that connections with Vodafone Essar Ltd. have, on average, 0.078 more relationships to other ASes than Bharti Airtel and 0.205 more than Aircel Ltd. This value however becomes more interesting when looking at the Average Weighted Degree, which takes the weights of the different directed relationships between the AS-nodes of each graph into consideration, resulting in a combination of degree and strength. Vodafone Essar Ltd. therefore has considerably stronger relationships to partnering ASes than Bharti Airtel Ltd. and Aircel Ltd. This however might be a result of the in Table 11 mentioned IPv4 BGP-peering relationship between Vodafone Essar Ltd. and Vodafone India Ltd. and the high out-degree to Cogent Communications.

Aircel Ltd. seems to be, on the basis of the low number of hop-observations, the most efficient mobile-broadband provider, since the low network diameter (6) indicates the largest distance a traceroute has to traverse from source to destination. The network diameter for Vodafone Essar Ltd.

(12) and Bharti Airtel Ltd. (10) indicate potentially less-efficient networks with higher upstream connectivity costs. This also fits with the calculated Average path lengths of 4.563 nodes for Vodafone Essar Ltd., 4.129 nodes for Bharti Airtel Ltd. and 2.423 nodes for Airtel Ltd.

Nevertheless, Vodafone Essar Ltd. has a higher Clustering Coefficient (0.170) than Bharti Airtel Ltd. (0.160) and Airtel Ltd. (0.105). We can therefore assume that Vodafone Essar Ltd. and Bharti Airtel Ltd. have a higher density of relationships between other ASes than Airtel Ltd., giving a preliminary indicator for potentially hierarchical network structures. While the Clustering Coefficient places higher value on low degree nodes, the Average Clustering Coefficient places higher value on high degree nodes. When considering this difference, Vodafone Essar Ltd. (0.257) still represents a higher density of AS-relationships than Bharti Airtel Ltd. (0.242) and Airtel Ltd. (0.167).

#### **4.4 Conclusion & Future Studies**

In mapping the traceroute observations from Internet Protocol (IPv4) addresses to their associated Autonomous System numbers (ASN), this exploratory analysis shows the expected outcome of higher frequencies between connections in Autonomous Systems than between the higher-granularity IPv4 addresses. Data packets, or connectivity in the total Autonomous System networks is lost between 28.76 – 39.68% of the time, indicating a potentially low Quality of Service (QoS) without considering the also collected received signal strength information. Interestingly, the observations at the converted ASN level covers 48.28% of all BGP observed Autonomous Systems with IPv4 Announcements in Hurricane Electric (2015a). The further separation into the respective Internet Service Providers shows, that only 7.8% of all observations are of high interest to this analysis. Vodafone Essar Ltd. connections show more relationships to other ASes than both Bharti Airtel and Airtel Ltd. Vodafone Essar Ltd. also shows considerably stronger relationships to partnering ASes than both Bharti Airtel Ltd. and Airtel Ltd. This might be a result of underlying IPv4 BGP-peering relationship between Vodafone Essar Ltd. and Vodafone India Ltd. and the high outgoing connections to Cogent Communications. Besides having stronger relationships to partnering ASes, Vodafone Essar Ltd. and Bharti Airtel Ltd. show a higher density of relationships. This is potentially indicating the occurrence of hierarchical network structures (Vazquez, Pastor-Satorras and Vespignani, 2002). Based on the graph interpretation, the network diameter and average traceroute path lengths, Airtel Ltd. seems to be the most efficient mobile-broadband provider without potentially unnecessary connections to other ISPs and therefore potentially lower upstream connectivity costs.

Surprisingly, none of the observed traceroute connections was making use of NIXI, the Indian Internet Exchange Point. Connections either stop before the IXP or pass along other routes in the Internet, avoiding connections to the IXP. One potential reason for this could lay in the BGP routing tables, where NIXI is not marked for any of the three studied providers. This lack of partnerships could also indicate underlying economically beneficial partnerships with other Internet Service Providers.

Future data collection experiments should disable Wi-Fi connections in the data collecting smartphone devices. By doing so, the data collection should reveal higher numbers of observations for the relevant Mobile Broadband Providers. Future studies could link the connectivity relationships data with the Quality of Service information, captured from the data collection as well. Additionally, future studies should analyse both the connection between mobile internet service providers to their local Internet Exchange Points, NIXI and internationality of connections in general, pointing towards the usage of settlement free peering in fair competition and service pricing. Furthermore, and given the indicators for dense relationships, future studies should test the preliminary exploratory findings of this article by correlating connectivity power law functions and clustering coefficient as they exhibit the structure of the underlying hierarchical organization.

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## Appendix

ASN Graph Identifier	Autonomous System Name	Average Degree	Average Weighted Degree	Network Diameter	Graph Density	Clustering Coefficient	Average Clustering Coefficient	Average Path Length
<b>G<sub>10029</sub></b>	Spectranet	2.308	23.696	15	0	0.298	0.374	5.464
<b>G<sub>55410</sub></b>	Vodafone India Ltd.	2.223	13.336	11	0.001	0.184	0.236	3.751
<b>G<sub>38266</sub></b>	<b>Vodafone Essar Ltd.</b>	<b>2.397</b>	<b>20.247</b>	<b>12</b>	<b>0.002</b>	<b>0.170</b>	<b>0.257</b>	<b>4.563</b>
<b>G<sub>4755</sub></b>	Tatacomm, formerly VSNL	2.285	14.976	11	0.001	0.172	0.244	4.645
<b>G<sub>24560</sub></b>	<b>Bharti Airtel Ltd.</b>	<b>2.319</b>	<b>11.907</b>	<b>10</b>	<b>0.001</b>	<b>0.160</b>	<b>0.242</b>	<b>4.129</b>
<b>G<sub>9829</sub></b>	BSNL Bharat Sanchar Nigam Ltd	2.355	14.831	10	0.002	0.151	0.244	3.663
<b>G<sub>23682</sub></b>	Broadband Pacenet Pvt Ltd.	2.471	14.127	10	0.003	0.223	0.328	3.705
<b>G<sub>55831</sub></b>	<b>Aircel Ltd.</b>	<b>2.192</b>	<b>9.098</b>	<b>6</b>	<b>0.004</b>	<b>0.105</b>	<b>0.167</b>	<b>2.423</b>
<b>G<sub>45271</sub></b>	Idea Cellular Ltd.	2.355	9.443	7	0.006	0.103	0.166	2.693
<b>G<sub>56247</sub></b>	PT Quasar Jaringan Mandiri	2.378	9.442	6	0.009	0.133	0.220	2.150
<b>G<sub>45609</sub></b>	Bharti Airtel Ltd. (Mobility AS)	2.156	5.311	8	0.012	0.085	0.155	2.192
<b>G<sub>18101</sub></b>	Reliance Communications India	2.116	5.203	5	0.031	0.109	0.182	1.964

Table 17: Graph-associated Network Measurements, Source: elaborated using Gephi (2008).