Economics of Terragraph Backhaul for AT&T's 5G network in San Jose

Executive Summary

On 25th April 2018 it was announced (Tomás, n.d.) that ***AT&T and the city of San Jose have reached an agreement to install a network of 170 small cells on lampposts***. This was followed by a memorandum (sanjoseca.gov, n.d.) which was signed on May 1st, 2018 between the city of San Jose and AT&T.

AT&T plans to use this network to provide 5G mmWave access. This is going to be one of the earliest mmWave 5G deployments in the country. As this network expands one of the biggest issues AT&T will face is the access to Fiber drops at each lamppost.

Terragraph (Terragraph, n.d.) is a line of sight (LOS) based mmWave backhaul that operates at 60GHz.This paper demonstrates the practicality of using Terragraph to meet an operator like AT&T's needs of this rapidly growing deployment.

This paper goes over the following topics:

- Feasibility of Line of Sight between street lights in San Jose
- Terragraph backhaul performance
- Operator's 5-year rollout plan
- Economic analysis covering the capex and opex cost

The paper demonstrates that it is feasible to get line of sight between streetlights with an average distance of 73m. This would allow the operator to easily meet capacity requirements at 5G sites with fewer Fiber PoP.

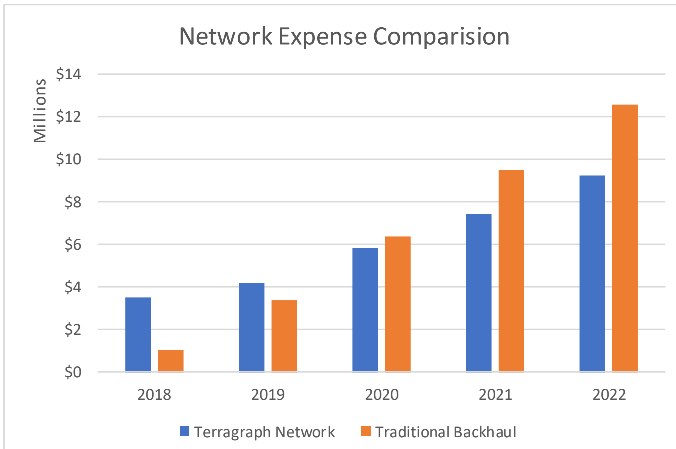


FIGURE 1 COMPARISON OF TERRAGRAPH WITH TRADITIONAL BACKHAUL

The paper also shows that the greatest cost driver that a 5G operator will face is the backhaul cost.

The economics analysis part of the paper shows that the ***operator can realize significant saving in backhaul by deploying Terragraph***. As shown in Figure 1 the Terragraph backhaul Network Expense breaks even in 2020 with increasing savings as the network grows.

Street Light LOS feasibility study

One of the most difficult task in any modeling exercise is access to relevant data. For this analysis the street light locations (Streetlights, n.d.) and LiDAR data (OCM Partners, 2018: Santa Clara County, California, n.d.) for Santa Clara County are publicly available.

The map in Figure 2 shows the LiDAR grid in Black from Santa Clara County that covers the city of San Jose. The city is covered by 204 LiDAR files with slightly more than 1 Billion points of data or 2.07 points/sqm.

The blue dots are the 63K street lights in the city. The red boundaries are the 10 council districts. As per the agreement (sanjoseca.gov, n.d.) the number of cell sites in each council district from the original 170 is predefined.

This LiDAR data & street light locations are used to compute Line of Sight between every street light and its neighbors. The process used to calculate LOS is described in Table 1.

Figure 3 below shows a zoomed in view of San Jose downtown and a residential neighborhood along with its LOS availability. The pictures clearly show the line of sight combinations possible along with obstruction due to buildings and trees. In the downtown picture, there is a whole street with no line of sight possibility due to presence of trees.

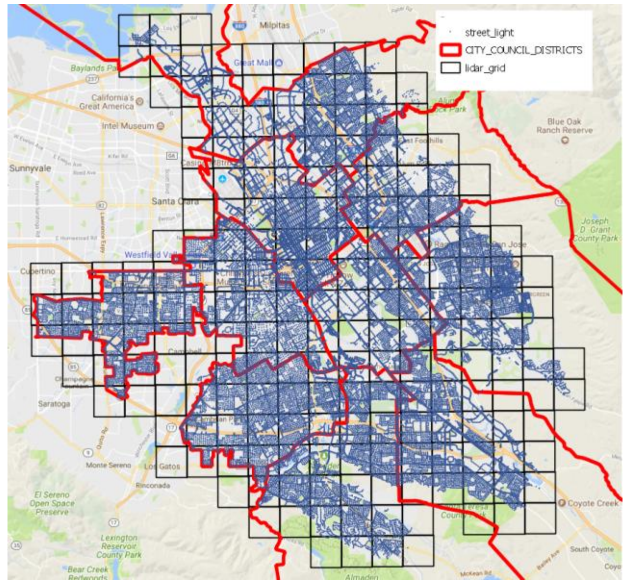
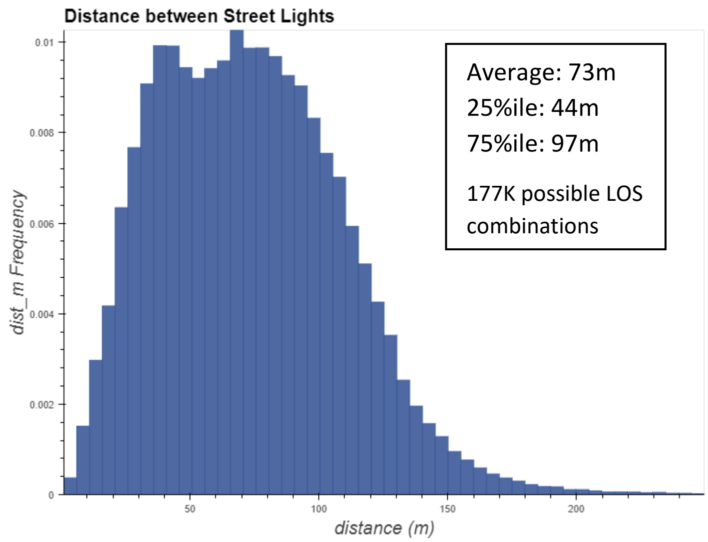


FIGURE 2 SAN JOSE OVERVIEW

1. Project all LiDAR and street light data to epsg projection 26910 (UTM)
2. Determine the Ground level at the base of each street light.
3. Calculate the height in meter for each street light above sea level assuming each pole is 9.1m (San Jose Downtown Street and Pedestrian Lighting Master Plan)
4. Compute LOS between each street light and its neighboring street lights.
5. Street Lights with no possibility of LOS links are dropped from the dataset.

TABLE 1 ALGORITHM USED FOR LOS CALCULATION BETWEEN STREET LIGHTS

FIGURE 3 LOS COMBINATIONS, RED DOTS: STREET LIGHTS, BLUE LINES: LOS LINKS, YELLOW: LOS BLOCKED BY TREES



The data set representing distance between street lights with LOS is shown as a histogram in Figure 4. On an average the distance between street lights with LOS is 73.3m with small percentile approaching 250m LOS.

At these distances of 250m and less, there will be no issue in maintaining a 60GHz mmWave link.

San Jose with clear LOS between large number of street lights is a good market for Terragraph deployment.

FIGURE 4 DISTRIBUTION OF DISTANCE BETWEEN LOS STREET LIGHTS

Terragraph Network Performance

AT&T's initial rollout has been announced to be 170 sites, but the memorandum released by city of San Jose (sanjoseca.gov, n.d.) shows 181 sites spread across 10 council districts.

For modeling purpose, this paper assumes 181 sites picked randomly from the existing street light locations while remaining consistent with the council district specific plans. These 181 locations represent the starting point of AT&T's network which will be fully deployed by end of 2018. Since this is a greenfield deployment by AT&T, it's fair to assume that each of these 181 sites will have access to a fiber PoP along with a mmWave Small Cell.

- Terragraph on average provides 2.5Gbps with bounds of (1Gbps, 3.8Gbps)
- Each links capacity is randomly calculated based on Normal distribution with a mean of 2.5Gbps and a standard deviation of 0.46Gbps
- Assuming a downlink to uplink traffic ratio of 7:3 and scaling available capacity by 0.7
- This capacity assumption can easily be replaced with a link budget based on 60GHz propagation model (3GPP, n.d.) and performance curves from engineering teams.
- Latency per hop = 1ms. Max acceptable multi-hop latency is 10ms.

TABLE 2 TERRAGRAPH NETWORK ASSUMPTIONS

EOY 2018 with 181 sites represents AT&T's baseline network. Starting year 2019 an operator like AT&T will have two choices, either use Terragraph for their backhaul or to put in a fiber PoP at each street light.
This paper is focused on providing a framework to help operator's in making a correct decision for their backhaul architecture.

Since Terragraph requires line of sight for backhaul, each additional site that is brought into the network needs to have LOS with a site connected to Fiber PoP either directly or indirectly. The number of hops needed to reach the Fiber Pop adds to the latency and contribute to cumulative traffic at each hop. This cumulative traffic on each hop limits the number of sites that can be daisy chained together.

Due to its architecture the coverage of a Terragraph network will expand in a hub and spoke configuration from existing sites which have fiber PoPs. As these deployments expand the spokes will overlap (Figure 7) to give a uniform coverage and greater diversity of connectivity.

To understand the dynamics of this network, a sensitivity model is run by varying the demand per site from 100Mbps to 2.5Gbps and varying the site count from 181 to 2000. By running the model for a range of scenarios while keeping the Fiber PoP the same, we can simulate network performace as it is loaded with additional demand and sites.

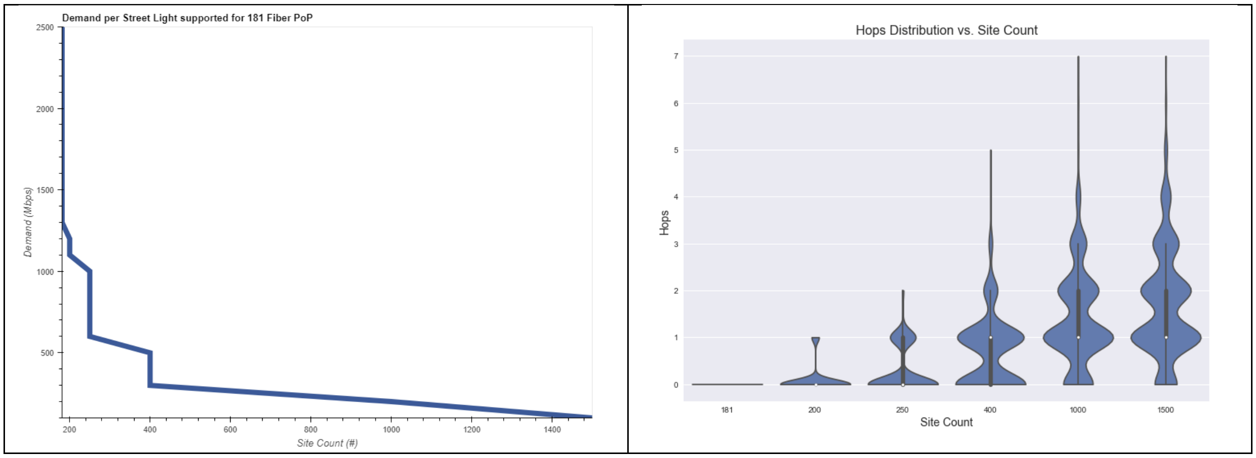


FIGURE 5 IMPACT OF INCREASING SITE COUNT ON SUPPORTED DEMAND AND #HOPS

The Figure 5 above shows results of modeling San Jose with these scenarios. Figure 5 on left shows that, as site count increases the amount of demand that can be supported per site reduces. This is mainly due to limitation of the capacity of each hop and the cumulative traffic that had to be carried as site count increases. Figure 5 on right shows the distribution of the number of hops required to reach Fiber PoP. Its clear that the number of hops will increase as the number of sites increase.

If we define a minimum target demand of 500Mbps per site, our network as shown in Figure 5 on left can only support approx. 300 sites. At 400 sites the number of hops to Fiber PoP increases, due to which the demand per Street light needs to be lowered to remain within the capacity available at each hop. To grow our network to 2000 sites, we need to significantly increase our Fiber PoP beyond the original 181.

Based on results of Figure 5 and while keeping in mind the capacity on each hop, this paper assumes that the network needs to support a minimum of 500Mbps of traffic at each site.

AT&T plans to grows their network to 1000 sites (sanjoseca.gov, n.d.) covering San Jose over the next 2-3 Years. For this paper we assume that the following table represents operator's phased deployment over the next 5 years with a minimum demand of 500Mbps per site.

	2018	2019	2020	2021	2022
Operator Sites	181	600	1000	1500	2000

Terragraph Network roll out

The starting base line network has 181 street lights with all connected to Fiber PoP. Starting from Year 2 sites are added one at time as per the algorithm described in Table 3 .

1. The new site should have a LOS to an existing site.
2. Once the new site is added, the network is tested to see if it can handle the additional traffic.
3. If the network fails, a Fiber PoP is added at the location of new site.
4. Calculate traffic flow for the full network
5. Any hops with no traffic are dropped to minimize DN cost.

TABLE 3 ALGORITHM FOR ADDING NEW SITES

The plots shown in the figures below show the street light deployments by year. Since we have a requirement that all new sites have a LOS to existing sites, we can observe that the coverage gradually spreads out.

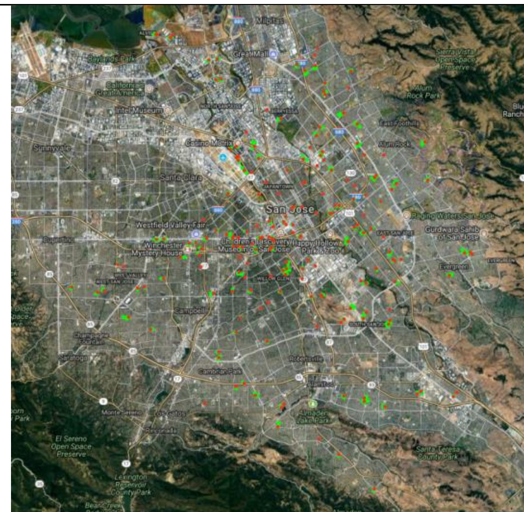
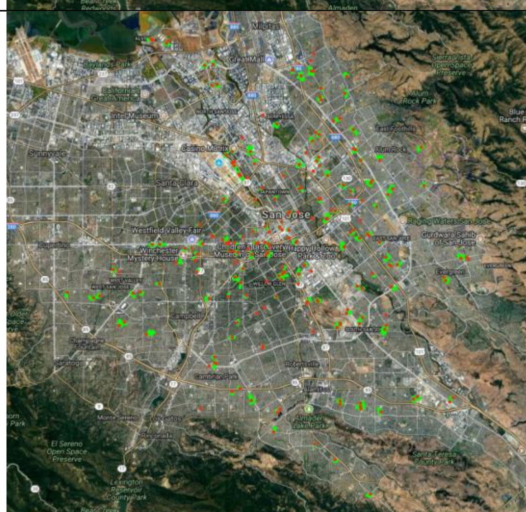
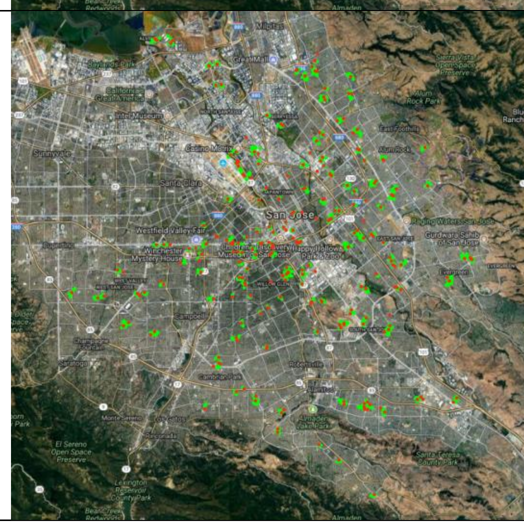
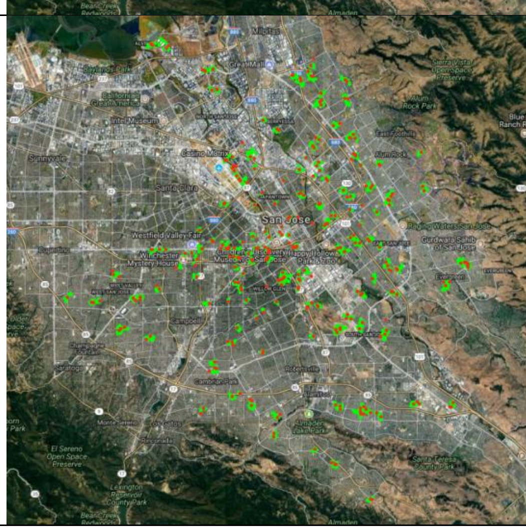
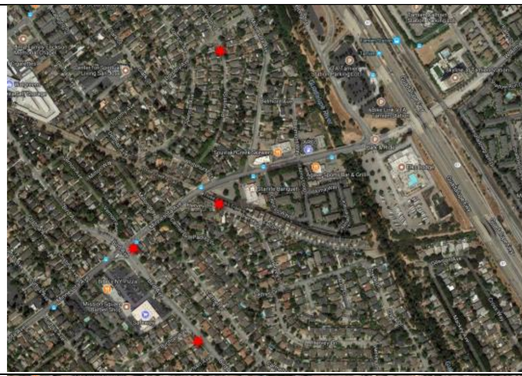
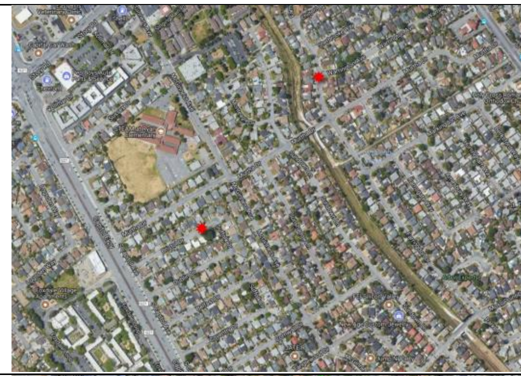
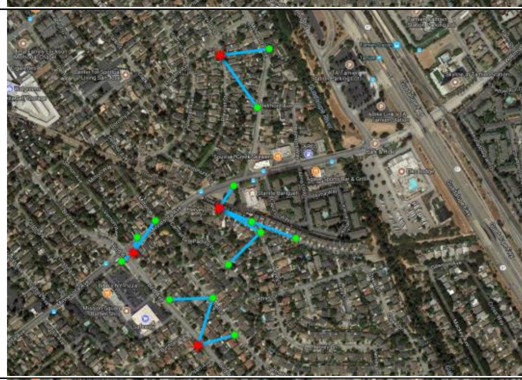
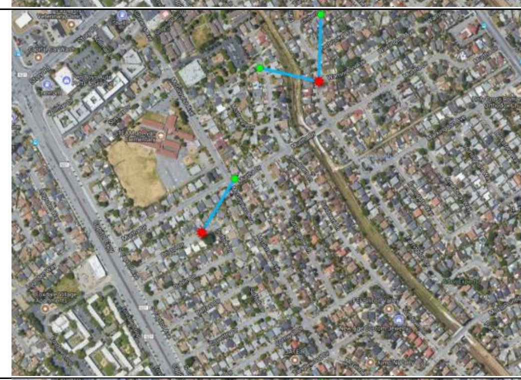
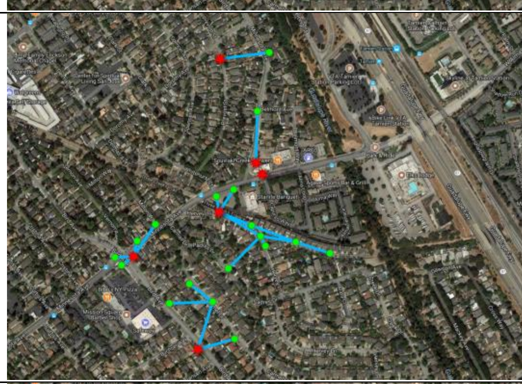
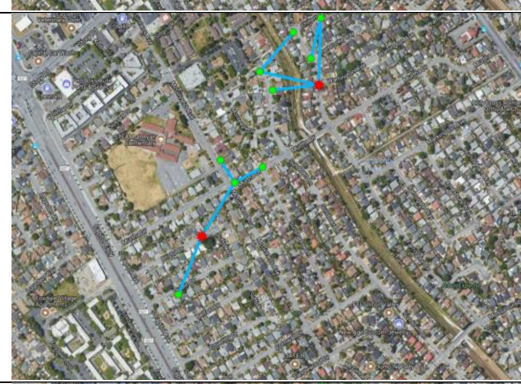
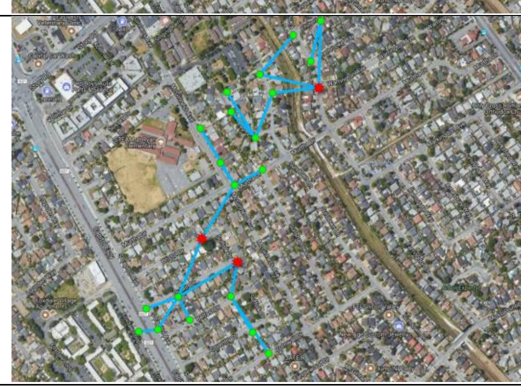
2018 - 2019		
2020 - 2021		
2022		

FIGURE 6 SAN JOSE STREET LIGHT INSTALLATIONS, RED DOTS: FIBER POP, GREEN DOTS: TERRAGRAPH STREET LIGHTS

The plots below show a zoomed in view of two different neighborhoods. The red stars represent location of Fiber PoP, the green dots are street lights and the Blue line is the LOS link between two street lights with a Distribution Node (DN) at each end.

Year	Zoom View 1	Zoom View 2
2018 181 Sites		
2019 600 Sites		
2020 1K Sites		
2021 1.5K Sites		

2022
2K Sites

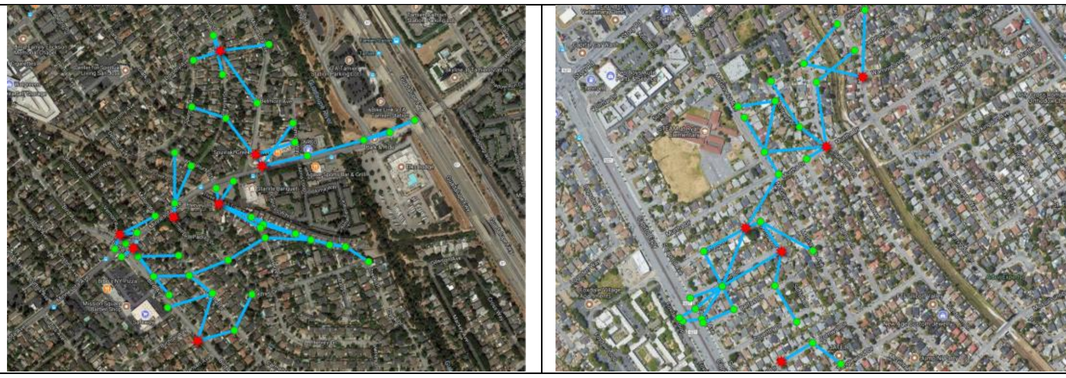


FIGURE 7 VIEW OF TWO NEIGHBORHOODS. RED STAR: FIBER POP, GREEN DOT: STREET LIGHT, BLUE LINE: LOS LINK

In 2018 as shown in Figure 7 above, only Street lights with Fiber PoP's are active. In the following years multiple sites are enabled using Terragraph with Fiber PoP's added for capacity as needed.

We now have full network model by year along with all the underlaying metrics, which are shown in figures below. These figures show the impact of adding site on inter-site distance, number of hops, flow on Terragraph links and the number of Distribution Nodes (DN) per street light.

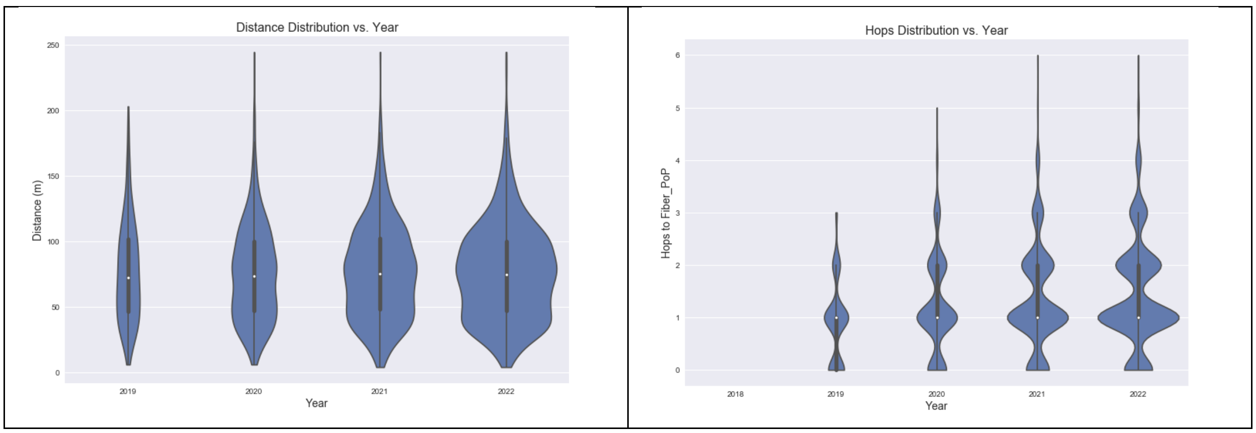


FIGURE 8 LOS & HOPS DISTRIBUTION BY YEAR

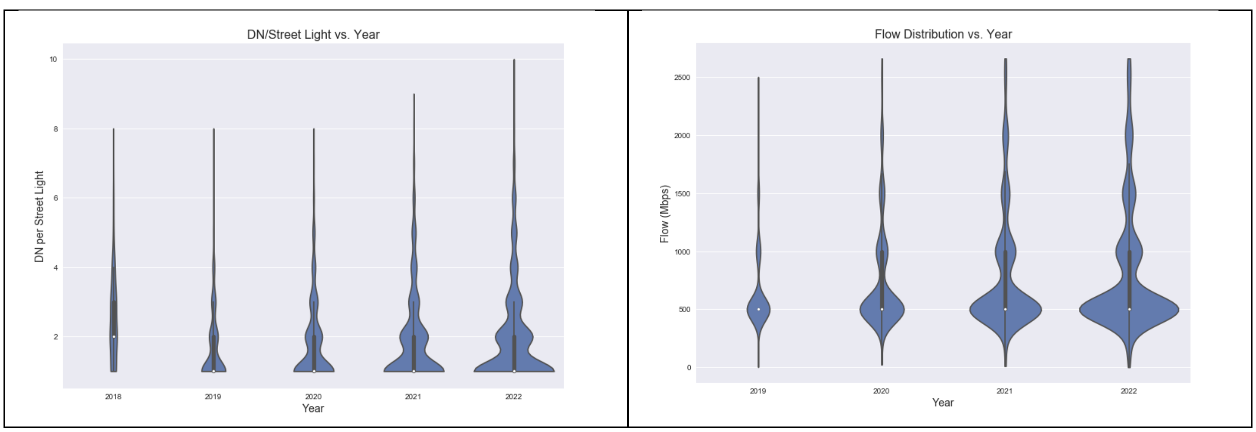


FIGURE 9 DN/STREET LIGHT & FLOW DISTRIBUTION BY YEAR

The Table 4 below summarizes the infrastructure required to support a Terragraph based backhaul derived from the network model shown above.

	2018	2019	2020	2021	2022
Operator Sites	181	600	1000	1500	2000
DN Count	455	1012	1811	2847	3905
Fiber PoP	181	194	219	261	313

TABLE 4 TERRAGRAPH INFRASTRUCTURE REQUIRED

Economics of Backhaul

An operator has multiple options to meet its backhaul needs for a 5G small cell. One option that we have considered is using Terragraph as shown in Table 4.

The other option is to run a dedicated Fiber PoP to each Street light, in that case the infrastructure required is as shown in Table 5 below.

	2018	2019	2020	2021	2022
Operator Sites	181	600	1000	1500	2000
Fiber PoP	181	600	1000	1500	2000

TABLE 5 TRADITIONAL INFRASTRUCTURE REQUIRED

For this analysis we are assuming that each Terragraph Fiber PoP needs to be 5Gbps which means it has enough capacity to support 10 sites based on our demand of 500Mbps. A 5Gbps backhaul is assumed to cost ~$18K per year (Comcast, n.d.). The capital expenditure, operating expenditure and the Present Value of all the expense over the 5-year period is shown in Table 6 below.

Cumulative Count				**2018**	**2019**	**2020**	**2021**	**2022**
	node			181	600	1000	1500	2000
	DN			455	1012	1811	2847	3905
	fiber_PoP			181	194	219	261	313
Incremental Count				**2018**	**2019**	**2020**	**2021**	**2022**
	node			181	419	400	500	500
	DN			455	557	799	1036	1058
	fiber_PoP			181	13	25	42	52
Capital Expenditure								
Groups	**Subgroups**	**Unit Cost**	**Unit**	**2018**	**2019**	**2020**	**2021**	**2022**
San Jose City	Process Improvements	$1,000,000	City	$1,000,000				
San Jose City	Front Permit Fee		City	$850,000				
Cell Site	Site acquisition and preparation	$1,000	per Street Light	$181,000	$419,000	$400,000	$500,000	$500,000
Cell Site	DN	$450	per DN	$204,750	$250,650	$359,550	$466,200	$476,100
Cell Site	Broadband Install (5Gbps)	$1,000	per Fiber_PoP	$181,000	$13,000	$25,000	$42,000	$52,000
	Total Investment			$2,416,750	$682,650	$784,550	$1,008,200	$1,028,100
Operating Expenditure								
Groups	**Subgroups**		**Unit**	**2018**	**2019**	**2020**	**2021**	**2022**
Cell Site	Small cell site license	$1,500	Per site	$0	$321,500	$1,500,000	$2,250,000	$3,000,000
Cell Site	Broadband Lease (5Gbps)	$18,000	per Fiber_PoP	$3,258,000	$3,492,000	$3,942,000	$4,698,000	$5,634,000
	Total Expense			$3,258,000	$3,813,500	$5,442,000	$6,948,000	$8,634,000
	PV of Annual Cost	6%	ATT WACC	$5,353,538	$4,001,557	$5,227,931	$6,302,056	$7,220,083
	PV Total Expense			**$28,105,165**				

TABLE 6 TERRAGRAPH CAPEX/OPEX

The line items “Process Improvements”, “Front Permit Fee” & “Small Cell Site license” are from the memorandum (sanjoseca.gov, n.d.) signed between San Jose city & AT&T.

The Fiber PoP used in the traditional backhaul architecture is dimensioned to support 0.5Gbps since it only needs to support one site. A 0.5Gbps backhaul is assumed to cost $4.5K per year (Comcast, n.d.). The capital expenditure, operating expenditure and the Present Value of all the expense over the 5-year period is shown in Table 7 below.

Cumulative Count				**2018**	**2019**	**2020**	**2021**	**2022**
	node			181	600	1000	1500	2000
	fiber_PoP			181	600	1000	1500	2000
Incremental Count				**2018**	**2019**	**2020**	**2021**	**2022**
	node			181	419	400	500	500
	fiber_PoP			181	419	400	500	500
Capital Expenditure								
Groups	**Subgroups**	**Unit Cost**	**Unit**	**2018**	**2019**	**2020**	**2021**	**2022**
San Jose City	Process Improvements	$1,000,000	City	$1,000,000				
San Jose City	Front Permit Fee		City	$850,000				
Cell Site	Site acquisition and preparation	$1,000	per Street Light	$181,000	$419,000	$400,000	$500,000	$500,000
Cell Site	Broadband Install (500Mbps)	$1,000	per Fiber_PoP	$181,000	$419,000	$400,000	$500,000	$500,000
	Total Investment			$2,212,000	$838,000	$800,000	$1,000,000	$1,000,000
Operating Expenditure								
Groups	**Subgroups**		**Unit**	**2018**	**2019**	**2020**	**2021**	**2022**
Cell Site	Small cell site license	$1,500	Per site	$0	$321,500	$1,500,000	$2,250,000	$3,000,000
Cell Site	Broadband Lease (500Mbps)	$4,500	per Fiber_PoP	$814,500	$2,700,000	$4,500,000	$6,750,000	$9,000,000
	Total Expense			$814,500	$3,021,500	$6,000,000	$9,000,000	$12,000,000
	PV of Annual Cost	6%	ATT WACC	$2,855,189	$3,434,941	$5,709,411	$7,920,937	$9,714,356
	PV Total Expense			**$29,634,834**				

TABLE 7 TRADITIONAL BACKHAUL CAPEX/OPEX

There are 3 main differences in these two approaches of deploying backhaul

1. Terragraph network requires fewer Fiber PoP
2. Terragraph network has an additional cost for DN
3. Terragraph network shares its Fiber PoP between multiple sites resulting in higher capacity requirement per Fiber PoP.

A metric which is very useful to understand for operator network economics is Network Expense which is depreciated capital expenditure + operating expenditure by year as shown in Table 8 & Table 9.

	Subgroups		**Dep Period**	**2018**	**2019**	**2020**	**2021**	**2022**
Capex	Process Improvements		18	$55,556	$55,556	$55,556	$55,556	$55,556
	Front Permit Fee		5	$170,000	$170,000	$170,000	$170,000	$170,000
	Site acquisition and preparation		18	$10,056	$33,333	$55,556	$83,333	$111,111
	DN		8	$25,594	$56,925	$101,869	$160,144	$219,656
	Broadband Install (5Gbps)		8	$22,625	$24,250	$27,375	$32,625	$39,125
Opex	Small cell site license			$0	$321,500	$1,500,000	$2,250,000	$3,000,000
	Broadband Lease (5Gbps)			$3,258,000	$3,492,000	$3,942,000	$4,698,000	$5,634,000
	Total			$3,541,830	$4,153,564	$5,852,355	$7,449,658	$9,229,448

TABLE 8 TERRAGRAPH NETWORK EXPENSE

	Subgroups	Dep Period	2018	2019	2020	2021	2022
Capex	Process Improvements	18	$55,556	$55,556	$55,556	$55,556	$55,556
	Front Permit Fee	5	$170,000	$170,000	$170,000	$170,000	$170,000
	Site acquisition and preparation	18	$10,056	$33,333	$55,556	$83,333	$111,111
	DN						
	Broadband Install (500Mbps)	8	$22,625	$75,000	$125,000	$187,500	$250,000
Opex	Small cell site license		$0	$321,500	$1,500,000	$2,250,000	$3,000,000
	Broadband Lease (500Mbps)		$814,500	$2,700,000	$4,500,000	$6,750,000	$9,000,000
	Total		$1,072,736	$3,355,389	$6,406,111	$9,496,389	$12,586,667

TABLE 9 ATT FIBER BACKHAUL NETWORK EXPENSE

Network expense is important because it aligns with Income statement and can be paired with revenue and operating expense.

Figure 10 compares the Network expense of these two backhaul options. From the charts the Backhaul lease dominates the Network expense and will be the driver for the final economic decision.

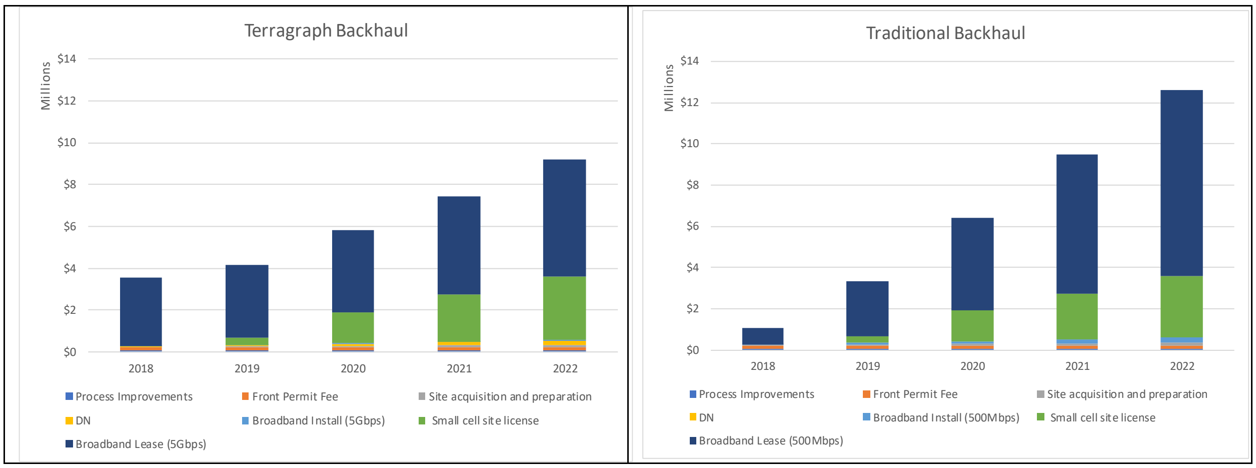


FIGURE 10 NETWORK EXPENSE COMPARISON

In the year 2018/2019 due to the cost of additional equipment and higher rate Fiber POP the network expense for Terragraph is higher. From year 2020 onwards as the network grows so do the savings resulting in lower network expense over a 5-year period and beyond.

Since the backhaul cost can be market specific its important to understand its sensitivity to change.

		Traditional Backhaul Cost				
	-$1,529,668	$ 3,000	$ 3,500	$ 4,000	$ 4,500	$ 6,000
Terragraph Backhaul Cost	$ 6,000	$ (6,804,152)	$ (8,917,667)	$ (11,031,181)	$ (13,144,695)	$ (19,485,238)
	$ 9,000	$ (3,900,396)	$ (6,013,910)	$ (8,127,424)	$ (10,240,939)	$ (16,581,482)
	$ 12,000	$ (996,639)	$ (3,110,153)	$ (5,223,668)	$ (7,337,182)	$ (13,677,725)
	$ 15,000	$ 1,907,118	$ (206,396)	$ (2,319,911)	$ (4,433,425)	$ (10,773,968)
	$ 18,000	$ 4,810,875	$ 2,697,360	$ 583,846	$ (1,529,668)	$ (7,870,212)

TABLE 10 BACKHAUL COST SCENARIO (PV TERRAGRAPH – PV TRADITIONAL BACKHAUL)

Table 10 above compares the Present Values of total expense for a range of backhaul costs for Terragraph vs traditional option. In this deployment its clear that Terragraph offers a better economic solution.

The case for a traditional deployment with Fiber PoP at every site is optimal only in scenarios where there is a significant cost differential between the two backhaul options.

Conclusion

This study has demonstrated that Terragraph offers better performance at lower cost for a small cell network.

Terragraph network has an added advantage of being able to move unused capacity from one end of the network to an area where it is needed most, enabled by its mesh-based architecture. This results in better utilization of Fiber PoP and lower effective $/Mbps.

In terms of economics and ease of deployment, Terragraph has clear advantages which get better with time and larger network deployments.

It is essential that operators planning for high density small cell deployment seriously consider Terragraph as an option before any 5G rollouts begin.

Any infrastructure vendor planning to provide small cells for 4G/5G deployments should consider integrating their product with a Terragraph like backhaul for ease of deployment and management.

About the Author

Sameer Lalwani (MBA, MSEE)
sameerlalwani@gmail.com
linkedin.com/in/lalwanisameer

Telecom industry professional skilled in helping drive technology decisions by wireless operators, regulators, and infrastructure vendors. Quantify impact of technology decision by building Digital twins of networks to generate economic analysis and ROI calculations, significantly reducing uncertainty while making major decisions.

Known for effective listening and thinking outside the box; sincere willingness to learn. Experienced in working with cross-functional teams driving wireless technologies to provide connectivity and data services across globe. Always approachable, bring positive attitude to every project. Partner across Business Development, R&D, Network Deployment, and Finance.

An article describing how an economic analysis like this can be used to drive technology decisions "Convincing a customer to change their core technology" is available here https://bit.ly/2xMZkIt.

If you are interested in 5G coverage check out the article "How much 5G coverage will you really get from lampposts?" https://bit.ly/2sFWEqk.

For more details about types of projects he has worked on check out his LinkedIn profile.

Tools used:

- Modeling: All code for this analysis has been written in Python.
- LiDAR data processing: laspy library used to process LiDAR files.
- Analytics: pandas, Dask used to process large datasets & distributed processing.
- Graph analytics: networkx used to calculate traffic flow.
- GIS: QGIS, geopandas used for plotting maps and reprojection of maps.
- Charts: Python, holoview, seaborn.
- Economic Analysis: Excel.

Next Steps

- Replace Terragraph capacity assumptions with link budget-based capacity.
- Calculate LOS to each UE location.
- Use UE data rate to estimate capacity at each site instead of picking a fixed value.
- Model access at UE, this can be done for both Terragraph CN & mmWave 5G. This can then be used to compare access performance and economics of 5G vs. Terragraph CN
- Place sites using machine learning clustering algorithms for targeted coverage.

References

3GPP. (n.d.). *Study on channel model for frequencies from 0.5 to 100 GHz*. Retrieved from 3GPP Portal: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3173

Comcast. (n.d.). Retrieved from https://business.comcast.com/internet/business-internet

OCM Partners, 2018: Santa Clara County, California. (n.d.). Retrieved from InPort: https://inport.nmfs.noaa.gov/inport/item/49636

San Jose Downtown Street and Pedestrian Lighting Master Plan. (n.d.). Retrieved from San Jose Redevelopment Agency: www.sjredevelopment.org/PublicationsPlans/lighting.pdf

sanjoseca.gov. (n.d.). *Actions Related to the Agreement with AT&T DBA New Cingular Wireless PCS, LLC for Permitting Small Cells.* Retrieved from sanjoseca.gov: https://sanjose.legistar.com/LegislationDetail.aspx?ID=3477923&GUID=124D8045-09F4-4B17-8DA9-16AD30110702&Options=&Search=

Streetlights. (n.d.). Retrieved from sanjoseca.gov: https://data.sanjoseca.gov/datasets/179288/streetlights/

Terragraph. (n.d.). Retrieved from Millimeter Wave (mmWave) Networks: https://telecominfraproject.com/mmwave/

Tomás, J. P. (n.d.). *AT&T to deploy small cells in San Jose; signs new macro tower deal*. Retrieved from https://www.rcrwireless.com: https://www.rcrwireless.com/20180425/network-infrastructure/att-reaches-tentative-agreement-deploy-small-cell-network-san-jose-tag23

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