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Cost model for a 5G smart light pole network

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Abstract—The adoption of 5G smart light poles can facilitate the massive deployment of communications equipment in the urban environment, accelerating the advent of new smart city services. In this article, we define a cost model for a 5G smart light pole network that includes (1) four pole configurations with different hardware components, (2) a grid-based deployment structure that assigns poles to zones with different demand requirements, and (3) the evolution of key cost items due to prototype improvement, volume sale discounts, and price erosion. The model estimates the total deployment cost (TDC), including capital and operational expenses. We estimate a TDC of 4.84 M€/km² for a minimum deployment providing uniform coverage of basic services. We also estimate a TDC of 6.57 M€/km² for a massive deployment providing heterogeneous coverage of advanced services. These values can potentially decrease to 3.23 M€/km² and 4.05 M€/km² when cost evolution is considered. Although more than 30% cost reduction might be possible, this is mainly caused by the improvement of prototype components, given that public works are less sensible to cost evolution. Therefore, we recommend cities to promptly start civil works and to select upgrade-able pole designs.

Index Terms—Smart city, 5G, small cells, smart light poles

I. INTRODUCTION

Future smart city services will require new street-level networks capable of providing 5G connectivity, sensor data collection, accurate positioning, and more. However, the massive deployment of communications equipment (e.g. 5G small cells, video cameras) in an urban environment faces the challenge of increasing deployment costs per subscriber (in comparison to previous mobile generations) and the lack of new sites due to stricter municipal regulations [1]. Recently, it has been proposed to integrate communications equipment into light poles since they are ubiquitous in streets and may remain there for the foreseeable future [2]. In addition, regulators may issue local spectrum licenses to attract additional investment from local players [3]. To contribute to this proposal, we study the cost structure and the main cost items of a 5G smart light pole network.

A large body of literature exists on the cost structure of access mobile networks however, studies typically concentrate on nationwide macro-cell infrastructure [4]. More recently, numerous publications examined the deployment of 5G networks, including the role of small cells [5, 6]. Although some of these publications address the case of dense urban areas, they typically focus on the mobile service alone. In contrast, other publications focus on the cost of smart light poles that provide LED-based smart lighting [7]. Although smart light

poles may include low-power sensors or even Wi-Fi access, their ability to support future smart city services is limited e.g. due to the lack of device mobility management.

To fill this gap, we propose a cost model for a 5G smart light pole network which not only provides 5G connectivity but other smart city services e.g. video signage, electrical vehicle (EV) charging while collecting real-time sensor data e.g. video surveillance, air quality and weather monitoring. The model includes (1) four pole configurations with different hardware components, (2) a grid-based deployment structure that assigns poles to zones with different demand requirements, and (3) the evolution of key cost items due to prototype improvement, volume sale discounts, and price erosion. We estimate the total deployment cost (TDC) of two scenarios via probabilistic sensitivity analysis, including variation for deployment parameters and the cost evolution of key cost items.

This article is organized as follows. Section 2 briefly describes the employed method. Section 3 defines the cost model, including the structure and different output calculations. Section 4 reports the obtained cost data derived from the minimum and the massive deployment scenarios. While Section 5 draws conclusions, Section 6 describes limitations and future work. Finally, Appendices provide detailed cost data.

II. METHOD

The cost model has been developed in an iterative manner, incorporating feedback from experts at each iteration. We interviewed experts from Finnish cities, network equipment vendors, Mobile Network Operators, and Small and Medium Enterprises, who have been involved in the LuxTurrin5G project.

Cost data is obtained from partner quotations, field trial invoices, and expert interviews. In order to cover for uncertainties, probability distributions are assigned to key cost items, enabling a sensitivity analysis on the TDC.

III. COST MODEL DEFINITION

A. Structure

The cost model is made of three modules:

1) *Pole Configuration Module*: It defines four pole configurations each of which includes a different set of hardware components, allowing for multiple combinations of sensors.

2) *Infrastructure Module*: It estimates capital and operational expenses for the deployment of the pole network to satisfy coverage requirements from different pole components.

3) *Cost Evolution Module*: It estimates future cost values for pole configurations and infrastructure considering prototype improvement, volume sale discounts, and price erosion.

B. Pole Configuration Module

We define four pole configurations each of which includes a different set of hardware components, as shown in Table I.

- The **Light-Only (LO)** provides smart lighting using LED technology.
- The **Light + 5G (L5G)** additionally provides connectivity (i.e., broadband or IoT services) via 28 GHz small cell base stations.
- The **Light + 5G + Sensors (L5GS)** additionally provides sensor coverage including video surveillance, weather and air quality monitoring, sound sensing and audio reproduction, and RTK positioning.
- The **Full configuration** provides complete smart city functionality by additionally supporting high quality video surveillance, EV charging, and information displays.

Table I also includes today's cost for each configuration and it anticipates possible future cost ranges. These ranges are obtained via the Cost Evolution Module described in Section III-D. Note that while some components are already available in the market, others are still in the prototype stage. Detailed cost data can be found in Appendix B.

C. Infrastructure Module

We estimate the capital and operational expenses to conduct a greenfield deployment that satisfies the coverage requirements from different pole components. The model assumes fiber-based backhaul since civil works are anyway conducted due to greenfield deployment.

1) *Total number of poles (P_{total})*: Given the full size of the area to be covered (A), we remove the percentage of area (α) where no light poles are needed or cannot be deployed e.g. woods, agriculture fields or lakes. We denote the rest of the area as the Area of Interest (AoI). Then, we calculate the number of necessary poles assuming a grid-based deployment

with an adjustable pole-to-pole distance (d_{ptp}), which should be aligned with the corresponding city regulation.

$$P_{total} = \left(\frac{\sqrt{A}}{d_{ptp}} + 1 \right)^2 \cdot \alpha \quad (1)$$

2) *Number of poles per configuration (P_{config})*: To satisfy different demand requirements, we define zones with different device density and device speed, as shown in Table II. Based on these zones, we allocate a different mix of pole configurations considering the coverage of pole components e.g. 28 GHz small cells, weather stations, and video cameras.

TABLE II
DEPLOYMENT ZONES

Zone	Device density	Device speed	Example area
1	Low	High	Commuting
2	Medium	Medium	Suburban
3	High	Low	City center

3) *Average infrastructure cost per pole (C_{infra})*: Given a defined grid-based deployment, we estimate costs for digging the trenches in between poles, installing power and fiber cables, installing protective tubes, installing the concrete base where the pole will stand, reconstructing the street surface, and installing a telematics center. The total infrastructure cost is averaged to the number of poles, thus generating an average infrastructure cost per pole. Detailed cost data can be found in Appendix A.

D. Cost Evolution Module

We model the cost evolution of key cost items by considering cost reduction due to prototype improvement, volume sale discounts, and price erosion.

1) *Prototype improvement*: Since some pole hardware components are under development, we can expect their manufacturing cost to decrease due to engineering optimization, utilization of cheaper sub-components, and reduction in labour caused by mass production. Thousands of these components may be needed to serve an increasing demand for 5G smart light poles by the world's cities.

TABLE I
POLE CONFIGURATIONS

	Prototype (P) / Market (M)	Lights Only (LO)	Lights + 5G (L5G)	Lights + 5G + Sensors (L5GS)	Full
Pole shaft	M	x	x	x	x
Pole base	M	x	x	x	x
Utility box	P	x	x	x	x
Common radome unit	P		x	x	x
Smart lights	M	x	x	x	x
Weather & air quality sensor	M			x	x
External camera system	M				x
Integrated camera system	M			x	x
Sound sensing & speaker	M			x	x
External information display	P				x
RTK positioning	P			x	x
EV charger	M				x
Drone station	P				x
28 GHz 5G base station	P		x	x	x
Today's cost		7 000 €	15 000 €	31 000 €	60 000 €
Future cost range		4 500 € - 7 000 €	8 000 € - 15 000 €	20 000 € - 31 000 €	34 000 € - 60 000 €

2) *Volume sale discounts*: Component providers and civil work companies may concede price discounts for large purchasing orders and deployments, respectively.

3) *Price erosion*: We take into account potential price reductions due to component manufacturing improvements and the emergence of competing component providers.

E. Today and Future TDC

To calculate the TDC, we first multiply the number of poles in each configuration by the cost of their respective configuration. Next, we add the multiplication of the total number of poles by the infrastructure cost. This infrastructure cost is the average cost of deploying a pole considering capital and operational expenses. Equation 2 presents the mathematical formulation.

$$TDC = \sum_{config} (P_{config} \cdot C_{config}) + P_{total} \cdot C_{infra} \quad (2)$$

1) *Today TDC*: The model estimates the TDC of today as a function of multiple deployment parameters d_i , as shown by Equation 3.

$$C_{infra} = C_{infra}(d_i) \quad (3)$$

2) *Future TDC*: The model estimates the *Future TDC* as a function of deployment parameters and the evolution of key cost items. The evolution of the pole cost includes variations derived from prototype improvement (p), volume sale discounts (v), and price erosion (e). The infrastructure cost only depends on volume sale discounts, and price erosion.

$$\begin{aligned} C_{config} &= C_{config}(p, v, e) \\ C_{infra} &= C_{infra}(v, e, d_i) \end{aligned} \quad (4)$$

IV. SMART CITY DEPLOYMENTS

A. Minimum and massive deployments

We evaluate the cost model for a minimum deployment scenario and a massive deployment scenario. The minimum deployment provides uniform and seamless coverage for smart lighting and 5G small cell access. In addition, it provides RTK positioning and low-resolution video surveillance when in close proximity of poles (i.e., basic smart city services).

The massive deployment scenario introduces a more realistic study case in which the area of interest is divided among the three zone types defined in Table II. Further, it additionally provides high-resolution surveillance, EV charging, video signage via information displays, and drone docking and charging services (i.e. advanced smart city services).

Table III shows the pole configuration mix used for the deployments. To calculate these mixes, we assume that 28 GHz small cells have a coverage radius of 100m [8], which defines the fraction of L5G and L5GS poles. We also assume that weather stations have a 500m radius, which is the most demanding in the Full configuration, defining the fraction of Full poles.

TABLE III
POLE CONFIGURATION MIX

	LO	L5G	L5GS	Full
Minimum deployment				
uniform	88 %	6 %	5.4 %	0.6 %
Massive deployment				
zone 1	40 %	30 %	26 %	4 %
zone 2	40 %	40 %	20 %	0 %
zone 3	30 %	40 %	26 %	4 %

Fig. 1. Espoo-specific grid-based deployment structure

Figure 1 shows the grid-based deployed employed by the model assuming an inter-pole distance of 50m, as defined by Espoo city.

Table IV presents TDC calculation details, including additional input parameters, the number of poles for each configuration, and *Today TDC* and *Future TDC*.

TABLE IV
DEPLOYMENT DETAILS

Input parameters	Minimum	Massive
Area	10 km ²	
Pole-to-pole distance	50 m	
α	70 %	
Prototype impr. (p)	0.4	
Volume discounts (v)	0.1	
Price erosion (e)	0.2	
Zone alloc.	unif.	33% each zone
Pole configurations		
Total	2890	2890
LO	2526	1060
L5G	182	1060
L5GS	164	694
Full	18	77
TDC results		
Today TDC	48.4 M€	65.7 M€
Future TDC	32.3 M€	40.5 M€
Cost evolution reduction	34.1%	38.4%
Today Min-Mass diff	28.5 %	
Future Min-Mass diff	20.0 %	

Results from the minimum deployment scenario reveal that a 48.4 M€ investment is required to cover a 10 km², which translates into a baseline deployment cost of 4.84 M€/km². This cost can potentially decrease by a 34.1% due to cost evolution to 3.23 M€/km². Results from the massive deployment scenario indicate a deployment cost of 6.57 M€/km² which could decrease to 4.05M€/km² due to a cost evolution size of 38.4%. If we compare both deployment scenarios, we observe that the massive deployment requires an investment that is 28.5% higher (or 20% in the future) than the minimum deployment, albeit it potentially providing more services.

B. Effect of cost evolution on TDC

Figure 2 shows the effect of prototype improvement, volume sale discounts, and price erosion on the pole cost and the infrastructure cost for the minimum and the massive deployment scenario. We observe that the pole cost has a larger cost reduction potential than the infrastructure cost, particularly in the massive deployment scenario. This difference is mainly caused by the fact that prototype improvement does not

apply to the infrastructure cost and the operational expenses associated with civil works are highly linked to the size of the deployment, which remains the same.

C. Relative contribution of individual cost items

Figure 3 shows the relative contribution of individual cost items to *Today TDC* and *Future TDC* for the minimum and the massive deployments.

In the minimum deployment, the top seven contributors to TDC, which have a weight larger than 5%, either belong to civil works (i.e., protective tubes, cabling, digging, surface reconstruction, concrete base) or to shared parts of the pole (i.e., pole shaft, utility box). In contrast, in the massive deployment, the small cell base station accounts for a large fraction of the TDC. More importantly, this fraction significantly decreases from a 22% in the *Today TDC* to a 15% in the *Future TDC*. The RTK positioning also significantly decreases its contribution from a 5% in the *Today TDC* to 3% in the *Future TDC*. Hence, we conclude that the cost evolution of these two components has the largest cost reduction impact to TDC.

Fig. 2. Evolution of *Future TDC* for the minimum deployment (left figure) and the massive deployment (right figure)

Fig. 3. Individual item cost contribution to the minimum deployment (left figure) and the massive deployment (right figure)

Fig. 4. Probability distribution of *Today TDC* and *Future TDC* for the minimum deployment (left figure) and the massive deployment (right figure)

V. SENSITIVITY ANALYSIS

We run a probabilistic sensitivity analysis allowing for variation in certain variables, as shown by the probability distributions in Table V. We select the Beta-PERT distribution, where PERT stands for Program Evaluation and Review Technique, because it is typically used to identify project risks, given its ability to cover variable skewness. Like the triangular distribution, the Beta-PERT distribution emphasizes the “most likely” value over the minimum and maximum estimates.

TABLE V
VARIABLE DISTRIBUTIONS

Deployment parameters	
α	$\beta PERT(0.6; 0.7; 0.8)$
28GHz small cell coverage	$\beta PERT(75; 100; 200)$
Weather station coverage	$\beta PERT(200; 500; 800)$
Cost evolution parameters	
Prototype improvement (p)	$\beta PERT(0.2; 0.4; 0.6)$
Volume sale discounts (v)	$\beta PERT(0.05; 0.1; 0.15)$
Price erosion (e)	$\beta PERT(0.1; 0.2; 0.3)$

Figure 4 shows the obtained empirical probability distribution of *Today TDC* and *Future TDC* resulting from the sensitivity analysis, which included ten thousand iterations. We observe how the *Future TDC* could vary between [2.8 - 4.3] M€/km² for the minimum deployment and between [3 - 5.4] M€/km² for the massive deployment.

An additional result from the sensitivity analysis can be observed in Figure 3, where error bars show the change in cost contribution due to probability distributions.

VI. CONCLUSION

In this paper, we model the total deployment cost (TDC) for a 5G smart light pole network, including capital and operational expenses. The model includes four pole configurations, a grid-based deployment structure, and it accounts for prototype improvement, volume sale discounts, and price erosion.

We estimate a TDC of 4.84 M€/km² for a minimum deployment providing uniform coverage of basic services. We also estimate a TDC of 6.57 M€/km² for a massive deployment providing heterogeneous coverage of advanced services.

These values can potentially decrease to 3.23 M€/km² and 4.05 M€/km² when cost evolution is considered. After conducting a sensitivity analysis, we observe that the *Future TDC* could vary between [2.8 - 4.3] M€/km² for the minimum deployment and between [3 - 5.4] M€/km² for the massive deployment. Overall, the massive deployment requires an investment that is 28.5% higher (or 20% in the future) while potentially providing advanced services. Hence, it may be worth investing in pole configurations capable of providing advanced smart city services only if these services increase the revenue creation of the network by at least this same fraction.

We study the cost reduction potential caused by the cost evolution of key cost components. When comparing the pole costs versus the infrastructure costs, we observe that the pole costs have a larger cost reduction potential, due to the benefits of prototype improvement. In more detail, looking at the individual pole components, we observe that the small cell base station and the RTK positioning not only have a significant contribution to the TDC but also a significant cost reduction potential. Hence, we recommend cities to promptly start civil works, enabling a fiber-based backhaul for present and future poles, and to select upgrade-able pole designs, which can accept new hardware components as soon as their prices become affordable.

VII. LIMITATIONS AND FUTURE WORK

The model assumes a fiber-based backhaul because green-field deployments facilitate civil works. Thus, poles can be connected to fiber regardless of their current configuration, allowing for future updates. Future work aims to include brownfield deployments accounting for wireless-based mesh backhaul with mmW antennae.

Future work will relate this cost model with revenue models, thus searching for pole configurations and deployment structures that ensure the sustainability of a 5G smart light pole operator.

APPENDIX A POLE COST DATA

The cost data are collected from industry experts and from quotations from project partners and field trial. Due to non-

disclosure agreements, we are not allowed to show the exact costs for each task. Data is presented in Table VI. Long term estimated cost is estimated via the Cost Evolution Module using parameters defined in Table IV.

TABLE VI
POLE COST DATA

Smart light pole components costs		
Component	Today's cost	Long term estimated cost
Weather sensor	8500 €	6100 €
28 GHz BS	8000 €	3500 €
EV charger	4800 €	3500 €
RTK positioning	4100 €	1800 €
Pole shaft	3900 €	2800 €
Information display	3200 €	1400 €
CRU camera	2800 €	2000 €
Utility box	2400 €	1200 €
Drone station	2000 €	900 €
External camera	1800 €	1300 €
Sound sensor	530 €	400 €
Smart lights	360 €	250 €
CRU chassis	260 €	200 €
Pole base	200 €	150 €
SUM	42800 €	25500 €

APPENDIX B
INFRASTRUCTURE COST DATA

The infrastructure cost data are mainly extracted from construction company offers concerning a 50 000 square meter campus area. Table VII shows the average infrastructure cost per a single pole regardless of its configuration, provided a 50 meter inter-pole distance.

Electricity and telematics centers, which are mandatory for controlling the power and data flow, are covered under separate concepts. Note that there roughly is one telematics center for every 100 poles. The considered concrete base can be up to three meters in height whereas just 30 to 90 cm is above the ground and the rest is underground. The diameter is usually around 50 cm. Regarding surface reconstruction, it considers the reconstruction of pavement and lawn after the digging and construction work.

Long term estimated cost is estimated via the Cost Evolution Module using parameters defined in Table IV.

TABLE VII
INFRASTRUCTURE COST DATA

Infrastructure work components costs		
Component	Today's cost	Long term estimated cost
Cabling	2300 €	1700 €
Protective tubes	2800 €	2000 €
Digging	1700 €	1250 €
Surface reconstruction	1300 €	950 €
Concrete base	100 €	60 €
Telematics center	35 €	25 €
SUM	8235 €	5985 €

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