Lighting-Enabled Smart City Applications and Ecosystems Based on the IoT

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***Abstract*—The Internet of Things is poised to transform lighting from a simple illumination source, which is most often taken for granted, into a smart and data-rich infrastructure for the cities. To this end, we propose the Lighting-Enabled Smart City APplications and Ecosystems (LENSCAPEs) framework. LENSCAPEs involve i) city-wide *wireless Outdoor Lighting Networks* (OLNs), to connect the streetlights using either mesh, or cellular networks, ii) *sensors*, to collect heterogeneous spatio-temporal data about the city, iii) *controllers*, to actuate physical processes, such as lighting, and iv) other *cloud-based applications*, to process the data that is collected and disseminated by the city-wide wireless sensor network. Mesh-based networking technologies for OLNs, such as IEEE 802.15.4g, are evaluated by simulating network capacity and comparing with cellular technologies. *Light-on-Demand* (LoD), an adaptive energy-efficient lighting system based on wireless mesh networks, is presented as the primary application of small-scale OLNs. We also present a case study on a *real-world deployment of LoD*, which resulted in 92% energy savings over conventional luminaires.**

I. Introduction

Outdoor lighting in public spaces is the cornerstone of urban livability. It plays several critical roles in the daily lives of the citizens, namely i) enabling vehicular movement at night and reducing the associated risks of night-time accidents ii) assisting in the protection of property iii) discouraging crime and vandalism iv) making the residents feel secure, and v) beautifying the urban landscapes.

In addition to enabling these crucial urban activities, outdoor lighting is also a major consumer of electricity and significantly impacts cities' energy budgets. In the United States (US), outdoor lighting consumes enough energy to power six million homes for a year, costing cities about $10 billion annually [2]. Moreover, streetlight systems can account for up to 60 percent of a city's electricity bill for public amenities [16]. Consequently, urban lighting has been, and continues to be, a top-priority for local governments, like municipalities and county administrations in the US. Additionally, in January 2015, President Obama, in conjunction with the Department of Energy (DoE), launched the Presidential Challenge for Advanced Outdoor Lighting to encourage American cities to focus on outdoor lighting as a driver for energy efficiency.

In this context, the *Internet of Things* (IoT), which extends the World Wide Web (WWW)-based connectivity to physical entities [17], will be instrumental in enabling energy-efficient lighting. As outdoor luminaires, such as streetlights, become connected, access to real-time data about the luminaires will fundamentally change the business models in the lighting industry. *Motivated by the transformative nature of IoT, we present the Lighting-Enabled Smart-City APplications and Ecosystems (LENSCAPEs) framework.*

LENSCAPEs consist of i) city-wide *wireless Outdoor Lighting Networks* (OLNs), which connect the streetlights using either mesh, or cellular networks, ii) *sensors* that collect heterogeneous spatio-temporal data about the city, iii) *controllers* that actuate physical processes, such as lighting, and iv) other other cloud-based applications, which process the data that is collected and disseminated by the city-wide wireless sensor network. See Fig. 1 for an overview.

LENSCAPEs will transform urban lighting in three ways, see Fig. 1. Firstly, the IoT will transform large-scale lighting systems into Cyber-Physical Systems (CPSs) that sense their environment and accordingly provide the requisite amount of lighting, resulting in maximal energy savings. We call this *Light-on-Demand*. Secondly, access to real-time information about the health of the lighting system will enable remote monitoring and forecasting of the performance of the system. Consequently, lighting will become amenable to a service-based business models, which involve contractual guarantees of efficiency (measured in lumens per watt), sustainability, and availability. We call this *Light-as-a-Service* (LaaS). Finally, the city-wide OLN can be leveraged for *value-added services beyond lighting*.

Wireless technologies, ranging from mesh to cellular networks, will enable OLNs and support LENSCAPEs. The capacity of these city-wide networks will determine the type of applications that can be supported. To this end, we present simulations that evaluate mesh networking standards, such as IEEE 802.15.4g, and compare them with cellular networking technologies.

As an application of wireless OLNs, we present Light-on-Demand, an energy-efficient lighting system that was deployed at a US army base at Fort Sill, Oklahoma (OK). Networked luminaires, which are equipped with presence sensors, detect pedestrians and vehicles, and exchange information with each other over a wireless mesh network to regulate the lighting intensity. The deployment resulted in energy savings of 92% over conventional high-pressure sodium lamps.

We summarize the main contributions of our paper below.

- LENSCAPEs, an overarching philosophy for designing modern lighting controls as a data-rich infrastructure for smart cities is proposed.
- We present a simulation-based capacity analysis of

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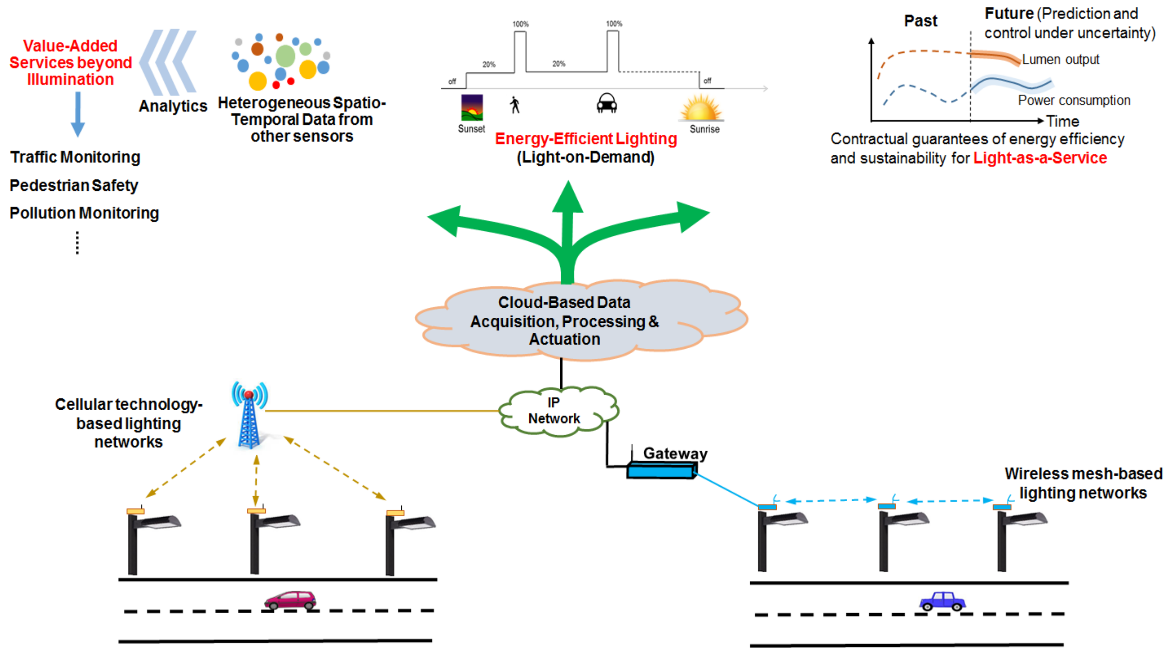


Fig. 1: LENSCAPEs: IoT will transform lighting into a city-wide infrastructure for data-driven applications that enable i) energy-efficient lighting, ii) novel business models for lighting, such as LaaS, and iii) value-added services beyond lighting.

IEEE 802.15.4g-based OLNs and compare such mesh-based networks with cellular technologies.

- We present a case study on Light-on-Demand, a real-world lighting control application that was deployed at a US army base. Results on energy-savings and other lessons that were learned are discussed.
- Ongoing work on other beyond-lighting value-added services that can be delivered via the LENSCAPEs framework is presented.

Our paper is organized as follows. Section II provides background on the lighting industry. Section III reviews networking technologies for LENSCAPEs and simulation results for 802.15.4g-based OLNs. Section IV presents Light-on-Demand. Section V presents an example of value-added services. Section VII presents our concluding remarks and directions for future work.

II. Background

Energy efficiency is the foremost challenge that city planners, administrators, and the citizens would face in the upcoming years. With cities accounting for 70 percent of the world's energy consumption and greenhouse gas emissions [12], there are increasing concerns about urban energy planning and its role in optimizing energy consumption and greenhouse emissions. Outdoor lighting can play a crucial role in addressing these city-wide challenges.

Consider the following. New York City (NYC) has about 262,000 streetlights and the entire United States (US) roadway lighting consists of about 52.6 million light fixtures. The street lights in NYC consume about 6% of the total 4.32 Billion kWh of annual energy usage, whereas roadway lighting across the US consumes about 52.8 TWh of energy annually [15]. Additionally, lighting systems have a significant carbon footprint: the combined CO2-equivalent emissions of roadway, garage, and parking-lot lighting in the US is approximately 71.6 million metric tonnes [9]. Municipalities and other local governments are prioritizing on lighting to save energy and improve the sustainability of this massive infrastructure.

The 288-city survey [13], published jointly by the U.S. Conference of Mayors and Philips in 2014, further highlights how cities are focusing on lighting solutions and systems for energy efficiency. Cities are already devoting attention and resources to lighting, particularly in outdoor areas and public buildings. Specifically, solid-state technologies, such as *Light Emitting Diodes* (LEDs), have received widespread attention: 29% of the cities that were surveyed voted "LEDs/Energy-Efficient Lighting" as their top priority over the next two years. Additionally, 82% of the cities voted LEDs to be the most promising technology for reducing energy consumption and carbon emissions among 15 different technologies. In addition to lower carbon emissions, LEDs offer *fine-grained intensity control* and are therefore much more energy-efficient as compared to traditional lighting technologies. Moreover, modern LED-based lighting systems entail remote monitoring and control via *wireless networking*. Such advanced lighting controls enable maximal energy savings beyond standalone LED luminaires.

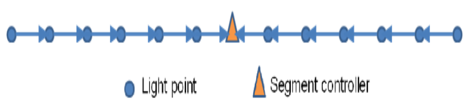
Connected LED-based lighting platforms form the basis of the LENSCAPEs framework. Energy-efficient lighting is just one of the possibilities. A city-wide OLN can be used as the platform for several other smart city applications. Light poles can be augmented with sensors to create a city-wide Wireless Sensor Network (WSN). Data-driven applications can then use lighting as the underlying infrastructure. The data transmission capacity of the OLNs will be a critical factor in enabling LENSCAPEs, which might entail data-intensive applications that compete with lighting controls. To this end, we present a simulation-based capacity analysis of wireless mesh-based OLNs in the next section.

III. Networking Technologies for LENSCAPEs

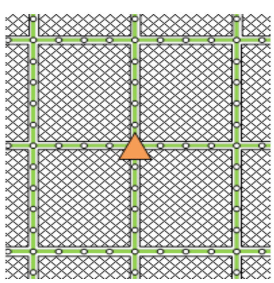
Wireless networks, the underlying infrastructure of the OLNs of LENSCAPEs, can be constructed using either wireless mesh networks, or cellular technologies. Network capacity and operational reliability are key to making a choice between the two. In this section, we present modeling and MATLAB-based simulation results for OLNs based on IEEE 802.15.4g, a relatively recent standard for large-scale wireless mesh networks. Capacity analysis, in terms of throughput per pole per day and network delay, is presented. We then compare mesh-based solutions to cellular OLNs in terms of their operational reliability. We begin with typical topologies for OLNs.

Linear and Grid-Based Topologies: A line topology was used to model a roadway lighting application scenario, see Fig. 2(a). It featured one Segment Controller (SC) and multiple light poles that were placed symmetrically on both sides of the SC. The light poles generated data packets, which were relayed to the SC.

A grid topology, similar to a downtown street map in many cities, was considered, see Fig. 2(b). It featured multiple rows and columns. The SC was placed in the middle of the topology. Due to the multi-hop nature of transmissions, the poles close to the SC could have much more traffic to transmit or forward than poles far away from the SC. As the SC is usually the most expensive device, the goal was to maximize the number of poles that could be supported by each SC.



(a) Line Topology.



(b) Grid Topology.

Fig. 2: Line and grid topologies used for simulating IEEE 802.15.4g-based OLNs. In the grid topology, the rows and columns indicate streets of a metropolitan area and the white circles denote the regularly spaced light poles. The SC is denoted by the orange triangle in the center.

In order to evaluate the network capacity under different physical layer (PHY) mode options, we consider a reporting-only tele-management application. Each light pole generates data towards the SC once every day. Network delay analysis assumes that each pole has 5 KB of data to transfer per day. Relevant performance parameters include the amount of data each pole is able to transmit towards the SC, as well as network delivery delay.

PHY/MAC-Layer Parameters: The IEEE 802.15.4g standard draft [1], support several modulation schemes. We chose Gaussian Frequency-Shift Keying (GFSK) and Orthogonal Frequency Division Multiplexing (OFDM) for our simulations as they have the broadest support in the standardization group. GFSK can achieve 200 kbps, while OFDM can deliver data rates of 800 kbps in the 902-928 MHz frequency band. The maximum PHY payload size of 802.15.4g is 2047 bytes. Assuming a receiver sensitivity of -90 dBm, an OFDM-based implementation of 802.15.4g can support transmission ranges of upto 2600 m.

We assume that each packet uses the shortest possible protocol header. Each frame includes a compressed 6LoWPAN header and a non-encrypted MAC frame. Therefore, each data frame has a 19-octet header including IP, UDP, MAC headers and a field for Frame Check Sequence. Some of the default parameters were as follows. Inter-pole distance: 100 m transmission power: 10 mW, path loss exponent: 2 (for line of sight (LOS) transmissions) and high attenuation through buildings is assumed for the grid topologies, Bit Error Rate (BER): 10^{-5} unless otherwise indicated.

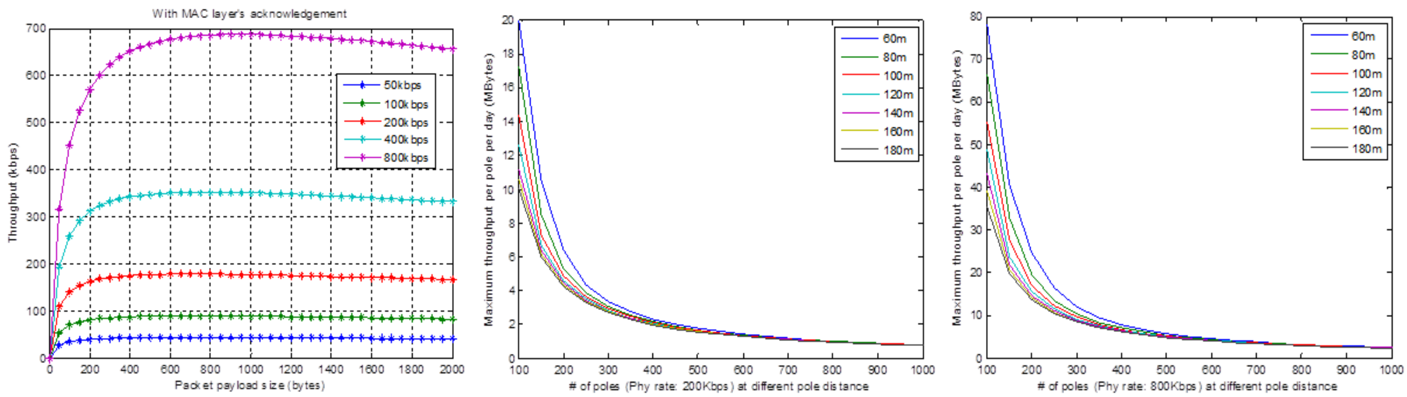
Optimized Link Layer Scheduling: The simulations were intended to test the limits of IEEE 802.15.4g schemes. To this end, we assumed that a smart scheduling algorithm is executed to avoid all medium-access collisions by maximizing spatial reuse, and consequently the network throughput. This helped us derive upper bounds for the network capacity.

Simulation Results: First we evaluated the performance of a single link assuming there are no other transmissions around it. The objective was to determine the impact of the different PHY data rates on the link throughput, which also depends on the packet payload size and the Signal-to-Noise Ratio (SNR). The MAC layer's acknowledgement was factored into the throughput calculations. Fig. 3 (a) shows the link throughput for different data rates as the payload size is varied from 0 to 2000 bytes. As expected, the throughput increases with packet size before saturating due to fragmentation and/or re-transmissions.

For linear topologies, we also studied the impact of inter-pole distance on the maximum throughput that can be delivered per pole per day. The inter-pole distance was varied from 60 m to 180 m. Fig. 3(b) shows the maximum throughput when the SNR is 9 dB and the data rate is 200 Kbps. Higher throughput can be achieved for small pole distances, especially when the total number of poles is small.

When the number of poles is large, the maximum throughput is not affected by pole distance. This is because of spatial reuse: higher inter-pole distance ensures that some poles are out of the interference range of others, which leads to lesser throughput degradation, as more poles could be scheduled for simultaneous transmissions. In Fig. 3(c), we used a much higher data rate of 800Kbps, which is enabled by OFDM with an SNR of 12dB. In this scenario, the pole distance leads to higher relative differences when the total number of poles is small. Additionally, the maximum throughput per pole is also much larger due to the higher data rate.

Throughput and network delay results for the two topologies are summarized in Table I. Each pair of values correspond to the results for linear and grid topologies respectively. The throughput refers to the all packets transmitted by each pole, including the forwarded packets. The assumed SNR values are rough approximations of real devices.



(a) Impact of packet size, BER=10^{-5}.

(b) Impact of inter-pole distance, data rate = 200 Kbps, SNR = 9 dB.

(c) Impact of inter-pole distance, data rate = 800 Kbps, SNR = 12 dB.

Fig. 3: Simulation results for IEEE 802.15.4g-based OLNs.

We can observe that IEEE 802.15.4g PHY modes can provide reasonable throughput of 1157.0 KB per day at 800 Kbps data rate when there are 1000 nodes in the OLN. The throughput decreases as the number of poles increase; when there are 10,000 poles, the throughput is significantly lower: 94.53 KB per day. A ten-fold increase in the number of nodes not only leads to a ten-fold increase in the traffic, but also leads to more traffic congestion and retransmissions. Consequently, the performance degrades by more than a factor of 10. For the grid topologies, we can also observe that the throughput decrease 22 times whe the number of pole increase only 10 times. This shows that the number of poles in the network can significantly impact the performance.

TABLE I: Maximum throughput and Network delivery delay given 5K bytes per pole per day for linear and grid topologies.

		Throughput (KB)			Delay (minutes)		
Data Rates (Kbps)		200	400	800	200	400	800
SNR (dB)		9	15	21	9	15	21
Number of Poles	1,000	779.67, 899.67	958.97, 1778.70	1157.0, 3477.72	9, 8	7, 4	6, 2
	5,000	149.88, 124.03	176.44, 210.34	192.99, 411.25	48, 58	40, 34	37, 17
	10,000	74.57, 58.64	87.35, 80.79	94.53, 155.99	96, 122	82, 89	76, 46

Discussion: The PHY data rates can significantly impact on the system performance. Although higher data rates most likely have higher SNR requirements, the gain in network capacity (e.g. amount of traffic or poles supported) is also significant. The need for network performance improvement will become much more evident as new applications, such as surveillance and environment sensing, are integrated into LENSCAPEs. IEEE 802.15.4g standards are well suited for delay-tolerant applications.

Inter-pole distance and communication radius can significantly impact the performance of small networks, where all poles are close to the SC. An increase in the inter-pole distance or a decrease in communication radius tends to increase the required number of hops to reach the SC. This leads to more contentions and worsens performance. However, these two parameters do not impact larger networks, where multi-hop transmissions are common. In summary, the interplay between the network topology and physical-layer parameters can be crucial for LENSCAPEs, especially for relatively small OLNs.

Our simulations make two crucial assumptions: the existence of a smart link-layer scheduling algorithm and network routing overheads being negligible for calculating throughputs. Despite these limitations, the simulations give us an upper bound on the capacity of IEEE 802.15.4g-based OLNs. Such simulations can be used to understand the performance limitations and tradeoffs that can impact the Quality of Service (QoS) rendered by LENSCAPEs.

Operational Reliability Issues

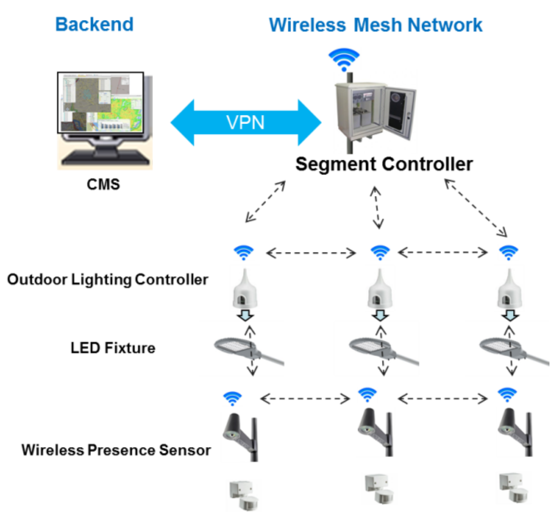
The simulation results indicate that using 802.15.4g with 800 kbps, a lighting network with 5,000 light poles can achieve a throughout of 192.99 Kbytes, which can be used to support other data-enabled sensing applications of the LENSCAPE framework (see Sec. V for examples). However, *large-scale deployments of wireless mesh networks in mission-critical projects are prone to reliability issues*. Node failures, which may occur randomly, can disrupt the links of the lighting network. Despite the self-healing nature of such networks, it is difficult to estimate performance degradation apriori. Consequently, the applications of the LENSCAPE framework would suffer from poor QoS. Moreover, detection and eventual recovery from such faults in large-scale outdoor networks are labor-intensive and potentially very expensive for a lighting service provider. Therefore, a pragmatic comparison of mesh-based solutions with cellular networks, which are maintained by external service providers and guarantee reliability and QoS, is critical for the LENSCAPE framework.

Operational reliability and QoS guarantees for large wireless mesh networks have been investigated by the research community extensively, see [3], [5], [4], [7]. Operational characteristics, such as Mean-Time-To-Failures (MTTF) and Mean-Time-To-Repair (MTTR), can significantly affect the QoS. As reported in [3], a large number of redundant nodes are needed for high availability. Specifically, *MTTF and network availability increase linearly with the number of redundant nodes*. The desired MTTR for city-wide wireless mesh networks is approximately four hours, see [7]. Therefore, node or link failures require low response times, which can be potentially expensive for service providers.

IV. IoT Enables Energy-Efficient Lighting

LENSCAPEs can be used to make lighting adaptive, and therefore more energy-efficient, as follows. The OLN can either be augmented with presence sensors, or utilize other datasets and historical patterns, to detect the presence of pedestrians or vehicles and accordingly provide the requisite amount of lighting. Mesh-based networks, such as the ones discussed in the previous section, can be used as the underlying infrastructure. We call this *Light-on-Demand* (LoD). In this section, we elaborate on the LoD system and present a case study on a real-world deployment.

The architecture of the LoD system, which is illustrated in Fig. 4 (a), is as follows. The luminaires, which are equipped with sensors, controllers, and radios, form a wireless mesh network to exchange event detection and lighting control information across the network. The RF modules, which connect the luminaires, operate in the 915 MHz band, which has been approved for unlicensed operation (according to FCC 47 CFR Section 15.247) and implement the IEEE 802.15.4 standard. The presence sensor is a camera that has a detection zone of up to 20 m - 30 m (20 m for pedestrians and 30 m for vehicles) radius around the luminaire. The Outdoor Lighting Controller (OLC) module regulates the illuminance of the luminaire by based on the information provided by the presence sensor and the neighboring luminaires.



(a) LoD Architecture.

Fig. 4: LoD: An adaptive lighting system based on the IoT.

The LoD system works as follows. The default level of lighting is usually set to around 10% of the maximum intensity. When a pedestrian or a vehicle enters the coverage area, the nearest presence sensor detects the motion and broadcasts the event to all the luminaires over the mesh network. When the lighting controllers of the luminaires receive the broadcast message, they increase the illumination to the maximum level for a pre-set amount of time. Different light levels can be configured for different objects. After the pre-defined interval has elapsed, the lighting is reset to 10% of the maximum intensity unless another event message is received from a neighboring luminaire.

LoD can also exploit the wireless network for over-the-air upgrades, easy installation, commissioning, and maintenance. The sensing and light actuation technology can also augment surveillance and emergency response systems by increasing the lighting intensity and coverage above normal levels.

A. *Case Study: LoD Implementation at Fort Sill, Oklahoma*

The LoD system was implemented and then deployed at the U.S. Army installation at Fort Sill, Oklahoma, as part of a Department of Defense (DoD)-sponsored research project, entitled "Dynamic Exterior Lighting for Energy and Cost Savings in DoD Installations" [8]. We elaborate on some of the findings from this real-world deployment.

The LoD system was deployed at a Tactical Equipment Maintenance Facility (TEMF) in Fort Sill. TEMFs, which resemble large parking lots, are used for parking military vehicles and occasionally carrying out maintenance work on them. This intermittent usage pattern makes them an ideal candidate for LoD-based adaptive lighting.

The wireless network for the deployment was based on the Starsense platform [10]. The camera-based sensor was made using commercial off-the-shelf components. Image-acquisition and digital signal processing were used to extract the relevant motion information (e.g. vehicles vs pedestrians) from image sequences. Before the actual deployment, a test bed was designed and constructed in a parking lot at Philips Research's Briarcliff campus for thorough debugging and testing. This test bed consists of 21 poles with 42 luminaires, OLCs, sensor nodes, one segment controller, modem, laptops for visualization and backend processing including debugging.

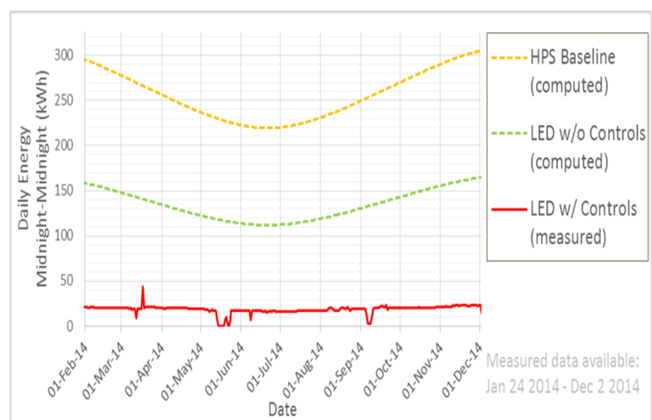


Fig. 5: Energy savings obtained by the LoD system at the TEMF at Fort Sill, OK.

Fig. 5 shows the energy savings obtained by the LoD system over the existing 454W High-Pressure Sodium (HPS) lamps. The HPS lamps were replaced by 280W LED luminaires. Measurements were conducted from January to December of 2014. The baseline power consumption, computed using on typical usage patterns, was 56.85 MWh. LoD deployment led to 92% average energy savings over the HPS lamps resulting in a power consumption of 4.54 MWh.

Moreover, Fig. 5 also shows the energy savings over LED-based luminaires that implement a static dimming schedule (shown in green). *The adaptive nature of LoD, enabled by the wireless sensor network, is instrumental in optimizing* *lighting to minimize the power consumption. In other words, limiting the luminaires to standalone LEDs can considerably undermine the power savings.*

The cost of building, deploying, commissioning, and maintaining LoD systems is critical to their adoption. The quality and the number of cameras (sensors) employed and their spatial distribution, can affect the overall cost of the system. Efficient techniques of placing the cameras, based on geometrical constraints, can help in minimizing deployment costs.

V. Smart Lighting Systems as Platforms for Value-Added Services

Connected lighting systems can go beyond lighting control by providing value-added services that benefit the citizens. Connected luminaires can be augmented with various types of sensors to create a city-wide Wireless Sensor Network (WSN). Light poles provide a widespread platform to implement WSN-based sensing environments, which can be used to collect data, derive insights using *analytics*, and eventually deliver useful services, as shown in Fig. 1. In this section, we elaborate one such WSN-based application Air Quality Monitoring.

Air quality monitoring entails measuring six main types of pollutants: Ozone, suspended particulate matter, carbon monoxide, nitrogen dioxide, sulphur dioxide, and lead. Additionally several hazardous air pollutants are monitored by the United States Environmental Protection Agency (EPA) [14]. Existing monitoring systems suffer from two main drawbacks: i) there is lack of fine-grained real-time measuring points, especially in urban areas, and ii) the high cost of the monitoring systems prevents widespread deployment. For example, the air quality in all the five boroughs of New York City is monitored by 17 stations. A much higher granularity of monitoring can be achieved by installing relatively cheaper sensors on light poles and using the existing OLN to disseminate the information. Accuracy of OLN-based monitoring and the associated data transmission costs are currently under investigation.

Sensing can take the following two approaches. One can measure for *compliance* or for *informative* purposes. Compliance-oriented sensing results from regulations, such as EU-regulations of the EPA's standards, and aims at meeting norms and regulations. For example, in the Netherlands, National Institute for Public Health and the Environment, RIVM, is commissioned by the Dutch government to ensure that the ambient air quality conforms to EU-regulations. On the other hand, Informative monitoring is intended to educate the public, e.g. on their outdoor activities. Compliance-oriented monitoring focuses on raw data collection, but informative measuring is all about translating this raw data into meaningful information meant for the public.

VI. Related Work

Implementing smart city platforms using the lighting infrastructure has been an active area of research. In this section, we review existing approaches and compare and contrast them with the LENSCAPE framework.

In [11], [18], authors propose to augment existing systems, such as power grids and light poles using the IoT framework. Such approaches leverage upcoming wired and wireless networking technologies to improve data acquisition, health monitoring, and control of large-scale systems. The LENSCAPE framework goes beyond enabling efficient operations of large systems in several ways. LENSCAPE envisions to transform lighting into a service-oriented platform that can host applications related to illumination, as well as other aspects of smart cities. LENSCAPE leverages the highly granular city-wide lighting infrastructure to render these services.

The concept of urban IoTs, proposed in [19], is closely related to the LENSCAPE framework. In [19], the authors present an extensive review of networking technologies that are suitable for city-wide IoT deployments. They also present a case study on the city of Podova, Italy, where a lighting-based IoT network was setup to monitor the correct operations of light bulbs, temperature, humidity and pollutant levels. A dedicated network was setup for these devices, which is in contrast with LENSCAPE, which utilizes existing networks of light poles to piggyback the data generated by smart city applications.

The scale of the underlying infrastructure presents several implementation challenges to LENSCAPE. Scalable discovery of identities of different entities, such as luminaires and segment controllers, and their computational resources is one such challenge. In [6], authors propose an infrastructure-discovery scheme, called "digcovery" for this purpose. Such mechanisms will be crucial for LENSCAPE, which depends on plug-and-play features of heterogeneous devices.

VII. Conclusion

We presented the LENSCAPEs framework to facilitate energy efficiency and sustainability for smart cities by enabling i) maximal energy savings from lighting, ii) transformative lighting business models, and iii) exciting new avenues of energy efficiency beyond illumination. We highlighted the potential of IoT-based lighting-enabled smart city applications using LoD, a real-world lighting control application, which maximizes energy savings as compared to conventional techniques.

Relatively small deployments, such as LoD, can leverage custom-built wireless mesh networks, whereas city-wide systems can benefit from the reliability and pragmatic nature of cellular technologies. *Today, two approaches to smart cities based on OLNs have emerged: a) monolithic customized technologies implemented by a small number of service providers, or b) existing technologies, such as cellular, that are relatively cheaper and widely available.*

Going forward, we will further investigate the aforementioned choices, including beyond-lighting value propositions. Additionally, the interplay between the data transmission capacity and the value derived from different types of sensors will be explored. Understanding the tradeoffs therein will help municipalities and other local governments strategize as they evolve their smart cities in the years to come.

Acknowledgment

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